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Review Article

Overview of Biochar-Based Nanocomposite Materials: A Comparative Analysis

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Abstract

Biochar has seen an increase in its usage across various fields due to its improved physical and chemical properties. Its reach has extended to cutting-edge scientific fields like energy, fuel cells, transportation, and membrane development. Specific synthesis conditions are crucial for biochar production, although they can sometimes face disruptions. Concerns persist regarding the separations and reusability of biochar, especially when it is in fine powder form. Integrating biochar into nanocomposites would be a significant advancement. Overcoming barriers to easy application requires practical and utilization-focused strategies. By enhancing the sorption potential of biochar nanocomposites through impregnation with various substances, like nano metal oxides or magnetic biochar, improvements can be made. This chapter discusses the comparison between pure biochar and nanocomposites, current research trends, potential applications, and areas needing further exploration in this field(Figure 1).

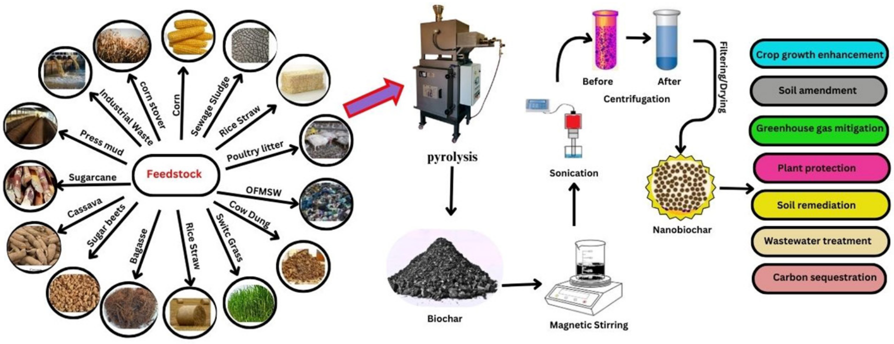

Figure 1: Graphical abstract for biochar nanocomposites.

Keywords: Biochar; Nanobiochar; Nanocomposites; Adsorption; Pyrolysis

Introduction

Carbon-based nanomaterials, like C60 fullerene, are gaining more attention across various fields such as biomedical, agriculture, energy, catalysis, and environmental protection. In plant growth, these materials are found to enhance the efficacy of fertilizers and pesticides, resulting in increased tomato and flower yields [1-3]. Nanocarbon, exemplified by nanotubes, has shown promise in cell membrane penetration and carrying drugs and genes [4,5]. Biochar is explored for its ability to remediate toxins like organic pollutants and heavy metals from wastewater, representing an affordable precursor to carbon nanoparticles. Ongoing research is focused on biochar, produced by controlled heating of biomass like waste from livestock and agriculture, with potential benefits for mitigating global warming. Waste materials like greenhouse gases and bulky biochar can be transformed into solid biochar, opening avenues for sustainable agricultural practices and environmental management [6,7]. The size of biochar particles produced during pyrolysis is measured in centimeters using a micrometer [8]. When these particles are reduced to the micron range (10-600μm), their adsorption capacity is improved by increasing the potential adsorption sites [9-11]. Research indicates that reducing biochar particles to the nanoscale (below 100nm) results in heightened surface energy, adsorption capacity, and biological activity [12-14]. The rise in popularity of nanobiochar is attributed to the fusion of nanotechnology and biochar technology. The size of nanoscale biochar-based materials is controlled by the pyrolysis or exfoliation temperature, offering various applications such as adsorption, influencing plant growth, carbon emissions, and mitigating global warming [15,16]. Biochar materials with nanoscale particles have demonstrated effective adsorption of aqueous solutions, making them valuable in removing contaminants due to their high adsorption capability, extensive surface area, environmental abundance, microporosity, and structural strength [17,18]. Thermal processing of biomass not only produces biochar but also biofuel and syngas. The success of pyrolysis depends on factors such as raw materials, pyrolysis technology, and conditions [19-21]. Powdered biochar can be difficult to remove from water when used for adsorption in water treatment due to its small size and limited adsorption capacity. Nanobiochar can enhance the chemical and physical properties of biochar, addressing some of its limitations. The unique nanostructure of nanobiochar improves surface area, mechanical stability, heat resistance, and adsorption capacity [22,23]. Carbon nanomaterials with topological defects can affect energy production and electron transfer [24]. Nanobiochar, with its porous structure and high alkalinity, shows promise for adsorbing pollutants like heavy metals, PCBs, PAHs, antibiotics, and enhancing enzymes in soil [25,26]. Nanobiochar is increasingly being used in various applications such as power generation, wastewater treatment, and organic dye absorption due to its unique properties like hydrophobicity, microporosity, and specific surface area [27,28]. It can also serve as a beneficial material in medicine due to its porous structure, high surface-to-volume ratio, and abundance of beneficial elements. Studies have demonstrated that nanocomposites can enhance the quality of pores, functional groups, and active sites, leading to improved catalyst performance and separation efficiency, especially when CNTs are combined with biochar. These hybrid nanocomposites have proven to be cost-effective for removing pollutants and pigments [29]. Nanocomposites have shown potential as effective adsorbents for heavy metal removal, such as in aqueous Cr (VI) systems [30]. Despite its advantages, nanobiochar has been associated with groundwater contamination as its nanoparticles can migrate through irrigation, surface runoff, and drainage systems, leading to the creation of nanobiochar-heavy-metal composites that pose a risk of spreading heavy metals and causing soil and water pollution. However, nanobiochar remains a promising, sustainable, and cost-effective solution for various agricultural and environmental challenges [31]. This comprehensive article examines current and past nanobiochar production methods, explores its applications in agriculture, environment, and material science, and provides detailed insights into the fabrication processes involved [32].

Manufacturing nanobiochar composites

The primary way biochar is commonly produced is through a process called pyrolysis, where the feedstock is heated to temperatures between 350 and 750 °C in an environment with very little oxygen [33]. Various thermochemical methods are utilized to create biochar from sources like agricultural waste, solid waste, animal waste, and woody biomass [34]. Gasification, torrefaction, carbonization, pyrolysis, and gasification are among the processes used. Pyrolysis in a low-oxygen environment can produce biochar along with a small amount of bio-oil [35,36]. Gasification is typically used to generate syngas for heat and energy, while fast pyrolysis is another method to create biofuels [37]. Lignocellulosic material is found to yield more biochar than municipal waste. Different chemical and physical alterations are made to enhance biochar's performance, such as using CO_2, chemical reactions, steam coating, acid or base treatments, and adding natural or synthetic nanoparticles. While physical modification techniques like ball milling are less common, early research has shown promising results [38,39].

Graphitic nanosheets were generated while creating nanobiochar directly through flash heating, rather than relying on mechanical methods. Oleszczuk and colleagues utilized a sonicator to produce nanosized particles by dispersing biochars with an ultrasonic vibrator. The most recommended method for producing biochar, as indicated by the current literature, is through ball milling [40]. This technique involves using particle impact to break down materials and increase particle size [41,42]. While double disc milling is less common due to high costs, it is another option for making nanobiochar. Additionally, vibrating disc grinding has been found to produce nanobiochars similar in size and shape to those made using the widely used stone method. Gu et al. [43] demonstrated the use of hydrothermal reactions with agricultural by-products and food residues to create nanobiochar. Large-scale production of biochar involves using cow manure and soybean straw as raw materials, which are decomposed in a high-pressure hydrothermal reactor with concentrated acids. Biochar nanodots ranging from 5nm to 4nm in size were produced through this method. Various techniques can be employed to produce nanobiochar, each with their own advantages and drawbacks. The emerging area of biochar-based nanocomposites has garnered significant interest due to their unique characteristics and potential uses, which will be explored further in the following subsection [44].

Types and synthesis of biochar nanocomposites

Figure 2 shows the process of creating biochar-based nanomaterials, including oxide/oxide biochar nanocomposites, magnetic biochar nanocomposites, and functional biochar coated with nanoparticles. These are divided into three groups as discussed in the article.

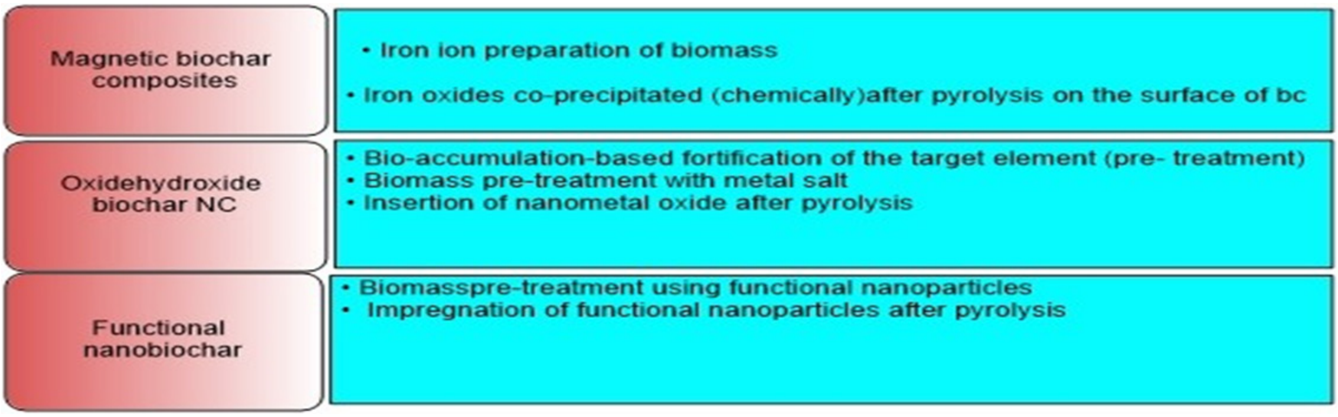

Figure 2: Methods of biochar nanocomposites.

Composites created with magnetic biochar and magnetic nano-biochar

Biochar-based magnetic composites can be created by incorporating iron oxides into biochar through various methods such as chemical precipitation or covering magnetic iron oxide particles like $CoFe_2O_4$ at the nanoscale. The magnetic properties of biochar aid in the removal of contaminants by increasing its adsorption capacity and attracting iron oxide to the surface [45,46]. Studies have shown that nanocomposites with large surface areas, active sites, and catalytic capabilities are more effective in removing bacteria from water. Nanocomposites containing a mix of reducing, oxidizing, and catalytic nanoparticles, like graphitic C_3N_4 and nanoscale zero-valent metals, can simultaneously absorb and break down harmful compounds. Biochar-based nanocomposites offer versatility in managing various types of waste and are suitable for numerous environmental applications [47,48].

Biochar nanocomposites of oxides and hydroxides

Three methods are employed in their creation: i) Enhancing target quality by increasing target efficiency through bioaccumulation is crucial, ii) Pretreatment is part of this process, iii) The study explores the release of nanometal oxides post-pyrolysis through two approaches: pre-impregnation with metals before biomass pyrolysis and direct addition of oxide/hydroxide nanometals into the pyrolyzed biochar.

Biochar coverage with functional nanoparticles or functional nanobiochar

Biochar-coated nanomaterial composites made of graphene, chitosan, carbon nanotubes, and double hydroxide layers are effective in eliminating different pollutants.

Biochar and biochar nanocomposites applications in the environment

While nanobiochar has been extensively studied for various environmental applications such as waste management, pollutant removal, and carbon sequestration, macrobiochar has also been explored by many researchers. Biochar, a renewable energy source, shows promise in combating environmental challenges like climate change. By capturing carbon dioxide during biomass combustion, plants help store carbon long-term. Biochar's ability to sequester carbon makes it a sustainable solution [49]. Researchers are investigating biochar for applications in electrodes, sustainable energy production, and enhancing properties through different modification techniques. Nanobiochar, known for its enhanced adsorption capacity, is effective in removing harmful substances like pharmaceuticals, hormones, insecticides, heavy metals, and personal care products [50].

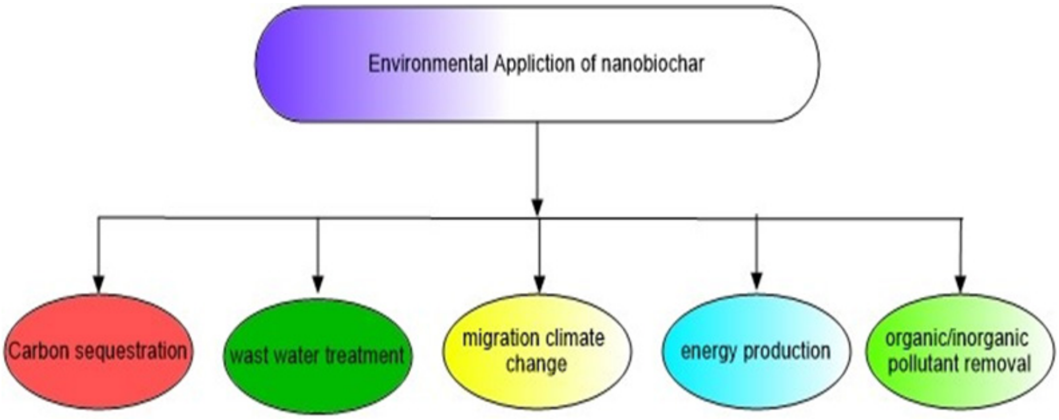

Figure 3: Biochar and biochar nanocomposites: uses in the environment.

Pollutants released from human activities like improper sewage systems, waste disposal, and pesticide usage pose risks to the environment and human well-being. Nanobiochar and biochar enhanced with nanomaterials are highly effective in adsorbing pollutants when compared to regular biochar [51,52]. Biochar is successful in eliminating dangerous substances such as pesticides and trapping metals, which helps tackle environmental and health concerns. Nanobiochar is being explored as a promising method for cleaning up different types of pollutants as well [53]; (Figure 3).

Removing pollution by utilizing adsorption with phytoremediation through the use of nanobiochar and biochar-based nanocomposites

Nanobiochar is an effective pollution adsorbent that undergoes various complex adsorption processes like ion exchange, complex formation, precipitation, antielectrostatic, and physical adsorption. These processes play a significant role in adsorbing pollutants from the environment, with different mechanisms observed for different pollutants such as glyphosate and Ni. The addition of acidic groups enhances electrostatic adsorption behavior, while high-temperature pyrolysis improves void structure richness favoring physical adsorption [54]. Biochar and nanocarbons are widely used for their adsorption properties in removing contaminants and natural organic materials, highlighting the importance of understanding adsorption mechanisms for effective pollution removal [55].

Studies have demonstrated that biochar, including nanobiochar, can successfully eliminate heavy metals, drugs/chemicals, dyes, and other contaminants from different organisms. Table 1 offers a detailed list of various nanobiochar composites and their effectiveness in this regard [56-79].

Table 1: Pollutants are removed by adsorption using nanobiochar and biochar nanocomposites.

Source of feed	Composite Nature	Contaminants Eliminated	Absorption/Removal Capability	References
Pinewood	produced from pinewood nano biochar	Carbamazepine (CBZ)	95%	[22]
(BC-PW) Pinewood	Nanobiochar with oxygen functionalization	CBZ	83% of the water that was tainted and 86% of the secondary wastewater were removed.	[23]
Hickory chips, bagasse from sugarcane	Functional CNT-biochar nanocomposite	M.B.	6.25mg/g	[43]
stove for maize	Ironoxide MCSBC magnetic corn stover biochar	Fluoride with inorganic matter	4.11mg/g is Q25 (250). Q35 and Q45 both have 3.45 and 3.41mg/g.	[50]
Dendro/waste biochar	Carbon nano biochar	Trichloroethylene (TCE), oxytetracycline (OTC)	For GL, it is 83mg/g and for OTC, it is 520mg/g.	[54]
hematite, natural pinewood	HPB (Hematite-modified Biochar, Magnetic Biochar)	As (V)	There are two types of HPB: 429mg/kg and PB (265mg/kg). types of biochar.	[56]
shredded cotton	A functional nanoparticle-coated graphene surface	M.B. (methylene blue) (Org)	174grams/g	[57]
Cotton trees, sugar beet hulls, peanut shells, and pine trees all contain sugarcane bagasse	MgO nanopowder	Nitrate and phosphate inorganic	Phosphorus content of 85mg/g and nitrate content of 95mg/g	[58]
A leaf of a tomato	Nanometal oxide particles are made up of MgO, $Mg(OH)_2$.	Inorganic Phosphate	R2 = 0.78 (Correlation: P removal rate versus Mg content in biochar) has $p < 0.001$.	[59]
Bagasse from bamboo and hickory chips	Biochar clay composite	MB	7.90mg/g	[60]
Wood from hickory	Biochar treated with $KMnO_4$ (Nano metal oxide))	Lead (II), Mercury (II), and Cd (II),	According to the results, Pb(II) (53.1mg/g), Cd(II) (28.1mg/g), and Cu(II) (34.2mg/g) were measured.	[61]
The pine tree	Composite of biochar and manganese oxide (Mn/BC)	Lead (II)	From 6.4% to 98.9%, lead(II) removal efficiency increased.	[62]
traces of eucalyptus leaves	Biochar that is magnetic	Lead (II)	Efficiency of desorption: 84.1%	[63]
pine tree	Foremost or BPB modified biochar MnCl24H2O (MBC), and manganese oxide (MO)	Arsenic(V)&Lead (II)	Specifically, unmodified MPB (0.59 and 4.91 g/kg), modified biochar (0.20 and 2.35 g/kg), and BPB (0.91 and 47.05 g/kg)	[64]
maize husk	Biochar that has been treated with manganese oxide	As	14.3mg/g	[65]
Michael stem	Calcium Oxide (CaO)	Phosphate	more than 100mg/g	[66]

Algal biomass handled with vermiculite	Nanocomposites of SiO_2-biochar, or VBC	Phosphate	As compared to pristine biochar (BC), which had phosphate adsorption of 98.2mg/g, VBC had 159.4mg/g, or almost 1.6 times greater.	[67]
maize straw	Ce-MSB is the term for maize straw biochar functionalized with nanocerium oxide.	PO_4^{3-}	78.1 milligrams	[68]
corn husk	Biochar with iron (Fe) impurities (FBC)	As(V)	FBC (600 times higher at 6.80mg/g), unaltered BC (0.017 mg/g)	[69]
Rice husk	Hydroxyapatite–biocharnano–composite, or HAP-BC	Copper II, Pb II, and Zinc II	Zinc(II), Pb(II), and Cu(II): 561,80 mg/g, 826,45 mg/g, and 925,93 mg/g BC; HAP: BC 1000 mg/g, 833,33 mg/g, and 935,93 mg/g	[70]
stove for corn	Biochar polluted with zinc and nano ZnS/ZnO (Nano metal oxide)	Copper(II), Lead(II), and Cr(VI)	91.2%, 24.5%, and 135.8% of a gram	[71]
leaves from a palm tree and rice straw	Leaf nano biochar from rice straw-palm trees	NH_4+ and H_2PO_4–	Infinite capacity	[72]
Rice husk	Clay/biochar composites with functionality	In addition to Cadmium (Cd)	The reductions of as (Atapulgite/ biochar1), Cd (36 and 44%), and as (79 and 82%) are all included in this.	[73]
Rice husk	The nano biochar of rice straw (Nano BCs)	Genes linked to antibiotic resistance-amp C, erm B	eDNA adsorption: Nano 700 (60%) and Nano 400 (31.3%)	[74]
grain straw	Nanobiochar with magnetic properties	Hg (II) with Tetracycycline with	Both 268.3 and 127.4mg/g,	[75]
Plantain leaves	Coating nano biochar with sodium hydroxide	Hydrochlorometformin (MFH)	Sea water (92.0%), wastewater (97.0%), and tap water (87.0%) all had MFH medication (10mg/L) removed.	[76]
chipped hickory wood	BC nanocomposites with copper oxide (CuO) modification	Radical Red 120, or RR120	1399mg/g, elimination effectiveness (46%).	[77]
Rice husk	Magnetic biochar based on calcium, or Ca-MBC	Both As and Cd	increased, on the 32nd day, the pH from 0.3 to 0.9 units and the CEC from -7.1 to 11.5 cmolc/kg of soil.)	[78]
Sawdust from red cedar (Thujaplicata).	magnetic biochar with an iron modification	As, Cadmium, and Lead	Within 24 hours, 20–30% of the As, Cd, and Pb were removed.	[79]

According to Naghdi et al. [11] the use of nanobiochar derived from pine wood effectively removed 95% of carbamazepine and other micropollutants from water. Ramanayaka et al. [43] employed grinding techniques to create nanobiochar from waste material. Dendro biochar-based graphitic nanobiochar was able to eliminate glyphosate, Cr(VI), OTC, and Cd(II). Li et al. [66] discovered that modified ZnO/ZnS nanobiochar had a higher adsorption capacity for Cu(II), Pb(II), and Cr(VI) compared to unmodified biochar [80,81].

The application of nano biochar and biochar nanocomposites for the treatment of wastewater pollution

Heavy metals in water gather and cannot be broken down, posing significant environmental challenges. Removing them is crucial, and various adsorbents like activated carbon and silica gel have drawbacks like limited capacity. Biochar has emerged as a promising solution, with advancements making it more effective in removing pollutants from water [82,83]. Coating biochar with catalytic chemicals enables it to adsorb and decompose organic contaminants simultaneously. Nanobiochars are now being developed to enhance their ability to remove ionic and water-soluble pollutants, including heavy metals like arsenic, chromium, lead, cadmium, and copper. Magnetic nanobiochar derived from wheat straw can swiftly reduce contaminants like TC and mercury in water within 12 hours [84,85]. This research showed that by utilizing photosynthetic organisms of Fe_3O_4/biochar nanocomposite, 82.1% of oxygen demand and 87.5% of NH_4 could be effectively removed from wastewater [86,87]. Various modified biochar materials like BC-MnOx, BC-NaOH, and BC-FeOx were tested in this study for their ability to adsorb cadmium (II) effectively, with impressive adsorption capacities. The most successful approach proved to be using iron oxide-impregnated mesoporous rice husk nanobiochar (IPMN) for arsenic removal [88-90].

Conclusion

Research indicates that biochar nanocomposites have the potential to address various agricultural and environmental issues such as heavy metals, dyes, and chemicals. These composites are effective in absorbing impurities, enhancing plant growth, recycling nutrients, and eradicating harmful effects. Nanobiochar and nanocarbon materials offer opportunities in diverse fields like sensors, electrodes, supercapacitors, and medical applications. Nevertheless, it is essential to consider biological and environmental aspects. This study underscores the necessity for further examination regarding the impact of nano-biochar feedstocks, particle size, PAH profile, fluctuating concentrations, and trace metals on plants, microbial populations, and other factors. Future research will concentrate on maximizing the production of nano-biochars, reducing agglomeration in electrode supercapacitors, and harnessing the potential of nanobionic plants for fertilizer delivery.

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