

Nanobiochar: A Novel Materials for Environmental Remediation

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Abstract

Nano biochar, a carbon-dense substance, is gaining attention for its essential contributions to sustainable farming and environmental stewardship. It is created by pyrolyzing biomass in a regulated environment, transforming organic material into a stable carbon form. Nanobiochar is a refined form of biochar at the nanoscale, featuring improved characteristics and versatility for many contemporary uses. It can be produced efficiently from larger chunks of biochar using methods such as ball-milling, centrifugation, sonication and hydrothermal synthesis. Additionally, nanobiochar can be altered or tailored to create “engineered nanobiochar” or biochar nanocomposites that possess superior properties and applications. Nano biochar has several important characteristics, including increased surface area and porosity, improved soil fertility, better nutrient retention and recycling, slow-release fertilizer properties, a boost in microbial populations and carbon sequestration. Additionally, biochar contributes to waste management by using agricultural residues as raw materials. Colloidal and nano-sized Biochar (nano-BC) have various characteristics, including hydrophobic surfaces, small size, a very high specific surface area, a micro-porous structure and a range of surface functionalities (such as hydroxyl, carboxy and lactonyl groups). These properties greatly improve the ability of nano-BC to adsorb and immobilize different pollutants, including heavy metals, pesticides, PCBs, PAHs and more. This review article outlines the significant characteristics of nanobiochar and its role in promoting sustainable development.

Keywords: Nanobiochar; Sustainable farming; High surface area; Porosity; Carbon sequestration; Phytoremediation

Introduction

Biochar is a carbon-rich by-product derived from lignocellulosic biomass through various thermochemical methods (Figure 1). By reducing its size to the nanoscale, biochar can be converted into “nano-biochar”. This nano-biochar exhibits exceptional physico-chemical properties compared to macro-biochar, such as enhanced stability, distinctive nanostructure, increased catalytic efficiency, larger specific surface area, greater porosity, improved surface functionality and a higher number of active sites on its surface [1]. Nano-biochar, created through ball milling and pyrolysis, has more substantial applications than traditional biochar. Biochar is a carbon-rich material produced from the anaerobic digestion of organic matter, either in total absence of oxygen (pyrolysis) or with some oxygen present (gasification). The solid material obtained from pyrolysis features micro-pores that enhance its sorption characteristics, a high specific surface area and multiple oxygen-containing functional groups. The sorption properties are significantly improved due to nano-enabled features, which include abundant oxyl groups, an expansive surface area and increased reactivity [2]. Biochar is a carbon-dense substance produced by pyrolyzing organic materials such as wood, agricultural residues or animal waste in a low-oxygen setting. It is commonly utilized in agriculture and environmental management because it improves soil fertility, sequesters carbon and reduces greenhouse gas emissions [3]. The use of biochar has grown in multiple areas due to its enhanced physical and chemical characteristics. Its applications now include advanced scientific domains such as energy, fuel cells, transportation and membrane technology [4].

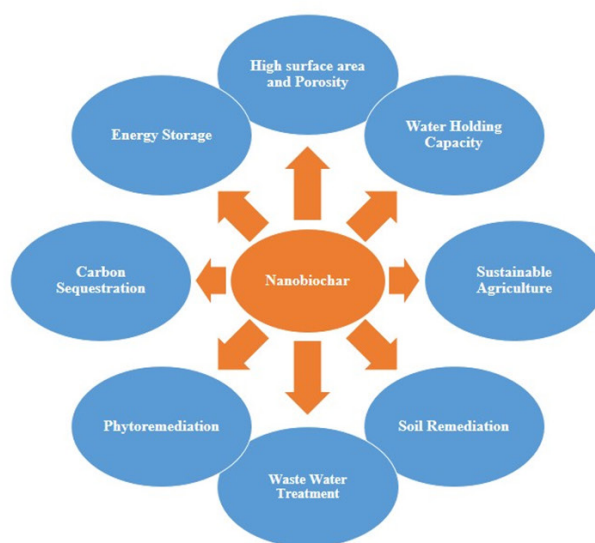


Figure 1: Graphical abstract of nanobiochar and its applications.

Nanomaterials, such as nanochar-composites, have the ability to absorb a wide range of contaminants and pollutants found in contaminated water. They offer several benefits, including the bioremediation of pollutants and pesticides, treatment of plant diseases, enhancement of plant growth and improvement of soil fertility, as well as wastewater treatment. The raw materials used to create biochar are readily accessible and inexpensive, contributing to the generally low production costs of nano composites [5]. Nanobiochar is versatile and can be applied in various fields, including wastewater treatment, healthcare, electrode materials, supercapacitors and sensors, due to its extensive physical and chemical characteristics [6]. Nano biochar, a carbon-rich substance, is gaining recognition for its essential role in promoting sustainable agriculture and environmental stewardship. It is created through the pyrolysis of biomass in controlled settings, transforming organic materials into a stable carbon form. This method effectively sequesters carbon and reduces greenhouse gas emissions while providing a valuable amendment for soil. In agricultural contexts, biochar presents numerous advantages. Its porous nature improves soil fertility and water retention, creating favorable conditions for plant growth. Additionally, biochar acts as a nutrient reservoir, allowing for gradual nutrient release and minimizing the risk of leaching and runoff. Furthermore, its neutral pH and high organic carbon levels enhance soil health and support microbial activity [7].

Advanced nanostructured materials, such as nanobiochar, have emerged as sustainable solutions to many contemporary challenges. Recently, carbon nanomaterials have been created as effective tools, thanks to their distinct properties and diverse applications across fields like energy, materials science, agriculture and environmental management, particularly in the phytoremediation of various organic, inorganic and heavy metal pollutants [8]. The creation of nano-biochar from biomass waste presents a sustainable, eco-friendly, affordable and potentially effective option. Due to its

improved textural and physicochemical characteristics, innovative nano-biochar materials may excel in carbon sequestration, pollutant elimination and catalytic degradation. Consequently, in the framework of the United Nations Sustainable Development Goals (SDGs) and the Carbon Neutrality strategy, there is an urgent need for new and sustainable approaches to the use of nano-biochar to promote a circular economy aligned with sustainable development principles [9].

Key Features of Nano Biochar

Nanobiochar is characterized by a much higher surface area than conventional biochar, along with increased porosity and an improved capacity for nutrient retention. Its extensive surface functionalities enable better adsorption of contaminants. Additionally, the nano-sized particles enhance its reactivity and interaction with surrounding substances, potentially benefiting soil fertility and microbial communities. This makes nanobiochar a valuable asset for carbon sequestration and environmental cleanup [7].

High surface area and porosity

Nano-BC produced at lower temperatures (300-400 °C) exhibits smaller surface areas (5.6-47.2m²/g). In contrast, nano-BC created at elevated temperatures (450-600 °C) has larger surface areas (342-430m²/g) because of the devolatilization of biomass and the formation of surface porosity [10]. Unlike conventional biochar, nano-Biochar (nano-BC) offers improved specific surface area, adsorption capacity and mobility in soil, which enhances soil quality, supports crop development and aids in environmental restoration. Furthermore, using nano-BC can facilitate carbon sequestration and decrease methane and nitrous oxide emissions from agricultural activities, thereby helping to combat climate change [11]. Biochar features a diverse array of pores, from nanometer to tens of micrometer sizes. According to the International Union of

Pure and Applied Chemistry (IUPAC), these pores can be classified into three categories: Micropores (<2nm), mesopores (2-50nm) and macropores (>50nm). The internal structure of biochar can be assessed by examining pore distribution, which assumes that the complex pore architecture of actual solids can be modeled using equivalent interactions and uniformly shaped pores [12].

Water holding capacity

The application of biochar as a soil enhancer has been proposed to improve water retention, yet there are only a few quantitative studies assessing its effectiveness in this regard. This study primarily aimed to evaluate the impact of incorporating woody biochar (derived from yellow pine pyrolyzed at 400 °C) on the water holding capacity of loamy sand soil at various mixture ratios. Findings indicate that a 9% biochar mixture (approximately 195 metric tons per hectare) can double the water holding capacity by mass, which is significant for agricultural use. Higher concentrations of biochar markedly enhance water retention [13]. The porous characteristics of nano biochar improve soil structure, boosting aeration and the ability to retain water. This benefits plant growth by promoting root development and nutrient absorption [7]. The use of biochar to boost soil's ability to retain water has attracted significant global interest. Adding biochar can improve the physical characteristics of soil and increase its water retention capacity, thanks to its high porosity and extensive specific surface area [14].

Nanobiochar use for sustainable agriculture

Biochar (BC) is currently being utilized in agriculture and environmental cleanup, showcasing a variety of benefits, although there are some limitations. Nano-biochar presents significant potential, particularly for addressing hazardous contaminants and enhancing crop yields. Its positive impact on the physical, chemical and biological properties of soil suggests it is well-suited for agricultural use. Furthermore, nano-BC can effectively manage the movement and absorption of essential micro-and macro-nutrients, as well as hazardous substances like toxic metals and pesticides [15]. Recent challenges related to climate change and technology have profoundly affected the agriculture sector. Specifically, issues concerning agriculture and soil can potentially be addressed through the application of nano-BC. This innovation not only diminishes the natural bioavailability of harmful substances but also helps rehabilitate compromised soils. By enhancing soil characteristics, nano-BC makes the environment more conducive for plant growth and development. It improves soil porosity, strength and water retention, creating an ideal habitat for beneficial bacteria, which are crucial for maintaining soil health [16]. Nano-biochar is a new material that is being explored for various applications, such as in agriculture and environmental cleanup. However, the potential risks it poses in the food chain require additional research. We conducted a study on how nano-biochar (N-BC) distributes and affects health in mice after dietary exposure. Using Balb/c mice, we evaluated the accumulation of N-BC in different organs and its effects on essential organs.

Nanobiochar use for soil remediation

Nanobiochar is primarily used for soil remediation as an efficient adsorbent because of its extensive surface area, which enables it to bind and immobilize a range of contaminants, including heavy metals, organic pollutants and pesticides in the soil. This process reduces the bioavailability and potential toxicity of these substances to plants and organisms, effectively serving as a soil amendment that enhances soil quality and promotes plant growth, even in polluted areas [17]. While there has been a growing interest in biochar for its environmental and agricultural uses, the role of nanobiochar in cleaning up environmental pollutants is not well understood. Unlike traditional bulk biochar, nanobiochar boasts enhanced physicochemical characteristics, including elevated catalytic activity, distinctive nanostructures, an extensive specific surface area and increased mobility within soil [18]. Although studies indicate that biochar can enhance soil health and promote plant growth in challenging conditions while eliminating harmful heavy metals and new pollutants, it remains insufficiently sustainable, cost-effective and efficient. As a result, researchers need to create nanomaterials to protect various aquatic and terrestrial species. Nano-biochar (N-BC), a carbon-based compound, can effectively address metal contamination and emerging pollutants [19].

Nanobiochar use for waste water treatment

Nanobiochar is a nanoscale form of biochar that boasts enhanced physical, chemical and surface characteristics. It offers various benefits, including promoting plant growth and improving soil quality, managing plant diseases, bioremediating pollutants and pesticides, treating wastewater and serving as a support medium for enzyme immobilization. Its cost-effectiveness, sustainability and eco-friendliness make it a promising alternative to traditional methods. Furthermore, it has the potential to combat climate change through its carbon sequestration capabilities [8]. Studies on the adsorption capability of biochar nanocomposites demonstrated that these materials were highly effective in eliminating a range of impurities from water, such as heavy metals, metalloids and both organic and inorganic pollutants [20]. Scaling down biochar to the nanoscale significantly improves its ability to adsorb contaminants. By decreasing the size of original biochar to the nanometer level, the specific surface areas, porosity, mineral exposure and surface functional groups are all increased compared to the original biochar. These enhancements result in better sorption of both inorganic and organic pollutants [21].

Nanobiochar use for phytoremediation

Phytoremediation is a method that utilizes plants to eliminate organic, inorganic and heavy metal pollutants from wastewater. This approach is visually appealing, widely accepted by the public, effective at addressing a wide range of contaminants and environmentally sustainable, with the added advantage of not requiring costly equipment. Various phytoremediation techniques exist, such as phytoextraction, rhizofiltration, phytostabilization

and phytovolatilization, each employing different mechanisms to remove contaminants [22]. While research into biochar has gained traction in environmental and agricultural fields, the role of nanobiochar in remediating environmental pollutants is not well understood. Unlike conventional biochar, nanobiochar exhibits enhanced physicochemical properties, including increased catalytic activity, a distinct nanostructure, a large specific surface area and improved mobility within soil. These distinctive traits position nanobiochar as a promising option for pollution remediation. However, studies on nanobiochar are still in the early stages, with most previous research focused primarily on examining its properties and environmental roles [18]. There is an urgent need to remediate contaminated water and soil to guarantee a sustainable supply of water and food production. Utilizing biochar can significantly aid in this remediation process. Multiple studies have shown that biochar effectively mitigates the harmful impacts of pesticides, antibiotic residues, antibiotic resistance genes and heavy metals [23].

Nanobiochar use for carbon sequestration

Biochar, a sustainable solid substance produced from the pyrolysis of biomass and rich in carbon, has gained attention as an effective method for capturing carbon in soil. This extensive review assesses the existing understanding of biochar's role in this area. It starts by investigating the characteristics and production techniques of biochar, emphasizing its durability as a possible stable carbon repository. Additionally, the review discusses how different feedstocks and pyrolysis conditions affect the physicochemical properties of biochar and its ability to sequester carbon in soil [24]. Biochar is regarded as an effective method for carbon sequestration primarily because it consists largely of recalcitrant carbon, which resists microbial degradation and can remain in the environment for centuries or even millennia. When biomass is converted into biochar, the carbon it contains becomes stabilized and sequestered, preventing its quick release into the atmosphere as CO₂ that would occur during the decomposition or consumption of the biomass. Therefore, as long as the biomass used to create biochar is sustainably managed, growing biomass for biochar production effectively sequesters atmospheric CO₂ in a stable form within the soil [25].

Nanobiochar use for energy storage

Biochar holds promise as an electrode material for energy generation in Microbial Fuel Cells (MFCs) and energy storage solutions such as supercapacitors and batteries. Traditional energy storage methods encounter issues related to resource limitations, expenses and environmental concerns. Derived from biomass through various processes including pyrolysis, hydrothermal treatment and flash pyrolysis, biochar provides a sustainable and environmentally friendly option [26]. Global warming, environmental pollution and an energy deficit in today's fossil fuel-based society may lead to a significant ecological crisis. Utilizing and converting renewable, variable and non-renewable energy sources such as solar, wind, geothermal, water or biomass could

offer a viable solution to this issue. Carbon materials might serve as the most adaptable platform for modern energy storage and conversion technologies. However, traditional carbon materials, derived from coal and petrochemicals, are often energy-heavy and require harsh production conditions. There is a strong need to create efficient methods for generating carbon materials from renewable sources that deliver high performance while minimizing environmental impact [27,28].

Conclusion

From the above study it is concluded that nanobiochar is an important asset for cleaning up of the environment and for sustainable development including various purposes such as energy storage, carbon sequestration, for phytoremediation, for waste water treatment, soil remediation, water holding capacity, sustainable agriculture, high surface area and porosity.

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