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REVIEW ARTICLE

Advancements in nanobiochar for environmental remediation: A comprehensive review

Rajarathinam Deepshikaa[1], Mohan Prasanthrajan[2*], Christopher Sharmila Rahale[1], Subramani Umesh Kanna[3], Ramasamy Mahendiran[4], Kalappan Thangamuthu Parthiban[5] & Vellingiri Geethalakshmi[3]

[1]Centre for Agricultural Nanotechnology, Tamil Nadu Agricultural University, Coimbatore -641 003, India

[2]Department of Environment Sciences, Tamil Nadu Agricultural University, Coimbatore -641 003, India

[3]Tamil Nadu Agricultural University, Coimbatore - 641 003, India

[4]Department of Renewable Energy Engineering, Tamil Nadu Agricultural University, Coimbatore -641 003, India

[5]Forest college and Research Institute, Tamil Nadu Agricultural University, Mettupalayam, Coimbatore -641 103, India

*Email: prasanthrajan.m@tnau.ac.in

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Abstract

This study delves into the diverse domain of biochar and its nano-variant, discussing their definitions, synthesis methods, properties and applications. Biochar, produced from various raw materials through different synthesis techniques, possesses unique characteristics that make it valuable for a wide range of uses. Nanobiochar, a new derivative, offers improved properties due to its nano-scale structure, enabling advanced applications. The study examines the physical and chemical attributes, surface area and pore structure of nanobiochar, along with methods for its functionalization and modifications. Synthesis techniques for nanobiochar are analyzed and compared with those for biochar and activated carbon. The versatility of nanobiochar is highlighted in its environmental, agricultural and energy applications, especially in water and soil purification, soil enhancement and energy storage. The environmental impact and safety considerations are also discussed, including eco-toxicity assessment, fate and transport in the environment and regulatory aspects. Additionally, the study addresses challenges, future perspectives, emerging trends and potential breakthroughs in nanobiochar research, emphasizing the need for ongoing exploration and innovation. In conclusion, nanobiochar shows great potential as a sustainable and versatile material with extensive applications, but it requires careful consideration of environmental and safety issues.

Keywords

Nanobiochar; synthesis methods; properties; applications

Introduction

The origin of biochar can be traced back to ancient Amerindian societies in the South American Amazon region (1). Investigations into the Amazonian dark earth, a man-made soil blend known as terra preta, indicate that these ancient civilizations utilized a carbonaceous material resembling biochar (2, 3). This substance was employed to enhance soil fertility and increase crop productivity. Throughout history, humanity has utilized carbon-rich materials, but it was scientists who introduced the term "biochar" to describe a pyrogenic carbonaceous solid material. This substance is prepared in oxygen-free environments at elevated temperatures and was originally referred to as "agrichar" (4). Researchers have taken a keen interest in biochar technology due to its capacity to address climate change, eliminate pollutants and enhance plant growth as well as improve soil health and fertility (5). Furthermore, biochar production is not only highly cost-effective and environmentally friendly but also effective in repurposing waste resources. It requires minimal energy input and can be produced at temperatures below 700 °C. This type of bioremediation technology has recently been established due to its sustainable, eco-friendly nature, ease of operation and low cost in comparison to traditional and advanced physico-chemical methods (6). Biochar is a carbon-rich material produced from the pyrolysis (heating in the absence of oxygen) of biomass such as wood, crop residues and agricultural waste. It is a stable form of carbon that can be used for various applications such as soil amendment, contaminant remediation and energy production (7). The progress in nanotechnology has enabled the reduction of biochar particle size to the nanoscale, reaching 100 nm or smaller. Recently, researchers have increasingly explored nano-compounds to enhance remediation techniques (8, 9). This development enhances the physical properties and biological effectiveness of biochar particles (10). Nanobiochar refers to biochar that has been engineered at the nanoscale (11). Nanobiochar attracts increasing interest due to its unique environmental behavior. Understanding the formation, physicochemical characteristics and stability of nanobiochar is still limited. However, recent research has been focused on exploring the potential applications and properties of nanobiochar (12). Some potential applications of nanobiochar include its use as a fertilizer for soil, improving nutrient availability and minimizing environmental contamination (13). Nanobiochar also shows promise in environmental remediation, acting as a low-cost adsorbent for the removal of heavy metals, organics, phosphate and pathogens (9). Concerted efforts have been made in recent years to find solutions to water and wastewater treatment challenges and eliminates the difficulties associated with treatment methods. Various techniques are used to ensure the recycling and reuse of water resources. Owing to their excellent chemical, physical and biological properties, nanomaterials play an important role when integrated into water/wastewater treatment technologies (14). For instance, magnetic iron oxide nanoparticles have been developed, offering a high specific surface area and the advantage of magnetic separability. These properties make them highly effective for purifying drinking water and extracting toxic elements, such as heavy metals, from contaminated waters and soils (15). The research community has shown significant interest in carbon-based nanomaterials because of their versatile applications across agriculture, the environment, catalysis, energy and biomedical fields (16). Escalating demand for products, raw materials and services has resulted in massive amounts of biowaste generated by agriculture, forestry and the processing industry, which is expected to reach 3.4 billion tonnes globally by 2050 (17). Nano-BC applications in agriculture are still in their infancy, with a dearth of transferability to large-scale field applications. While some studies have demonstrated that the interaction of nano-BC with the soil rhizosphere environment promotes microbial growth and restoration of heavy metal contaminated soil, numerous questions regarding its applicability remain unanswered (18). As researchers delve deeper into its applications, nanobiochar emerges as a promising tool that not only leverages the benefits of biochar but also harnesses the remarkable properties offered by nanotechnology for a more sustainable and resilient future.

Biochar: Definition, raw materials used, Synthesis, methods, characteristics and properties

Biochar is a solid, carbonized product derived from biomass feedstock, including agricultural waste and other lignocellulosic materials. It is produced through a controlled thermal decomposition process in the absence of oxygen (pyrolysis) or within a limited oxygen environment (gasification) (19). The raw materials used for biochar production can vary, but they are typically waste biomass from sources such as agricultural residues, forestry waste, kitchen scraps, animal manure and even aquatic plants. These raw materials are chosen for their extensive accessibility, low cost and potential to address environmental pollution issues. Using waste biomass as a raw material for biochar production not only aids in waste management but also has the potential to improve carbon sequestration, water quality and decrease greenhouse gas emissions in soil and water environments (20). Some of the main characteristics of nanobiochar with its applications are mentioned in the Table 1.

Table 1. Characteristics of nanobiochar with its applications.

Sl. No.	Characteristics	Applications	References
1.	Nanoscale particle size	Nanobiochar particles typically range from a few nanometers to tens of nanometers, providing a higher surface area per unit mass.	(91)
2.	Enhanced reactivity	The increased surface area and specific nanostructures contribute to enhanced reactivity, making nanobiochar suitable for applications such as catalysis and adsorption.	(92)
3.	Tailored properties	Synthesis methods allow for the precise control of particle size, structure and surface chemistry, enabling the tailoring of nanobiochar properties for specific applications.	(93)
4.	Improved dispersion	Nanobiochar particles often exhibit improved dispersion in liquids or matrices, facilitating their incorporation into various systems.	(94)
5.	Application versatility	Nanobiochar finds applications in diverse fields, including environmental remediation, agriculture, nanocomposites and as a platform for advanced materials due to its unique characteristics.	(95)

Methods

The production of biochar commonly involves thermal decomposition with various thermo chemical conversion methods such as pyrolysis, torrefaction, hydrothermal carbonization and gasification. Pyrolysis involves the thermal degradation of organic molecules in the absence of oxygen, typically occurring at temperatures ranging from 250 to 900 °C. This process can be classified as either fast or slow depending on various factors such as temperature, heating rate, residence time and pressure. Hydrothermal carbonization (HTC) is another method where organic biomass, such as agricultural residues, algae or organic waste, is converted into carbon-rich material in the presence of water at elevated temperatures and pressures. This process typically takes place in a reactor under subcritical or supercritical water conditions and is economically advantageous due to its operation at relatively low temperatures; around 180-250 ° C (21). Gasification is a thermo chemical process that converts carbon-based materials into gaseous molecules, yielding syngas containing CH_4, H_2, CO, CO_2 and trace hydrocarbons. The outcome of gasification is influenced by factors such as the presence of air, steam, oxygen and heat sources (22). Torrefaction is a newer method for generating charcoal, involving mild pyrolysis with a moderate heating rate. This process utilizes inert ambient air in the absence of oxygen at 300 °C to remove carbon dioxide, oxygen and moisture from biomass (23).

The production of biochar typically involves thermal decomposition through various thermo chemical conversion methods such as pyrolysis, torrefaction, hydrothermal carbonization and gasification. Pyrolysis entails the thermal degradation of organic molecules without oxygen, usually occurring at temperatures between 250 and 900 °C. This process can be classified as either fast or slow based on factors like temperature, heating rate, residence time and pressure. Hydrothermal carbonization (HTC) is another method where organic biomass, such as agricultural residues, algae or organic waste, is converted into carbon-rich material in the presence of water at high temperatures and pressures. This process usually occurs in a reactor under subcritical or supercritical water conditions and is economically beneficial due to its operation at relatively low temperatures, around 180-250 °C (21). Gasification is a thermo chemical process that converts carbon-based materials into gaseous molecules, producing syngas that contains CH_4, H_2, CO, CO_2 and trace hydrocarbons. The outcome of gasification is influenced by factors like the presence of air, steam, oxygen and heat sources (22). Torrefaction is a newer method for generating charcoal, involving mild pyrolysis with a moderate heating rate. This process uses inert ambient air in the absence of oxygen at 300 °C to remove carbon dioxide, oxygen and moisture from biomass (23).

Nanobiochar: Definition, raw materials used, synthesis methods, characteristics:

Nanobiochar refers to biochar particles engineered or synthesized at the nanoscale, typically ranging from a few nanometers to tens of nanometers in size. This fine-scale variant of biochar displays unique properties and enhanced reactivity compared to its larger counterparts, making it suitable for various applications in environmental science, agriculture and materials science (24). The raw materials for synthesizing nanobiochar are similar to those used for traditional biochar production. Common biomass feedstocks include agricultural residues (such as crop residues and wood waste), forestry by-products and organic waste materials. The choice of raw material can affect the properties of the resulting nanobiochar. Additionally, precursors for nanobiochar may consist of carbon-rich compounds or biomass derivatives suitable for specific synthesis methods (25).

Synthesis Techniques for Nanobiochar:

Synthesizing nanobiochar involves various methods aimed at producing biochar particles at the nanoscale, enhancing their reactivity and versatility as shown in Fig. 1. Common synthesis techniques include ball milling, where mechanical forces break down larger biochar particles into nanoscale fragments and ultrasonication, which uses high -frequency sound waves to disintegrate biochar into well-dispersed nanoparticles (26). Colloid nanoparticle synthesis involves creating nanobiochar particles by carefully controlling the aggregation and stabilization of biochar nanoparticles within a colloidal solution (27). Pyrolysis with nanoscale catalysts introduces catalysts during the carbonization process to influence the formation of nanobiochar (28). Template-assisted synthesis uses templates or sacrificial materials to guide the creation of nanostructures with controlled size and morphology (29). Chemical vapor deposition (CVD) involves depositing carbon onto a substrate from gaseous precursors to produce well-defined nanostructures (30). Hydrothermal carbonization (HTC) employs water-rich conditions at high temperatures to produce nanobiochar with unique properties (31). The sol-gel method converts liquid precursors into a gel, facilitating the formation of nanobiochar with controlled characteristics (32). Finally, the biological synthesis method uses biological systems, such as plant extracts or microbial cultures to reduce and

Fig. 1. Properties of nanobiochar.

stabilize metal salts into nanobiochar particles, offering an environmentally friendly and sustainable alternative. This approach not only reduces the reliance on harsh chemicals but also utilizes natural resources, aligning with the principles of green chemistry (33). These methods provide flexibility in tailoring nanobiochar for specific applications, such as environmental remediation, energy storage and advanced materials. Thorough characterization ensures the confirmation of nanoscale features and properties in the synthesized nanobiochar (22).

Properties of Nanobiochar:

1. Physical Properties:

Nanobiochar, a carbonaceous substance consisting of particles in the nanoscale range, possesses unique physical and chemical attributes that contribute to its versatile applications are mentioned in Fig. 2 (34). Regarding its physical characteristics, nanobiochar is distinguished by its nanoscale particle size, typically ranging from a few nanometers to tens of nanometers. The morphology can vary, encompassing nanoparticles, nanofibers or other nanostructures, depending on the chosen synthesis method. This nanoscale dimension results in a larger surface area compared to conventional biochar, boosting its reactivity and suitability for applications such as adsorption and catalysis (35). The porosity of nanobiochar is a crucial feature, providing an increased number of active sites for interactions with gases, liquids or other substances. Furthermore, the surface charge of nanobiochar influences its interactions with particles or substances, particularly in water treatment applications (36).

2. Chemical Properties:

In terms of chemical properties, nanobiochar displays diverse functional groups on its surface, including hydroxyl, carboxyl and phenolic groups. These functional groups enhance its reactivity and adsorption capabilities. The elemental composition, determined through techniques such as XPS or elemental analysis, offers insights into the carbon content and the presence of other elements. The surface chemistry and redox properties of nanobiochar play pivotal roles in adsorption/desorption processes and its application in redox-active systems (10). In summary, the customized physical and chemical properties of nanobiochar, coupled with its nanoscale dimensions, position it as a promising material for a range of applications, including water treatment, catalysis, energy storage and nanocomposite materials. Characterization techniques such as TEM, SEM, XPS, FTIR and BET analysis are commonly employed to comprehend and optimize these properties for specific applications properties to suit various functions (37) hereby increasing its versatility and effectiveness across different applications (38). In the Table 2, different physico-chemical and biological properties of biochar in the context of environmental applications are listed.

Synthesis methods of nanobiochar:

A. Production techniques for nanobiochar:

i.Ball Milling:

High energy ball milling is a mechanical method that involves the use of balls as grinding media to break down larger biochar particles into nano-scale particles. The collision and friction between balls and biochar lead to size reduction. Ball milling is a process in which materials are ground and mixed using rotating cylindrical chambers and hard balls as grinding media. This process helps to break down the materials into smaller particles, thereby increasing their surface area and reactivity. During ball milling, biochar is mixed with nanoparticles or other additives to produce nanobiochar. The ball milling process allows for the production of nanobiochar by breaking down the materials into smaller particles and increasing their surface area. This increased surface area enhances the adsorption capacity of the nanobiochar, making it more efficient in removing pollutants and pathogens from wastewater. By utilizing ball milling techniques in the production of nanobiochar, researchers hope to enhance its activity and effectiveness in both soil and industrial applications (39).

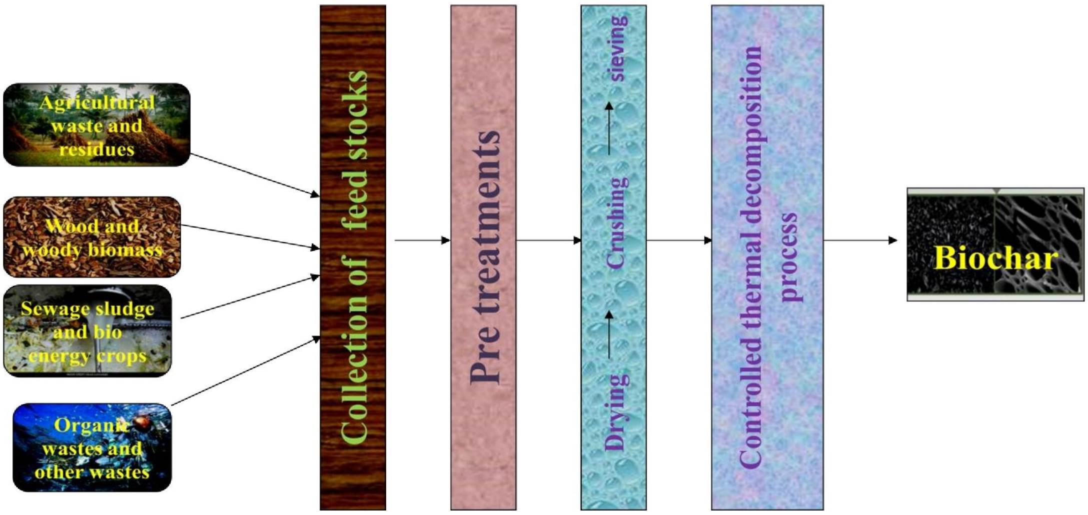


Fig. 2. Production techniques of nanobiochar.

Table 2. Physico-chemical and biological properties of biochar in the context of environmental applications**.**

Property category	Property	Impact on Environmental Applications of Biochar	References
Physical properties	Specific surface area	Large surface area and high cation exchange capacity Higher pyrolysis temperatures can break down certain molecular structures, exposing the core lignin and increasing the material's surface area. Increases the soil’s water-holding capacity and nutrient uptake.	(96)
	Density and porosity	Depend largely on the origin of the biomass. Biochar production conditions and pre-treatment. Activation promote biochar density and porosity. Increase biochar porosity using hydrothermal treatment or oxygenation Pyro-gasification and active temperature, CO_2 gas flowrate and wood residue type significantly affected the porosity.	(97-100)
	Carbon content and ash content	Pyrolysis temperature has a direct impact on biochar composition, with increased temperatures leading to higher carbon and ash percentages. Biochar's resistance to microbial degradation increases with the degree of aromatic structure formation, making it more suitable and persistent in the environment.	(101, 102)
	Mechanical stability	Determined by its density. Biomass moisture content, orientation and nanocomposite properties (high density and high lignin content) determine the mechanical strength. Interaction with the hydrologic cycle Anisotropy of the charring process makes the biochar less mechanically suitable; Evaporation of water during the heating process affects the mechanical stability.	(103)
	Pore volume and pore size distribution	Classified as large (pore size 1000-0.05µm), medium (0.05-0.002 µm) and micropore (0.05-0.0001) µm. Total pore volume increasing with increasing temperature. Particle size related to reaction temperature.	(103)
Chemical properties	Elemental composition	Volatile compounds initially fill biochar's micropores, but higher temperatures release them, freeing up the surface for ion interactions. Lower hydroxide content. Changes occurred in the temperature range of 200-400 °C. High-temperature biochar can achieve>95 % carbon contents and <5 % oxygen contents.	(103-105)
	Surface functional groups and CEC	Lower CEC leads to a more rapid decline in soil pH**.** Presence of a large number of surface functional groups, resulting in a high CEC value for biochar. Heating biomass to 350-650 °C creates new functional groups, such as carboxyl and phenol groups, through bond breaking and reforming. Biochar's high CEC helps retain soil nutrients, minimizing leaching and promoting soil fertility.	(106-108)
	pH and EC	Biochar's pH ranges from neutral to high with pyrolysis temperature, leading to a more alkaline product that can improve soil conditions, reduce contaminant mobility and promote a healthier soil environment. Rising pyrolysis temperatures lead to higher pH levels, more ash and increased oxygen functional groups in biochar. Increase in biochar EC with increasing temperature related to the loss of biomass volatiles during carbonization.	(103, 108-111)
Biological properties	Microorganism immobilization technology	Enhanced microbial activity and proliferation. Resistance to toxic compounds. Improved pollutant degradation and adsorption. Enhanced soil and water remediation. Cost-effectiveness and sustainability.	112,113
	Anaerobic digested (AD)	Enhanced adsorption capacities for contaminants. Improved waste management and bioenergy production. Enhanced efficiency of anaerobic digestion. Facilitation of redox reactions via active functional groups. Economic and environmental benefits.	(114, 115)
	Phytoremediation residue biochar (PMB)	Enhanced soil nutrient availability. Improved plant growth and health. Increased heavy metal immobilization in soil. Reduced phytotoxicity of contaminants. Cost-effective and sustainable soil remediation.	(116)

ii.Ultrasonication:

Ultrasonication involves the use of high-frequency sound waves to disintegrate biochar particles into smaller fragments. This method is effective in producing nanoscale biochar with improved dispersion in solvents or other matrices. By subjecting biochar to ultrasonication, the resulting nanobiochar exhibits increased surface area, improved porosity and enhanced physicochemical properties. This can be beneficial in soil and industrial applications as the increased surface area allows for better nutrient retention and pollutant adsorption. Additionally, the ultrasonication process can also facilitate the incorporation of nano-particles or nano-materials into biochar, further enhancing its properties and potential applications in areas such as environmental remediation, catalysis and energy storage (40).

iii.Pyrolysis with nanoscale Catalysts:

Pyrolysis is a process that involves the thermal decomposition of organic materials in the absence of oxygen. This process results in the production of various valuable products such as liquid bio-oil, solid biochar and non-condensable gases (41). Biomass pyrolysis, a type of pyrolysis that specifically uses biomass as the feedstock has gained increasing importance due to its potential as a renewable and sustainable source of energy. Recently, there has been a growing interest in exploring the use of nanoscale catalysts for biomass pyrolysis. These nanoscale catalysts have shown promising results in enhancing the efficiency and selectivity of the pyrolysis process, leading to improved yields of desired products such as bio-oil or hydrogen gas. Moreover, the utilization of nanoscale catalysts also offers several advantages over traditional pyrolysis techniques. These advantages include improved reaction kinetics, enhanced control over product distribution and the ability to tailor the catalyst properties for specific desired outcomes. Additionally, the use of nanoscale catalysts in bio mass pyrolysis can also help address some of the challenges associated with traditional pyrolysis methods, such as the formation of unwanted by-products and the need for high operating temperatures. Furthermore, the integration of nano-scale catalysts into biomass pyrolysis processes can also contribute to the development of a more sustainable and environmentally friendly approach to bioenergy production. By harnessing the synergistic effects of nanoscale catalysts, biomass pyrolysis can be optimized to maximize the production of high-value products while minimizing waste and reducing the overall environmental impact. In conclusion, the use of nano scale catalysts in biomass pyrolysis holds great promise for advancing the field and unlocking its full potential as a renewable energy source. Through the application of nanoscale catalysts, biomass pyrolysis can be optimized to improve efficiency, selectivity and product yields (25).

iv.Electrospinning:

Electro spinning is a technique where an electric field is used to draw a charged jet of biochar precursor solution, forming nanofibers. Subsequent pyrolysis of these nanofibers produces nanobiochar with a fibrous structure (42). Electrospinning is a versatile and effective method for producing nanostructured biochar materials with unique properties. During the electrospinning process, a high voltage is applied to a biochar solution, leading to the formation of ultrafine fibers with diameters in the nano-scale range. These nano-fibers exhibit a high aspect ratio and interconnected porous structure, which greatly elevates their surface area and porosity. The electro spun nanobiochar materials have shown great promise in various applications, including environmental remediation, energy storage and biomedical fields. Their enhanced surface area and porosity make them highly efficient in adsorbing a wide range of contaminants from water and air. Furthermore, the nanostructured biochar materials have demonstrated significant potential in the field of energy storage due to their high surface area and excellent electrical conductivity. In the biomedical domain, electrospun nanobiochar has garnered attention for its potential use in drug delivery systems and tissue engineering applications. The unique properties of the nanobiochar, such as its high surface area and biocompatibility, make it an attractive candidate for various biomedical applications (43).

v.Template-Assisted Synthesis:

Templates or sacrificial materials can be used to guide the formation of nanostructures. Biochar precursors are deposited onto or around templates and subsequent removal or decomposition of the template leaves behind nanobiochar with controlled morphology (44). In recent years, there has been an increasing need to develop advanced treatment technologies for the effective removal of potentially toxic compounds that traditional processes cannot eliminate. One promising technology that has emerged is the use of Template-Assisted Synthesis for the production of nanobiochar (45). This technique involves manipulating the structure of biochar at the nano-scale level, allowing for improved efficiency and performance in various applications, including wastewater treatment. By utilizing templates, such as porous materials or organic compounds, the nanobiochar can be tailored to have specific properties and functionalities, enhancing its adsorption capacity and selectivity towards target pollutants. These nanobiochar materials can be designed to have a high surface area to volume ratio, which provides more active sites for the adsorption of contaminants (46). Furthermore, the incorporation of nano-particles onto the surface of biochar during the synthesis process can enhance its photo catalytic and oxidative properties, enabling the degradation of harmful substances through advanced oxidation processes. This novel approach to nanobiochar production holds great promise for addressing water-related challenges. Some potential applications of TAS-based nanobiochar techniques include the removal of toxic metal ions, disease-causing microbes and organic and inorganic solutes from water. Additionally, the use of TAS-based nanobiochar can also contribute to soil improvement and nutrient enrichment, making it a sustainable and multifunctional solution for water and soil remediation. These advancements in nanobiochar production can revolutionize the wastewater treatment industry, providing more efficient and eco-friendly solutions to address water pollution challenges (46).

vi.Chemical Vapor Deposition (CVD):

CVD involves the deposition of carbon onto a substrate from gaseous precursors. By controlling the process parameters, such as temperature and gas composition, nanobiochar can be synthesized with specific characteristics (47). These techniques involve the deposition of a thin layer of carbon-based nanomaterials onto the biochar surface, thereby increasing its surface area and improving its adsorption capacity. This improved biochar, known as nanobiochar, has been shown to be more effective in removing toxic metal ions, disease-causing microbes and inorganic and organic solutes from water compared to traditional biochar. Additionally, the use of nanobiochar in wastewater treatment offers several advantages such as its high reactivity, enhanced adsorption capacity and the ability to be easily functionalized for specific treatment applications. Furthermore, the use of CVD allows for precise control over the deposition process, resulting in uniform and well-defined nanostructures on the biochar surface. The unique characteristics of nanobiochar, produced through CVD techniques, have shown great promise in enhancing its adsorption capacity and improving its effectiveness in removing pollutants from waste water (46).

vii.Hydrothermal Carbonization (HTC):

HTC at elevated temperatures and pressures in a water-rich environment can lead to the formation of nanoscale biochar particles. The choice of biomass feedstock and process parameters influences the particle size and properties (48). This technique involves subjecting biomass to high temperature and pressure in a water medium, resulting in the conversion of biomass into biochar. The HTC process not only produces biochar but also enhances its properties by creating a highly porous structure and increasing its surface area. Furthermore, HTC allows for the control of biochar properties such as particle size and surface functional groups, making it suitable for various applications including soil amendment, water purification and energy storage. Moreover, HTC has the advantage of being a more environmentally friendly and energy-efficient process compared to traditional pyrolysis methods. By utilizing HTC, the production of nanobiochar offers a sustainable and efficient approach to addressing various environmental challenges. Additionally, the use of HTC in nanobiochar production has the potential to contribute to the circular economy by converting biomass waste into a valuable resource and mitigating the need for disposal. Overall, HTC is a promising technique for the production of nanobiochar because it enhances biochar properties while offering environmental and energy efficiency benefits (31).

viii.Microwave-Assisted Pyrolysis:

Microwave heating can be employed during the pyrolysis process to achieve rapid and uniform heating of the biochar precursor. This method can result in nanobiochar with specific properties depending on the microwave conditions (49). Nano-biotechnology, an emerging technology, has shown great potential in various fields, including waste water treatment and green science. One promising technique in nanobiotechnology for wastewater treatment is microwave-assisted pyrolysis, which enables the production of nanobiochar with superior adsorption capabilities. This technique utilizes microwave energy to pyrolyze biomass, such as agricultural waste or sewage sludge, into biochar at high temperatures and in a short amount of time. The microwave-assisted pyrolysis process produces nanobiochar with a high surface to volume ratio and a high microstructure, enhancing its adsorption capabilities. This nanobiochar can be used as a highly efficient adsorbent material for removing pollutants and contaminants from waste water. The use of microwave-assisted pyrolysis in nanobiochar production has several advantages over traditional pyrolysis methods. Some of these advantages include: Faster and more efficient pyrolysis process due to the utilization of microwave energy, higher yields of nanobiochar due to the enhanced heating and decomposition of biomass, improved adsorption capabilities of the nanobiochar due to its unique microstructure. By utilizing microwave-assisted pyrolysis, researchers are able to produce nanobiochar with improved adsorption capabilities for wastewater treatment and environmental remediation purposes (46).

ix.Sol-Gel Method:

The sol-gel process involves the transformation of a liquid precursor solution into a gel and subsequent drying to form a solid material. By adapting this method to biochar precursors, nanobiochar can be synthesized with controlled particle size and structure (50). The Sol-Gel method is a widely used technique in materials science for the synthesis of nanoparticles. It involves the conversion of a precursor solution into a solid gel-like material through chemical reactions, followed by drying and calcination to obtain the desired nanoparticles. This method has gained attention in the field of biochar production due to its potential for creating nano-sized particles with improved properties and functionalities. By incorporating nanoparticles into biochar, the Sol-Gel method allows for enhanced nutrient retention and increased surface area, leading to improved soil amendment and industrial applications. Some potential benefits of using the Sol-Gel method for nanobiochar production include: increased nutrient availability, improved soil structure, enhanced water retention and reduced environmental impact. Furthermore, the Sol-gel method offers advantages such as control over particle size and morphology as well as the ability to tailor the properties of the biochar for specific applications (51).

x.Emulsion Techniques:

Biochar precursors can be emulsified in a suitable solvent and subsequent pyrolysis or other processes can result in the formation of nanobiochar particles. This method allows for the production of biochar nano-particles with controlled sizes (52). In recent years, there has been a growing interest in the development of emulsion-based techniques for the production of nanobiochar. These techniques involve the encapsulation of biochar particles within a nano-emulsion, which not only helps to improve their stability but also enhances their dispersibility and reactivity. By using emulsion-based techniques, researchers are able to control the size and composition of the nanobiochar particles, resulting in enhanced properties such as increased surface area and improved adsorption capacity. Furthermore, the use of emulsion techniques allows for more effective and efficient production processes as well as the potential for scaled-up production in industrial settings. This innovation in nanobiochar production holds great potential for various applications including soil enhancement, industrial processes and potentially even in the development of new functional foods incorporating bioactive compounds. By encapsulating biochar particles within a nano-emulsion using emulsion-based techniques, the stability, dispersibility and reactivity of nanobiochar can be significantly improved, allowing for enhanced performance in various applications. Moreover, the use of emulsion-based techniques for nanobiochar production can lead to the development of more sustainable agricultural practices by improving soil nutrient availability and retaining soil moisture, ultimately enhancing crop yield and reducing the need for synthetic fertilizers. In addition, the use of nanobiochar produced through emulsion techniques can also have positive environmental impacts by sequestering carbon dioxide and reducing greenhouse gas emissions. Overall, the use of emulsion-based techniques for nanobiochar production offers numerous advantages and potential applications in various fields. Some potential advantages of using emulsion-based techniques for nanobiochar production include improved stability, dispersibility and reactivity of the particles. This can lead to enhanced performance in applications such as soil enhancement, industrial processes and functional food development (43).

xi.Bacterial Method for Nanocellulose Synthesis:

Nano cellulose, a key nano-material used in nanobiochar production, can be synthesized using a bacterial method in a suitable culture. This technique involves the cultivation of bacteria capable of producing nano-cellulose under specific environmental conditions (53). The nano-cellulose produced can then be combined with biochar to create nanobiochar composites with enhanced properties. These synthesis techniques offer unique opportunities to tailor the properties of nanobiochar for various applications in environmental remediation, water purification and agricultural soil improvement (54). In recent years, there has been growing interest in the field of nano-biotechnology, particularly in the development of antimicrobial nano-materials. These nano materials have shown great potential in various applications, including the removal of pollutants and contaminants in wastewater treatment. One promising method in the field of wastewater treatment is the synthesis of bacterial nanobiochar. Bacterial nanobiochar synthesis involves the use of bacteria to produce biochar at the nano-scale. This method offers several advantages over traditional wastewater treatment methods. Firstly, bacterial nanobiochar synthesis is a sustainable and eco-friendly approach. It uses bacteria to convert organic waste into biochar, which can then be used as a filtration material to remove pollutants from wastewater. The use of bacteria in the synthesis of nanobiochar also allows for the functionalization of the biochar surface. This means that specific properties and functionalities can be tailored to enhance its pollutant removal capabilities. Additionally, bacterial nanobiochar synthesis is a cost-effective solution. It eliminates the need for expensive chemicals and complex treatment processes, making it a more affordable option for wastewater treatment. Furthermore, the incorporation of antimicrobial nano-materials into bacterial nanobiochar can further enhance its ability to remove pathogens and improve overall water quality in a wastewater treatment system (45).

It's important to note that the choice of method depends on the specific requirements of the application, and the produced nanobiochar should be thoroughly characterized using techniques such as transmission electron microscopy (TEM), scanning electron microscopy (SEM) and other analytical methods to confirm its nano-scale nature and properties (8). Additionally, in the Table 3, comparative analyses of various synthesis approaches among biochar, nanobiochar and activated carbon are listed.

Biochar Nano-composites: A Classification and Synthesis Overview:

In the Fig. 3, the fabrication methods of various biochar-based nano-materials and their classification has been illustrated. Nanobiochar composites are synthesized through different methods, all of which involve 2 common biomass treatment processes: pre-treatment and post-treatment. Biochar based nano-composites with enhanced properties, such as increased surface area, available active sites and improved catalytic capabilities, have demonstrated exceptional efficiency in contaminant removal. Research has consistently shown that these composites exhibit superior adsorption capacities, effectively removing a broad spectrum of contaminants from aqueous solutions. Furthermore, the integration of diverse nanoparticles with reductive, oxidative and catalytic properties enables these nano-composites to simultaneously adsorb and degrade various toxic substances, showcasing their vast potential for treating diverse waste materials and addressing various environmental challenges. Various modifications for the enrichment of biocomposite and biochar with other nano-particles are listed in the Table 4.

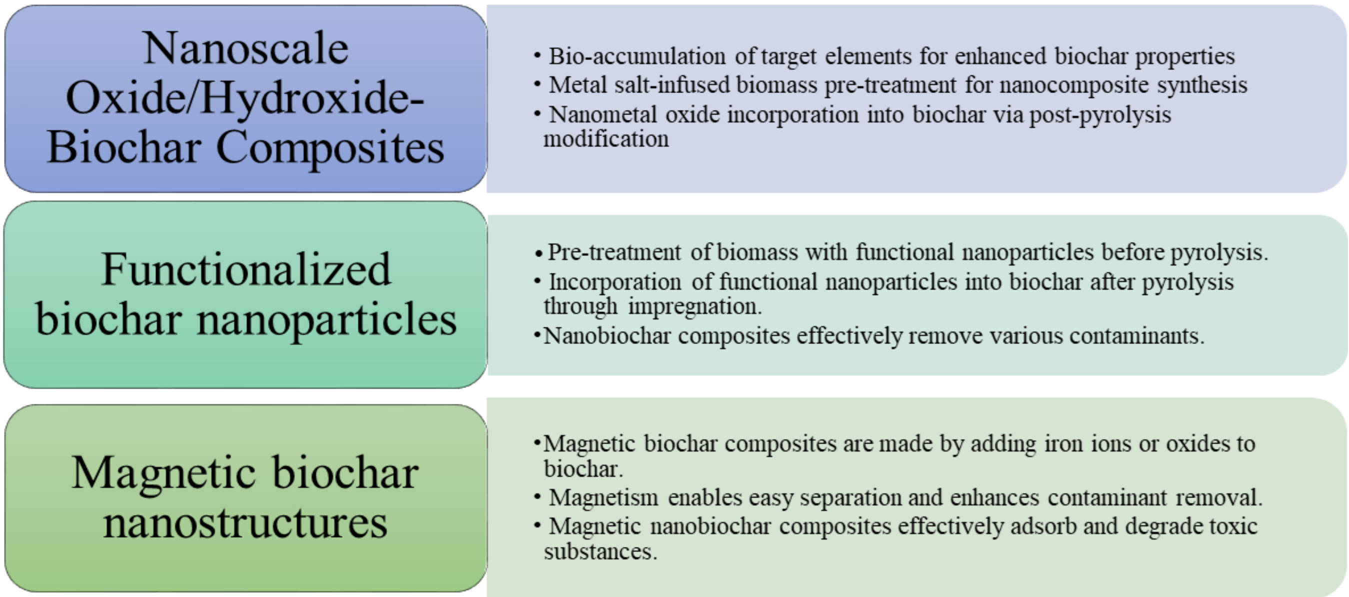
Applications of Nanobiochar:

A. Environmental sector: water and soil purification

Nanobiochar plays a pivotal role in the environmental sector, particularly in the realms of water and soil purification. Leveraging its exceptional properties, nanobiochar demonstrates efficacy in addressing

Table 3. Comparative analyses of various synthesis approaches among biochar, nanobiochar and activated carbon.

Sl. No.	Properties	Biochar	Nanobiochar	Activated charcoal	References
1.	Synthesis approaches	Produced through pyrolysis or carbonization of biomass in the absence of oxygen. Typically involves slow heating of biomass at temperatures ranging from 300 to 700 °C.	Synthesizedusing methods like ballmilling, ultrasonication and pyrolysis with nano-scale catalysts, electro spinning and template-assisted synthesis. Precise control over particle size and structure is achievable through these methods.	Produce through the activation of carbonaceous precursors, which can be natural materials like wood or synthetic materials like polymers. Activation methods include chemical activation (using activating agents) or physical activation (using gases like CO_2 or steam).	(29, 117, 118)
2.	Particle size and structure	The particle size distribution of biochar can vary widely, typically ranging from micrometers to millimeters. It can consist of both fine particles and larger chunks. The internal structure of biochar can be quite complex, consisting of a network of carbonaceous material with varying degrees of organization.	Characterized by nano-scale particle sizes, often in the range of a few nanometers to tens of nanometers. Can exhibit specific nano structures, such as nanoparticles or nanofibers, depending on the synthesis method.	Particle sizes can vary but are generally smaller compared to traditional biochar. Highly porous structure with a developed surface area, providing extensive adsorption capacity.	(119-121)
3.	Surface area and porosity	Relatively lower surface area compared to activated carbon. Porosity is present but may not be as well-developed as in activated carbon.	Enhanced surface area compared to traditional biochar due to smaller particle sizes. Porosity can be tailored based on the synthesis method.	High surface area and well-developed porosity, contributing to excellent adsorption properties. Porous structure created during the activation process.	(101, 122, 123)
4.	Applications	Primarily used in agriculture for soil improvement, carbon sequestration and water filtration. Limited applications in energy storage and composite materials.	Potential applications in drug delivery, nano-composites and as catalyst supports due to the unique nano-scale features. Environmental applications similar to traditional biochar but with improved performance in some cases.	Widely used for water and air purification, gas adsorption and in various industrial processes. Commonly employed in energy storage devices, such as super capacitors.	(124-126)
5.	Cost and scalability	Generally cost-effective and can be produced on a larger scale. The simplicity of the production methods contribute to scalability.	Some synthesis methods may involve additional costs due to the need for specialized equipment or materials. Scalability may vary depending on the chosen method.	Production costs can be higher, especially for high-quality activated carbon with specific properties. Scalability is achievable, but economic factors may limit large-scale production.	(19, 127, 128)



Nanoscale Oxide/Hydroxide-Biochar Composites

- Bio-accumulation of target elements for enhanced biochar properties
- Metal salt-infused biomass pre-treatment for nanocomposite synthesis
- Nanometal oxide incorporation into biochar via post-pyrolysis modification

Functionalized biochar nanoparticles

- Pre-treatment of biomass with functional nanoparticles before pyrolysis.
- Incorporation of functional nanoparticles into biochar after pyrolysis through impregnation.
- Nanobiochar composites effectively remove various contaminants.

Magnetic biochar nanostructures

- Magnetic biochar composites are made by adding iron ions or oxides to biochar.
- Magnetism enables easy separation and enhances contaminant removal.
- Magnetic nanobiochar composites effectively adsorb and degrade toxic substances.

Fig. 3. Classification and synthesis of biochar nano-composites.

Table 4. Enrichment of bio composite and biochar with other nanoparticles.

Sl. No.	Modifications	Target contaminants	Removal efficiency	Mechanisms involved	References
1.	Hydroxyapatite/ sodium bicarbonate (HAp-SB) bio composite	Lead ions (Pb^{2+})	92 % removal efficiency for initial Pb^{2+} concentrations above 50 mg/L	Electrostatic attraction and ion exchange, as indicated by the Langmuir and Freundlich theoretical models.	(129)
2.	Laboratory synthesis of hydroxyapatite	Strontium ions (Sr^{2+})	The HAp nanoparticles demonstrated high efficiency in removing Sr^{2+} ions from contaminated solutions through batch adsorption experiments.	Adsorption of Sr^{2+} ions onto hydroxyapatite (HAp) nanoparticles, likely involving electrostatic attraction and ion exchange.	(130)
3.	Iron oxide coated with cetyltrimethylammonium bromide (CTAB)	Arsenic ions (As (III))	The iron oxide coated with CTAB (IO-CTAB) demonstrated effective adsorption of As (III) ions from aqueous solutions.	The iron oxide component allows for easy magnetic separation of the bio composite from the treated water	(131)
4.	Synthesis of magnetite nanoparticles (nFe_3O_4)	Arsenic (As) andcopper (Cu)	69.5 % increase in adsorbed amount compared to commercial magnetite nanoparticles, with high adsorption capacity due to large specific surface area (100 m^2 g^{-1}) and small particle size (10 nm)	surface complexation and electrostatic attraction through the co-precipitation method, involving both Fe^{3+} and Fe^{2+} ions with a ratio of $Fe^{2+}/Fe^{3+} = 0.5$.	(15)
5.	Cross-linking with KOH functionalization with polyethyleneimine (PEI)	Copper ions (Cu^{2+})	High adsorption capacity of 491.68 mg· g^{-1}, with excellent reusability and practical application potential.	Adsorption of Cu^{2+} onto amine -functionalized biochar (PBC) through complexation, ion exchange, coprecipitation and physical adsorption.	(132)
6.	Nitrogen doping biochar	2,4-dichlorophenol	Enhanced oxidative degradation of 2,4-dichlorophenol through peroxymonosulfate (PMS) activation by nitrogen-doped biochar (NBC).	Catalytic oxidation involving the generation of reactive oxygen species (O^{2-} and $^1O_2$) through the interaction of PMS with ketonic (C=O) groups and structural defects on the NBC surface.	(133)
7.	Thiol modification in biochar	Inorganic Hg^{2+}, Organic CH_3Hg^+	High removal efficiency of 320.1 mg/g for Hg^{2+} and 104.9 mg/g for CH_3Hg^+ by thiol-modified biochar (BMS-biochar) synthesized through ball milling	Mechanism: Mercury species (Hg^{2+} and CH_3Hg^+) stick to the BMS-biochar surface through: Thiol (-SH) groups, oxygen containing groups, electrostatic attraction, ligand exchange, this happens through a process called surface diffusion, which is the slowest step.	(134)
8.	HNO_3 treatment	U(VI): Hexavalent uranium ions	High adsorption capacity of 355.6 mg/g, 40 times higher than untreated biochar.	Adsorption of U(VI) onto biochar through surface complexation and electrostatic interactions, facilitated by carboxyl (-COO) groups and reducing agents ($R\text{-}CH_2OH$ groups), with surface modification by HNO_3 treatment enhancing adsorption ability.	(135)
9.	KOH modification: The seaweed hydrochar derived from *Ascophyllum nodosum* was chemically treated with potassium hydroxide (KOH)	Vanadium (V)	Maximum uptake of 12.3 mg/g, with potential for reusability	Adsorption of V(V) onto KOH modified seaweed hydrochar (HCKOH) through weak binding, following a pseudo-second-order kinetics and Langmuir isotherm model, with film diffusion controlling the overall adsorption rate and involving exothermic and spontaneous thermodynamic processes.	(136)
10.	Hydrothermal synthesis acid digestion	Environmental pollutants	8.5-10 % yield of biochar nanodots from bulk-biochar	Hydrothermal synthesis of biochar nanoparticles from agricultural residuals (soybean straw and cattle manure) through digestion with nitric and sulfuric acid, followed by filtration and drying, resulting in 4-5 nm sized nanodots with a well-developed porous structure, suitable for environmental applications such as adsorption.	(137)

11.	Montmorillonite-biochar composites (MBC)	Ammonium(NH_4^+), Phosphate (PO_4^{3-})	High adsorption capacity of 12.52 mg/g for NH^{4+} and 105.28 mg/g for PO_4^{3-}, with slow release of 0.30-4.92 % for NH^{4+} and 2.63-5.09 % for PO_4^{3-} within 2-88 h.	Surface adsorption, cation exchange capacity (CEC) process, electrostatic attraction and ionic bonding, involving the contribution of both biochar and montmorillonite to the texture and structure, providing varied surface and adsorptive sites.	(138)
12.	Biologically modified biochar	Cadmium (Cd(II))	High sorption capacity of 2.1 times that of pristine biochar, with a maximum sorption capacity for Cd(II) removal from water.	Adsorption of Cd(II) onto biologically modified biochar (BCB24) through increased surface area, oxygen-containing functional groups and mineral components, resulting from anaerobic ensiling and anaerobic fermentation of corn stalks, followed by pyrolysis at 500 °C.	(139)
13.	Nanobiochar from pinewood	Carbamazepine (CBZ)	High removal efficiency of up to 95 % of CBZ(74 µg CBZ/g nanobiochar) after 3 h contact time, with enhanced adsorption at higher pH (2.3 folds) and in presence of surfactant (57 % increase).	Increased surface area and potentially electrostatic interactions.	(140)
14.	Oxidation of nanobiochar	Carbamazepine	High removal efficiency of 83 % in spiked water and 86 % in secondary effluent, with immobilized laccase preserving 70 % of initial activity after 3 cycles.	Immobilized laccase enzyme on modified nanobiochar breaks down carbamazepine through oxidation reactions, with enhanced stability and reusability.	(141)
15.	Fabrication of magnetic biochar through thermal pyrolysis of $FeCl^{3-}$ treated biomass	Aqueous arsenic	Excellent sorption ability, with easy separation of arsenic-laden composite from solution by magnet.	Physical entrapment of arsenic ions within the porous biochar matrix followed by magnetic separation of the arsenic-laden biochar/γ-Fe_2O_3 composite.	(142)
16.	Magnetic corn stoverbiochar (MCSBC)	Fluoride	Maximum fluoride removal at pH 2.0, with adsorption capacities of 6.42 mg/g (CSBC) and 4.11 mg/g (MCSBC) at 25 °C, decreasing with increasing temperature.	Electrostatic attraction, complexation and physical entrapment, following pseudo-first order kinetics, with magnetic properties.	(143)
17.	Graphitic nanobiochar	Glyphosate (GL), oxytetracycline (OTC)	GL (83 mg/g), OTC (520 mg/g)	positive cooperative adsorption mechanism.	(10)
18.	HPB (magnetic biochar- hematite-modified biochar)	As (V)	Much greater ability to remove As from aqueous solution compared to unmodified biochar, with easy isolation and removal using external magnets.	Adsorption of As onto γ-Fe_2O_3 particles on the carbon surface through electrostatic interactions.	(144)
19.	Graphene (functional nanoparticle coated)	Methylene blue (MB) (Org)	Adsorption capacity of 174 mg g^{-1}, more than 20 times higher than unmodified biochar.	Enhanced adsorption through strong π–π interactions between aromatic molecules and graphene sheets on biochar surface.	(145)
20.	MgO nanoflakes	Nitrate (Inorg), Phosphate	Nitrate (95 mg/g) and Phosphate (835 mg/g)	Adsorption of anions onto MgO nano-flakes dispersed on the mesoporous biochar matrix.	(89)
21.	MgO and $Mg(OH)_2$ particles (nanometal oxide)	Phosphate (Inorg)	$R^2 = 0.78$ and $p < 0.001$ (Correlation: P removal rate and biochar Mg content).	Phosphate (P) adsorbs onto tiny magnesium particles ($Mg(OH)_2$ and MgO) on the biochar surface, with more magnesium leading to better P removal.	(146)
22.	Clay-biochar composite	MB	5-fold increase in adsorption ability, with sTable recycling capacity of 7.90 mg/g	Adsorption through ion exchange with clay and electrostatic attraction with biochar.	(147)
23.	$KMnO_4$ treated biochar (nanometal oxide)	Cu(II), Cd(II) and Pb (II)	Cu (II) (34.2 mg/g), Cd (II) (28.1 mg/g), Pb (II) (53.1 mg/g).	Surface adsorption involving both MnOx particles and oxygen-containing groups on the engineered biochar surface.	(148)
24.	Manganese-oxide/ biochar composite (Mn/ BC)	Pb (II)	Removal efficiency of lead(II) increased from 6.4 % to 98.9 %.	Sorption of lead(II) through surface hydroxyls and manganese oxide, with a faster sorption rate and spontaneous, endothermic process.	(90)

25.	Magnetic biochar	Pb (II)	Desorption efficiency 84.1 %.	Chelation of Pb(II) by EDTA-2Na, allowing for efficient desorption and regeneration of magnetic biochar.	(149)
26.	Rice straw nanobiochar (Nano BCs)	Antibiotic resistance genes-amp C, erm B	Adsorption of eDNA-Nano-700 (60 %), Nano-400 (31.3 %).	- Nano-BCs damage and break down antibiotic resistance genes (eDNA) through: 1. Free radicals (PFRs) releasing harmful hydroxyl radicals 2. Direct contact with reactive sites on nano-BCs	(150)
27.	Copper oxide (CuO)-modified biochar (BC) nanocomposites	Anionic dyeRR120 (Reactive Red 120)	1399 mg/g, removal efficiency (46 %).	Strong electrostatic attraction between embedded CuO nanoparticles.	(151)

environmental challenges. In water purification, the high surface area and porous structure of nanobiochar make it an excellent adsorbent for a diverse array of contaminants. It can efficiently remove heavy metals, organic pollutants and various harmful substances from water sources through physical and chemical interactions. This capacity extends to microbial contaminants, contributing to the provision of safe drinking water. Moreover, nanobiochar's application in water filtration systems enhances its utility, ensuring the removal of fine particles and impurities (55). In soil purification, nanobiochar proves instrumental in nutrient retention and contaminant immobilization (56). Its porous structure acts as a reservoir for essential nutrients, gradually releasing them for plant uptake and promoting sustainable agriculture. Simultaneously, nanobiochar can sequester contaminants in the soil, preventing their leaching into groundwater and mitigating soil pollution. The incorporation of nanobiochar enhances soil structure, reduces erosion and aids in carbon sequestration, contributing to overall soil health. These applications underscore nanobiochar potential as a sustainable and multifaceted solution for environmental remediation, aligning with global efforts towards cleaner water sources and healthier soils (57). Ongoing research continues to refine and expand the applications of nanobiochar, further advancing its role in sustainable environmental management.

B. Agricultural sector: soil enhancement, nutrient retention:

Nanobiochar applications in the agricultural sector are centered on its capacity to enhance soil quality and improve nutrient retention, contributing to sustainable and efficient farming practices. The high surface area and porous structure of nanobiochar make it a valuable soil amendment for various purposes. Firstly, nanobiochar enhances water retention in the soil, addressing issues related to water scarcity by improving drought resistance in plants and optimizing water use efficiency (58). Additionally, its incorporation promotes a healthier soil structure, preventing compaction and fostering stable aggregates that facilitate better aeration, water infiltration and root development. Nanobiochar can also act as a pH buffer, neutralizing acidic soils or adjusting alkalinity to create an environment conducive to plant growth (59). In terms of nutrient management, nanobiochar serves as a reservoir for essential elements, sequestering nutrients in its porous matrix and releasing them gradually over time. This slow and sustained nutrient release improves overall nutrient use efficiency and reduces the need for frequent fertilization. The increased cation exchange capacity (CEC) of the soil due to nanobiochar enhances nutrient retention and exchange with plant roots, ensuring improved nutrient availability for optimal crop growth. Furthermore, nanobiochar positively influences microbial activity in the soil, providing a habitat for beneficial microorganisms. This contributes to nutrient cycling, organic matter decomposition and overall soil health (60).

Beyond its impact on soil properties, nanobiochar applications have been associated with increased crop yields and improved stress tolerance in plants. The ability of nanobiochar to mitigate nutrient runoff into water bodies helps minimize environmental pollution and eutrophication. Moreover, by introducing nanobiochar into the soil, carbon sequestration is achieved, contributing to climate change mitigation (61). Overall, nanobiochar applications in agriculture exemplify its potential as a multifaceted solution for sustainable and precision farming. Ongoing research and development efforts continue to explore optimal formulations, application methods and specific agricultural contexts to maximize the benefits of nanobiochar, ultimately supporting global efforts towards more resilient and environmentally conscious agricultural practices (62).

C. Potential energy sector in storage and biomedical fields:

In the energy sector, nanobiochar holds significant potential for energy storage applications, particularly in the development of advanced super capacitors and batteries. The unique properties of nanobiochar, including its high surface area, enhanced electrical conductivity and tailored surface functionalities, make it a promising material for improving the performance of energy storage devices. Nanobiochar can serve as an electrode material in super capacitors, contributing to higher capacitance and faster charge-discharge cycles (63). Its porosity allows for efficient ion transport, leading to enhanced energy storage capabilities. Additionally, nanobiochar-based composite materials, incorporating conductive polymers or other nanomaterials, demonstrate improved electrochemical performance (64). In the biomedical field, nanobiochar finds applications in drug delivery systems and medical imaging. The biocompatibility and porous structure of nanobiochar make it suitable for drug encapsulation and controlled release, addressing challenges in drug (65). Furthermore, nanobiochar's ability to adsorb and transport contrast agents in medical imaging enhances its utility in magnetic resonance imaging (MRI) and other diagnostic techniques (66). The combination of properties, such as biocompatibility, surface functionality and adsorption capabilities, positions nanobiochar as a versatile material with promising applications in both the energy storage and biomedical sectors (67). Ongoing research continues to explore innovative approaches and optimize nanobiochar formulations to unlock its full potential in these dynamic fields (18). Various applications of nanobiochar are given in the Fig. 4.

Fig. 4. Applications of biochar.

Nanobiochar environmental impact and safety considerations:

A. Eco toxicity assessment:

The eco-toxicity assessment of nanobiochar is a crucial aspect in understanding its potential environmental impacts. As nanobiochar gains prominence for various applications, ranging from water and soil remediation to agricultural enhancements, evaluating its effects on ecosystems becomes paramount. Eco-toxicological studies systematically investigate how nanobiochar interacts with living organisms and the environment. Assessments encompass a range of organisms, including bacteria, algae, aquatic invertebrates and higher organisms, to comprehensively understand the potential risks associated with nanobiochar exposure (68). In these studies, researchers evaluate various endpoints such as growth inhibition, reproductive success and changes in behavior or physiology of the exposed organisms. The unique properties of nanobiochar, such as its surface characteristics, particle size and chemical composition, are scrutinized to identify potential mechanisms of toxicity (69). The fate and transport of nanobiochar in different environmental compartments, along with its potential to leach harmful substances are also considered (70).

While nanobiochar is generally considered a low-risk material due to its biocompatible and carbonaceous nature, it is crucial to conduct eco-toxicity assessments under realistic exposure scenarios. Research in this area aims to establish safe usage guidelines, effective risk management strategies and the development of modified nanobiochar formulations that minimize any adverse effects on the environment (71). Ongoing advancements in eco-toxicology studies of nanobiochar contribute to a comprehensive understanding of its environmental behavior and potential risks, guiding the responsible and sustainable deployment of this nanomaterial across various applications. Regular updates to assessment methodologies, incorporation of diverse environmental scenarios and collaboration between researchers and regulatory bodies ensure that nanobiochar is harnessed for its beneficial applications without compromising environmental integrity (72).

B. Fate and transport in the environment:

The fate and transport of nanobiochar in the environment are critical considerations for understanding its behavior and potential impacts on ecosystems. The unique physicochemical properties of nanobiochar, including particle size, surface area and porosity, influence its environmental interactions. Upon application, nanobiochar may undergo various processes that dictate its fate and transport (73). In soils, nanobiochar can adhere to soil particles, influencing its retention and distribution. The porous structure of nanobiochar enhances its water retention capacity and nutrient-holding ability, affecting soil moisture and fertility. The potential leaching of nanobiochar components into groundwater is a concern, necessitating an understanding of its mobility in different soil types (74). In aquatic environments, nanobiochar may disperse and undergo sedimentation processes. The surface charge and functional groups on nanobiochar particles influence their interactions with water molecules and aquatic organisms. Aggregation and settling dynamics are crucial factors governing nanobiochar's fate in water bodies, impacting its potential to reach downstream ecosystems (75).

The fate of nanobiochar in the atmosphere is influenced by its physical characteristics, such as particle size and aerodynamic properties. Airborne transport and deposition can occur, especially during application processes or under specific environmental conditions. Understanding the potential for nanobiochar inhalation and its deposition in different environmental compartments is essential for assessing human and ecological exposure risks (76). Furthermore, the transformation of nanobiochar over time is a critical aspect of its fate. Biodegradation and weathering processes can alter its surface properties, potentially affecting its reactivity and interactions with the environment (77). Environmental fate and transport studies involve comprehensive assessments of these processes using various analytical techniques, including spectroscopy, microscopy, and modeling approaches. These studies contribute to the development of guidelines for responsible nanobiochar application, minimizing any adverse effects on ecosystems and ensuring its sustainable utilization in environmental remediation, agriculture and other fields (78). As research in this area progresses, a more nuanced understanding of nanobiochar's behavior in different environmental matrices emerges, facilitating informed decision-making for its safe and effective deployment (79).

C. Regulatory aspects and safety concerns:

Regulatory aspects and safety concerns surrounding nanobiochar are crucial considerations to ensure responsible and sustainable deployment of this nanomaterial. Nanobiochar, being a product of nanotechnology, is subject to scrutiny by regulatory agencies worldwide to assess its potential impact on human health, environmental ecosystems and industrial processes. Regulatory bodies such as the U.S. Environmental Protection Agency (EPA), the European Chemicals Agency (ECHA) and others play key roles in establishing guidelines and standards for the production, labeling and application of nano-materials (80). One primary safety concern revolves around the potential for human exposure, especially during the manufacturing, handling and application of nanobiochar. Due to its nanoscale dimensions, there are concerns about respiratory exposure and potential adverse effects on human health. Robust toxicological studies are conducted to evaluate the impact of nanobiochar on cellular structures, genotoxicity and potential long-term health effects. The need for comprehensive risk assessments is underscored to establish safe exposure limits and guidelines (81).

Environmental safety is another critical aspect, emphasizing the potential impacts of nanobiochar on ecosystems. Concerns range from its fate and transport in soil and water to potential toxicity to aquatic and terrestrial organisms. Assessing bioaccumulation potential and understanding the persistence of nanobiochar in environmental matrices are crucial components of regulatory evaluations (82). Regulatory frameworks often require manufacturers to provide detailed information on the physicochemical properties, stability and potential hazards associated with nanobiochar. This information is instrumental in establishing safety guidelines, exposure limits and risk management strategies. Additionally, regulatory bodies may tailor specific regulations for nanomaterials, considering their unique characteristics and potential risks (83). While nanobiochar holds immense promise for diverse applications, including environmental remediation and agriculture, a precautionary approach is advocated to address safety concerns. Regular updates and revisions to regulatory frameworks are essential to keep abreast of advancements in nanotechnology, ensuring that the regulatory landscape evolves alongside technological innovations. Striking a balance between fostering innovation and ensuring safety remains paramount for the responsible integration of nanobiochar into various industrial, agricultural and environmental practices (84).

Challenges and Future perspectives of nanobiochar:

A. Limitations and challenges in nanobiochar application:

The application of nanobiochar, despite its promising attributes, encounters certain limitations and challenges that necessitate careful consideration. One primary challenge is related to the potential toxicity and environmental impact of nanobiochar. The unique properties that make nanobiochar effective, such as its high surface area and reactivity, also raise concerns about unintended consequences, including potential harm to aquatic and terrestrial ecosystems. Understanding the long-term fate and transport of nanobiochar in different environmental matrices is crucial for assessing its overall ecological impact. Another limitation lies in the potential health risks associated with human exposure during the production, handling and application of nanobiochar. The fine particle size and airborne nature of nanomaterials raise concerns about respiratory exposure and other potential adverse health effects, necessitating comprehensive risk assessments and the establishment of safety guidelines (85).

Furthermore, the scalability and cost-effectiveness of nanobiochar production pose challenges for large-scale applications. Manufacturing processes for nanobiochar may require specialized equipment and entail additional costs, impacting its economic feasibility and widespread adoption. Achieving a balance between cost efficiency and maintaining the unique properties of nanobiochar is an ongoing challenge in scaling up production. In the agricultural sector, the variability in the effectiveness of nanobiochar across different soil types and crop varieties presents a challenge. The optimal dosage and application methods may vary, requiring tailored approaches for different agricultural contexts. Understanding these nuances is critical for maximizing the benefits of nanobiochar in sustainable agriculture (86). Additionally; there is a need for standardized testing protocols and regulatory frameworks specifically designed for nano-materials, including nanobiochar. The lack of universally accepted standards complicates the evaluation of safety and efficacy, hindering the seamless integration of nanobiochar into various industries. Addressing these limitations and challenges requires multidisciplinary research efforts, involving toxicologists, environmental scientists, engineers and regulatory experts. Ongoing studies aim to refine production processes, develop comprehensive risk assessment methodologies and establish clear guidelines for the safe and effective use of nanobiochar across diverse applications. By addressing these challenges, the full potential of nanobiochar can be harnessed while ensuring its responsible and sustainable deployment (87).

B. Potential breakthroughs and innovations:

Potential breakthroughs and innovations in nanobiochar research hold the promise of transforming numerous industries and addressing pressing global challenges. One notable area is the development of advanced water purification technologies. Nanobiochar's exceptional adsorption properties and tailored surface functionalities create opportunities for breakthroughs in removing emerging contaminants, heavy metals and pollutants from water sources with unprecedented efficiency. This innovation could significantly impact water treatment processes and contribute to providing clean and safe drinking water globally (88). In agriculture, potential breakthroughs lie in precision farming and sustainable soil management. Nanobiochar's ability to enhance nutrient retention, improve soil structure and mitigate environmental degradation suggests revolutionary applications. Precision agriculture, incorporating nanobiochar has the potential to optimize crop yields, reduce environmental impact and promote sustainable farming practices (89).

Biomedical breakthroughs are anticipated in the realm of drug delivery and medical imaging. Nanobiochar's biocompatibility and surface characteristics offer opportunities for innovative drug delivery systems, allowing controlled release and targeted therapy. Additionally, advancements in utilizing nanobiochar for medical imaging purposes, such as magnetic resonance imaging (MRI), may usher in a new era of diagnostic tools with improved sensitivity and specificity (90). Sustainable energy storage is another area where nanobiochar holds promise for breakthroughs. Research is focused on developing high-performance super capacitors and batteries by leveraging the unique properties of nanobiochar. Innovations in energy storage technologies using nanobiochar could lead to more efficient and environmentally friendly energy solutions, contributing to the advancement of renewable energy systems. Furthermore, potential breakthroughs in the synthesis and scalable production of nanobiochar are on the horizon. Green synthesis methods, utilizing waste biomass and sustainable resources may revolutionize the manufacturing processes, making nanobiochar production more economically viable and environmentally friendly. Collaborative efforts between disciplines such as nanotechnology, materials science, environmental engineering and medicine are likely to drive these breakthroughs. Interdisciplinary research approaches foster synergies, enabling a holistic understanding of nanobiochar's potential applications and promoting transformative innovations. Overall, the potential breakthroughs and innovations in nanobiochar underscore its versatility and the transformative impact it could have on diverse fields. As research advances, these breakthroughs have the potential to address critical challenges, improve resource efficiency and contribute to sustainable solutions for a wide range of global issues (18).

Conclusion

In summary, nanobiochar emerges as a versatile and promising solution across various sectors, encompassing environmental remediation, agriculture, energy storage and biomedical applications. Its distinct characteristics, stemming from biochar and further refined at the nano-scale, offer a wide array of opportunities for tackling modern challenges. Extensive research into the synthesis methods and properties of nanobiochar has laid the groundwork for tailored applications in diverse fields. Nevertheless, challenges such as eco-toxicity, regulatory considerations and scalability must be addressed to ensure its safe and sustainable implementation. Despite these hurdles, burgeoning trends signal a growing interest in optimizing nanobiochar for specific purposes and exploring innovative approaches in its synthesis and utilization. Through collaborative endeavors and interdisciplinary research, the potential for breakthroughs and innovations in nanobiochar holds the promise of revolutionizing industries, mitigating environmental impacts and fostering sustainable development. Moving forward, addressing these challenges and embracing emerging trends will be pivotal in fully realizing the benefits of nanobiochar and advancing towards a more sustainable future.

Emerging trends and future directions in research:

Emerging trends and future directions in nanobiochar research are characterized by a growing emphasis on optimizing applications across various domains and addressing key challenges. In environmental remediation, there is a trend towards exploring novel nanobiochar formulations for enhanced pollutant adsorption and efficient water purification. Researchers are investigating surface modification techniques and composite materials to tailor nanobiochar for specific contaminants, expanding its utility in diverse environmental matrices. Additionally, advancements in understanding the fate and transport of nanobiochar in soils and water contribute to more sustainable and effective environmental solutions. In agriculture, future research directions involve fine-tuning nanobiochar properties to maximize soil enhancement and nutrient retention. Tailored formulations are being explored to optimize nutrient release kinetics, mitigate soil degradation and improve crop yields. Precision agriculture approaches, incorporating nanobiochar, are gaining traction to address site-specific agricultural challenges and promote sustainable farming practices. Biomedical applications of nanobiochar are also gaining attention. Ongoing research explores its potential in drug delivery systems, bio imaging and therapeutics. The biocompatibility and unique surface characteristics of nanobiochar offer opportunities for innovative solutions in medical science, such as targeted drug delivery systems with controlled release profiles.

Furthermore, research is focusing on the sustainable production of nanobiochar. Green synthesis methods and the utilization of waste biomass for nanobiochar production align with the broader trend of promoting eco-friendly and resource-efficient processes. These sustainable approaches not only contribute to the circular economy but also address concerns related to the environmental impact of nanobiochar production. As the field advances, interdisciplinary collaborations are becoming more prevalent, bringing together experts in nanotechnology, environmental science, agriculture, medicine and materials engineering. This collaborative approach fosters holistic solutions and deeper understanding of the multifaceted applications of nanobiochar. The integration of artificial intelligence and machine learning in nanobiochar research is another emerging trend. These technologies assist in data analysis, prediction modeling and optimization of nanobiochar properties, accelerating the pace of research and development. Overall, the future directions in nanobiochar research are marked by a convergence of disciplines, a focus on sustainability and the exploration of innovative applications. These trends contribute to unlocking the full potential of nanobiochar, positioning it as a versatile and sustainable solution for a wide range of contemporary challenges.

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Authors' contributions

RD conceptualized and designed the structure of the review article. Led the literature search, data collection and drafted the sections on the synthesis and characterization of nanobiochar. MP focused on environmental remediation applications of nanobiochar, particularly its role in water and soil treatment. Contributed to data analysis and critically revised the manuscript for important intellectual content. CSR, SUK, RM contributed to the final manuscript editing and revisions to ensure clarity and cohesion across the sections. KTP and VG provided critical feedback on all sections and contributed significantly to revising the manuscript. All authors read and approved the final manuscript.

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