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Furtherance in nano biochar: An encyclopedic review

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Abstract

Biochar, a carbonaceous material with ancient origins in Amazonian dark earth, has evolved significantly with the advent of nanotechnology, giving rise to nanobiochar. This advanced form of biochar, produced from biomass through methods like pyrolysis and gasification, exhibits unique properties such as high surface area, enhanced reactivity, and diverse functional groups. Nanobiochar's applications span environmental remediation, agriculture, energy storage, and biomedical fields. It effectively removes contaminants from water and soil, enhances soil quality and nutrient retention, and shows promise in energy storage and drug delivery systems. Recent research focuses on optimizing nanobiochar synthesis, exploring sustainable production methods, and tailoring its properties for specific applications. Despite challenges like eco-toxicity and scalability, the integration of artificial intelligence and interdisciplinary collaborations are driving advancements. Emerging trends emphasize sustainable production and innovative applications, positioning nanobiochar as a versatile and promising solution for modern environmental and agricultural challenges, fostering sustainable development, and revolutionizing various industries.

Keywords: Nano biochar, 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 technologies has recently been established due to their 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, several authors have focused on the use of nano-compounds in the development of better remediation methods [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]. The research community has shown significant interest in carbon-based nano materials because of their versatile applications across agriculture, the environment, catalysis, energy, and biomedicalfields [14]. 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 [15]. 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 [16]. As researchers explore 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) [17]. 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, cheap cost, and potential to solve environmental pollution issues. Using waste biomass as a raw material for biochar production not only helps in waste management but also has the potential to improve carbon sequestration, water quality, and decrease greenhouse gas emissions in soil and water environments [18].

Methods

Biochar production involves thermal decomposition through methods like pyrolysis, torrefaction, hydrothermal carbonization, and gasification. Pyrolysis degrades organic molecules in the absence of oxygen at 250-900 degrees Celsius. Hydrothermal carbonization converts organic biomass into carbon-rich material at elevated temperatures and pressures, making it economically advantageous due to its low operating temperature [19]. 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 [20]. 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 degrees Celsius to remove carbon dioxide, oxygen, and moisture from biomass [21].

Nano biochar: Definition, raw materials used, synthesis methods, characteristics

Nano biochar refers to biochar particles that have been engineered or synthesized at the nano scale, typically with dimensions ranging from a few nanometers to tens of nanometers. This fine-scale biochar variant exhibits unique properties and enhanced reactivity compared to its larger counterparts, making it suitable for various applications in fields such as environmental science, agriculture, and materials science [22]. The raw materials for nano biochar synthesis 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 influence the properties of the resulting nano biochar. Additionally, precursors for nano biochar may include carbon-rich compounds or biomass derivatives suitable for specific synthesis methods [23].

Synthesis Techniques for Nano biochar

Synthesizing nano biochar involves several methods designed to produce biochar particles at the nano scale, enhancing their reactivity and versatility. Common synthesis approaches include ball milling, where mechanical forces reduce larger biochar particles into nano scale fragments, and ultrasonication, utilizing high-frequency sound waves to disintegrate biochar into well-dispersed nanoparticles [24]. Colloid nano particle synthesis entails creating nano biochar particles by carefully inducing the controlled aggregation and stabilization of biochar nanoparticles within a colloidal solution [25]. Pyrolysis with nano scale catalysts introduces catalysts during the carbonization process, influencing the formation of nano biochar [26]. Template-assisted synthesis employs templates or sacrificial materials to guide the creation of nanostructures with controlled size and morphology [27]. Chemical vapor deposition (CVD) deposits carbon onto a substrate from gaseous precursors, allowing the production of well-defined nanostructures [28]. Hydrothermal carbonization (HTC) utilizes water-rich conditions at elevated temperatures to produce nano biochar with unique properties [29]. The sol-gel method transforms liquid precursors into a gel, facilitating the formation of nano biochar with controlled characteristics [30]. Lastly, in biological synthesis method, the use of biological systems, such as plant extracts or microbial cultures, for the reduction and stabilization of metal salts into nano biochar particles offers 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 [31]. These methods offer flexibility in tailoring nano biochar for specific applications, such as environmental remediation, energy storage, and advanced materials. Thorough characterization ensures the confirmation of nano scale features and properties in the synthesized nano biochar [32].

Properties of Nano biochar

Nano biochar, a carbonaceous substance consisting of particles in the nano scale range, possesses unique physical and chemical attributes that contribute to its versatile applications [33]. Regarding its physical characteristics, nano biochar is distinguished by its nano scale particle size, typically ranging from a few nanometers to tens of nanometers. The morphology can vary, encompassing nanoparticles, nano fibers, or other nanostructures, depending on the chosen synthesis method. This nano scale dimension results in a larger surface area compared to conventional biochar, boosting its reactivity and suitability for applications such as adsorption and catalysis [34]. The porosity of nano biochar is a crucial feature, providing an increased number of active sites for interactions with gases, liquids, or other substances. Furthermore, the surface charge of nano biochar influences its interactions with particles or substances, particularly in water treatment applications [35]. In terms of chemical properties, nano biochar 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 nano biochar play pivotal roles in adsorption/desorption processes and its application in redox-active systems [10]. In summary, the customized physical and chemical properties of nano biochar, coupled with its nano scale dimensions, position it as a promising material for a range of applications, including water treatment, catalysis, energy storage, and nano composite materials [36]. 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, thereby increasing its versatility and effectiveness across different applications [37].

Applications of Nano biochar

Environmental sector: water and soil purification

Nano biochar is a highly effective solution for water and soil purification due to its high surface area and porous structure. It effectively removes contaminants, including heavy metals and organic pollutants, ensuring safe drinking water [38]. In soil purification, nano biochar retains nutrients and immobilizes contaminants, promoting sustainable agriculture. It also aids in carbon sequestration, enhancing soil health [39]. Research continues to refine and expand nano biochar's applications, advancing its role in sustainable environmental management [40].

Agricultural sector: soil enhancement, nutrient retention

Nano biochar is a valuable soil amendment that enhances soil quality and nutrient retention, contributing to sustainable farming practices [41]. Its high surface area and porous structure promote healthier soil structures, aeration, and root development [42]. Nano biochar also acts as a pH buffer, neutralizing acidic soils and adjusting alkalinity for plant growth [43]. It sequesters essential elements, reducing the need for frequent fertilization. Its increased cation exchange capacity enhances nutrient retention and exchange with plant roots, ensuring optimal crop growth [44]. Nano biochar also contributes to climate change mitigation by achieving carbon sequestration. Research and development efforts are ongoing to maximize its benefits.

Potential energy sector in storage and biomedical fields

Nano biochar is a promising material for energy storage and biomedical applications due to its high surface area, enhanced electrical conductivity, and tailored surface functionalities [45]. It can improve performance in super capacitors and batteries, enhance ion transport, and improve electrochemical performance [46]. In the biomedical field, it is used in drug delivery systems and medical imaging, due to its biocompatibility and porous structure [47]. Further research is needed to optimize nano biochar formulations.

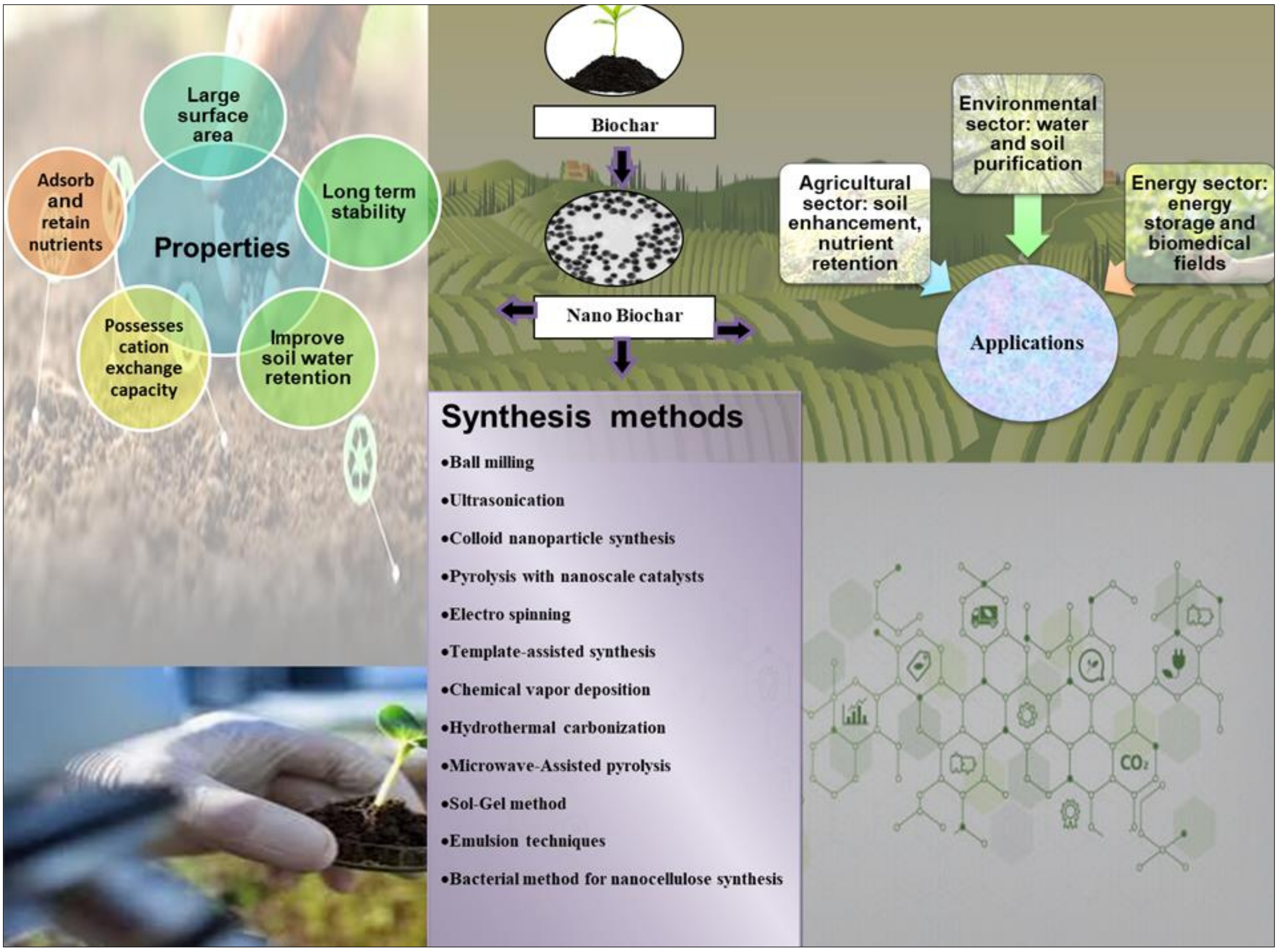

Fig 1: Graphical Abstract

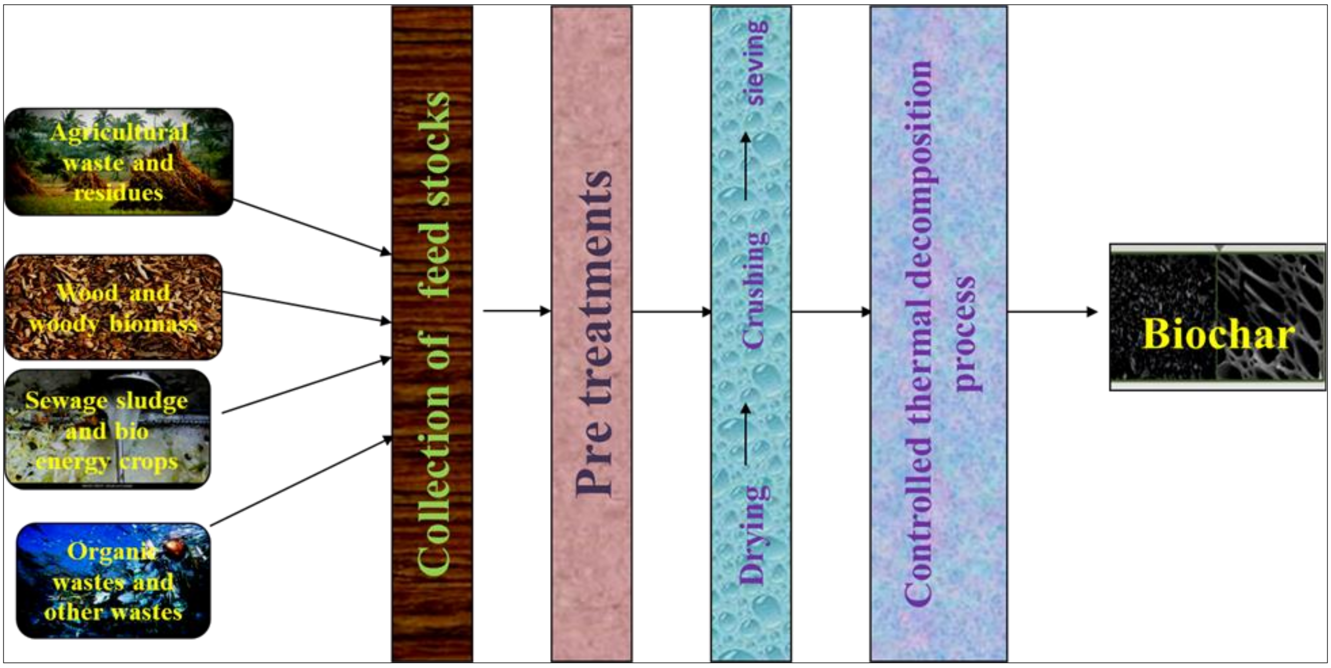

Fig 2: Synthesis process of Biochar

Fig 3: Applications of Biochar

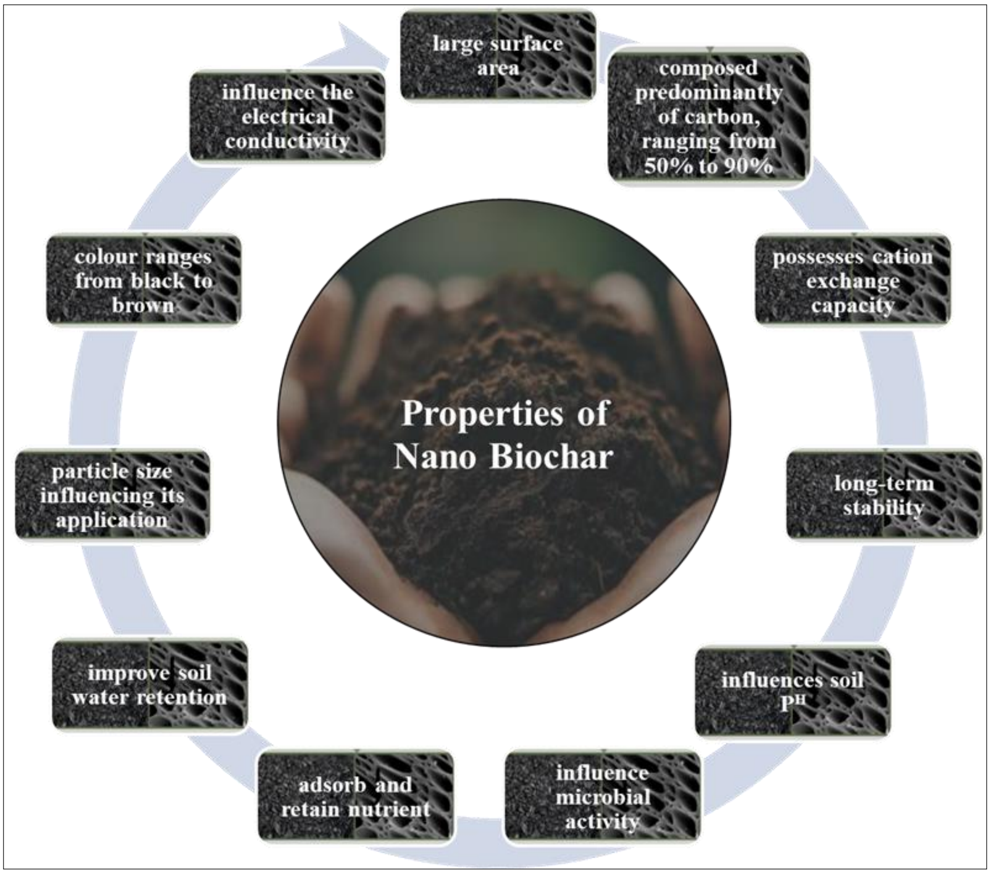

Fig 4: Properties of Nano biochar

Table 1: Characteristics of nano biochar with its applications

S.No.	Characteristics	Applications	References
1.	Nano scale Particle Size	Nano biochar particles typically range from a few nanometers to tens of nanometers, providing a higher surface area per unit mass.	[33]
2.	Enhanced Reactivity	The increased surface area and specific nanostructures contribute to enhanced reactivity, making nano biochar suitable for applications such as catalysis and adsorption.	[32]
3.	Tailored Properties	Synthesis methods allow for the precise control of particle size, structure, and surface chemistry, enabling the tailoring of nano biochar properties for specific applications.	[34]
4.	Improved Dispersion	Nano biochar particles often exhibit improved dispersion in liquids or matrices, facilitating their incorporation into various systems.	[35]
5.	Application Versatility	Nano biochar finds applications in diverse fields, including environmental remediation, agriculture, nano composites, and as a platform for advanced materials due to its unique characteristics.	[36]

Table 2: Comparative analyses of various synthesis approaches among biochar, nano biochar, activated carbon

S. No	Properties	Biochar	Nano biochar	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.	▪ Synthesized Using 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.	▪ Produced 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 CO2 or steam).	[27, 58, 59]
2.	Particle Size and Structure	▪ The particle sizes 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	▪ 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 nano particles or nano fibers, 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.	[60-62]

		carbonaceous material with varying degrees of organization.			
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.	[63-65]
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.	[66-68]
5.	Cost and Scalability	▪ Generally Cost-effective and can be produced on a larger scale. ▪ The simplicity Of the Production methods contributes 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.	[17, 69, 70]

Conclusion

In summary, nano biochar 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 nanoscale, offer a wide array of opportunities for mitigating modern challenges. Extensive research into the synthesis methods and properties of nano biochar 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 nano biochar 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 nano biochar 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 nano biochar and advancing towards a more sustainable future.

Emerging trends and future directions in research

Emerging trends and future directions in nano biochar 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 nano biochar formulations for enhanced pollutant adsorption and efficient water purification. Researchers are investigating surface modification techniques and composite materials to tailor nano biochar for specific contaminants, expanding its utility in diverse environmental matrices. Additionally, advancements in understanding the fate and transport of nano biochar in soils and water contribute to more sustainable and effective environmental solutions. In agriculture, future research directions involve fine-tuning nano biochar 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 nano biochar, are gaining traction to address site-specific agricultural challenges and promote sustainable farming practices. Biomedical applications of nano biochar are also gaining attention. Ongoing research explores its potential in drug delivery systems, bio imaging, and therapeutics. The biocompatibility and unique surface characteristics of nano biochar 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 nano biochar. Green synthesis methods and the utilization of waste biomass for nano biochar 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 nano biochar 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 nano biochar. The integration of artificial intelligence and machine learning in nano biochar research is another emerging trend. These technologies assist in data analysis, prediction modeling, and optimization of nano biochar properties, accelerating the pace of research and development. Overall, the future directions in nano biochar 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 nano biochar, positioning it as a versatile and sustainable solution for a wide range of contemporary challenges.

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