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Nano-Biochar: A promising tool for sustainable agriculture under climate change era

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ABSTRACT

Nano-biochar, a highly porous and innovative material derived from biomass, presents significant opportunities for sustainable agriculture and environmental remediation. Its unique sponge-like structure enables exceptional carbon capture and sequestration, contributing to long-term improvements in soil fertility and acting as a vital tool in climate change mitigation. This review explores the properties and production methods of nano-biochar, highlighting its enhanced nutrient retention, controlled release capabilities, and superior water-holding capacity compared to traditional biochar. These characteristics not only enhance plant growth and agricultural productivity but also promote a healthier soil ecosystem by stimulating microbial activity. Furthermore, nano-biochar's ability to adsorb heavy metals and organic pollutants offers promising applications in soil and water remediation, thus preventing environmental contamination. Despite its numerous advantages, the review identifies critical knowledge gaps regarding the long-term ecological impacts of nano-biochar and the best practices for its production and application. The paper calls for further research to address these challenges and optimize the use of nano-biochar, ensuring its responsible development within agricultural systems. By integrating insights from current literature, this review contributes to a comprehensive understanding of nano-biochar's potential and outlines future research directions to enhance its effectiveness in promoting sustainable agricultural practices.

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1. INTRODUCTION

Rising atmospheric concentrations of greenhouse gases, particularly carbon dioxide, induce an upward trend in planetary warming, and its consequences specifically impact the agriculture sector (IPCC, 2001). Agriculture represents about 11 % of total global anthropogenic GHG emissions in 2023 (Statista, 2024). Biochar is a charcoal-like material produced by pyrolysis of biomass under limited oxygen conditions and has gained prominence as a soil amendment. It holds significant potential for sequestrating atmospheric CO_2 into forms that are stored stably in soil (Lehmann & Joseph, 2024). Through biochar addition in soils, long-term carbon sequestration can be encouraged, probably offsetting agricultural emissions and forming part of the strategies toward mitigating climate change (Lehmann et al., 2006)).

Several studies in recent times have explored the use of nano-biochar, a derivative of biochar with nano-range particle sizes, for enhanced environmental applications (Li et al., 2016). Nano-biochar and conventional biochar are both carbon-rich materials derived from biomass pyrolysis, but nano-biochar offers enhanced functionality due to its

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nanoscale size and physicochemical properties. Unlike traditional biochar, which typically has a larger particle size and limited surface area, nano-biochar features a significantly higher surface area, greater porosity, and more reactive functional groups, making it more effective in nutrient retention in soil, water conservation, and pollutant removal (Mukherjee et al., 2011; Titirici et al., 2007). These unique properties make nano-biochar a powerful tool in precision agriculture, environmental remediation, and water treatment, allowing it to outperform conventional biochar in a wide range of applications. One of the key advantages of nano-biochar is its efficiency; it requires smaller quantities to achieve equal or better results than conventional biochar. This efficiency has the potential to mitigate challenges like limited feedstock availability, which is a significant bottleneck for the widespread use of conventional biochar. Furthermore, nano-biochar contributes to stable carbon sequestration, enhancing its role in climate change mitigation efforts.

The production process of nano-biochar can also be optimized to tailor its properties. Factors such as the feedstock material and process conditions during pyrolysis, or other methods, like hydrothermal carbonization and ball milling, can significantly affect its surface area, pore size distribution, and surface chemistry (Zhao et al., 2019). These tailored properties unlock substantial benefits, particularly in agricultural management, by improving soil health, nutrient retention, and crop productivity. However, the advanced techniques required for nano-biochar production can increase costs. Their superior performance and versatility often offset these costs, making them a valuable investment for sustainable practices. Overall, nano-biochar not only amplifies the benefits of conventional biochar but also addresses key scalability and efficiency challenges, positioning it as a promising solution for sustainable agriculture and environmental management.

The potential application of nano-biochar in the agricultural sector improves soil fertility and plant growth, reducing the number of applied fertilizers and pesticides, and continuing to store carbon in soils (Jeffery et al., 2011; Lehmann & Joseph, 2024; Liu et al., 2018). Furthermore, the development of possible uses for its adsorption and immobilization capacity of pollutants such as heavy metals and organic contaminants in soil may give way to the remediation of contaminated agricultural land (Xu et al., 2013). Nano-biochar is a viable option to accomplish some of the sustainable development goals (SDGs) and circular bioeconomy such as SDG 1 (no poverty), SDG 2 (zero hunger), SDG 3 (good health and well-being), SDG 6 (clean water and sanitation), SDG 12 (responsible consumption, and production) and SDG 13 (climate action) (Patro et al., 2024; Sani et al., 2023). With its unique properties and promising applications, nano-biochar is rapidly emerging as one of the major players in sustainable agriculture and environment management.

The aim of this review paper is to take stock of the current state of knowledge concerning nano-biochar by describing different methods used for its preparation and characterization. An attempt has been made to analyze the potential advantages that nano-biochar can bring to agriculture with respect to soil fertility, plant growth, and carbon sequestration (Jeffery et al., 2011; Lehmann & Joseph, 2024; Liu et al., 2018). A balanced approach would, however, require a critical view of the challenges associated with nano-biochar applications. In this regard, a review of environmental considerations, potential risks related to nano-biochar particle release into the environment, knowledge gaps in nano-biochar, and their impact on soil ecosystems would aid in further research (Wang et al., 2020). Focus on long-term studies of nano-biochar fate in the environment and possible ecological risks in soil, as well as the development of standardized protocols for its production, characterization, and safe application, is also critical (Osman et al., 2022). This review summarizes in detail the possible benefits, challenges, and knowledge gaps in nano-biochar to help researchers, policymakers, and the stakeholders involved in agricultural practices navigate this newly developed material's responsible development and application.

2. Feedstock selection, Preparation Methods, and Characterization Techniques

Feedstock selection is the key step involved in nano-biochar production, followed by the process involved in conversion, particle size reduction, optimization of properties, characterization, and application (Fig. 1). There are several promising nano-biochar production methods (Fig. 2), which include hydrothermal carbonization (HTC), pyrolysis, ball milling, chemical activation, etc., each having its own characteristics, advantages, and limitations. The most appropriate method is based on the desired properties of nano-biochar, feedstock biomass, and other economic issues. The optimization of production methodology and development of new approaches advance the research and reveal the potential of nano-biochar.

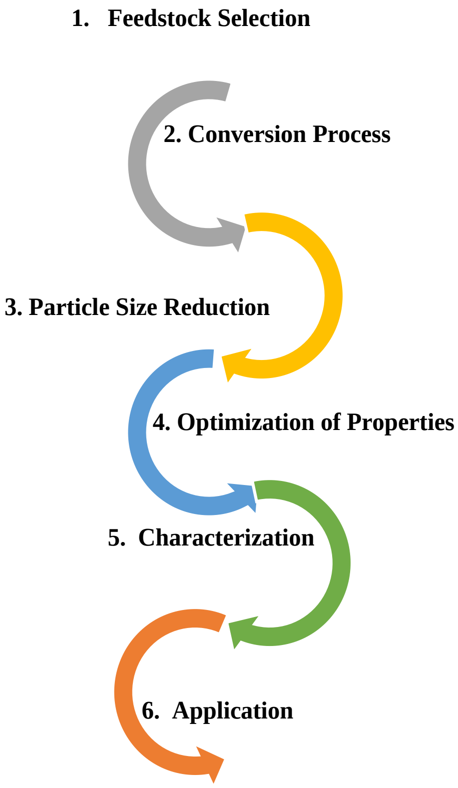

Figure 1. Steps to prepare Nano-biochar

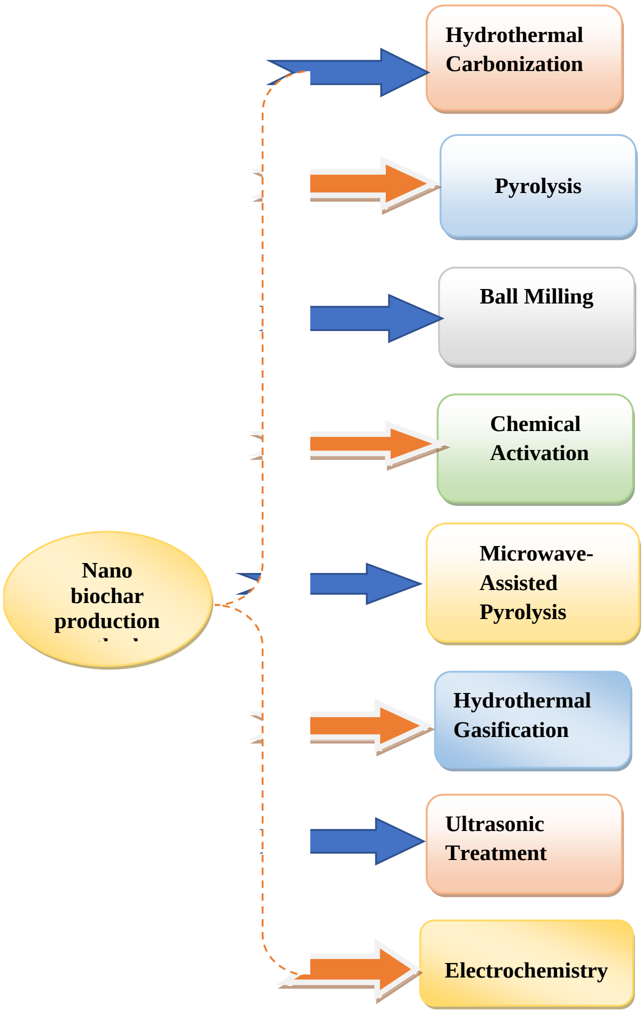

Figure 2. Nano-biochar production methods

2.1. Feedstock selection and composition

Nano-biochar production methods are influenced not only by the choice of production method but also significantly by the selection of feedstock biomass, which dictates the properties, characteristics, and potential applications of the resulting nano-biochar (Rajput et al., 2022; Sarmah et al., 2023). The proportions of lignin, cellulose, and hemicellulose in the feedstock biomass significantly influence the predominant characteristics of the final nano-biochar product (Kim et al., 2011; Yang et al., 2017). Feedstocks rich in cellulose and hemicellulose, such as wood or plant materials, tend to yield nano-biochar with high surface area and porosity (Chen et al., 2020; Ramanayaka et al., 2020; Sultan et al., 2024), making it suitable for applications like adsorption and filtration, where a large, accessible surface area is essential for capturing contaminants or desired molecules.

Studies also indicated that biomass with high hemicellulose content tends to yield nano-biochar with low carbon content and high oxygen content (Aziz et al., 2023; Chaubey et al., 2024; Jiang et al., 2023; Weber & Quicker, 2018). Conversely, feedstocks with higher lignin content, such as fruit shells or pits, may result in nano-biochar with a more aromatic structure (Ramadan et al., 2020). This type of nano-biochar shows promise for applications like soil stabilization or contaminant degradation due to its unique chemical properties. The ash content in the feedstock also influences the final nano-biochar product. Ash content varies based on feedstock source and extraction method. For instance, as particle sizes decrease, ash content increases, which is specifically observed in nano-biochar produced from plant biomass sources compared to nano-biochars prepared from manure and sludge (Qian et al., 2016; Song et al., 2019). Moreover, the ash content of nano-biochar produced from agricultural waste depends on the type of crop residues. For example, nanobiochar made from rice straw has higher ash content than corn straw (Ma et al., 2019) and wheat straw (Song et al., 2019). In addition to feedstock material, the temperature maintained during extraction method also influences the ash content (Anupama & Khare, 2021; Ramanayaka et al., 2020). The ultrasonic nano biochar has significantly lower ash content compared to pristine biochar (Jiang et al., 2023) whereas, wet ball milling increases the ash content of resulting nanobiochars (Ramanayaka et al., 2020; Tomczyk et al., 2020; H. Yuan et al., 2020). Also, the ash content was higher for nano biochar prepared through sonication/centrifugation compared to the hydrothermal route (Behnam & Firouzi, 2023; Xu et al., 2020). High ash content can increase the mineral content in nano-biochar, potentially affecting its surface properties and reactivity (Okolie et al., 2020). For instance, using manure as a feedstock can produce nano-biochar beneficial for soil amendment and nutrient delivery due to its inherent nutrient content (Zhang et al., 2024). However, the high ash content in manure may require pre-treatment steps to optimize the production process and achieve desired product characteristics.

Feedstock availability and cost also play a significant role, especially for large-scale production, where locally available and cost-effective feedstocks are preferred to ensure economic viability (Ku Aizuddin et al., 2023). The complex inter-relations between feedstock selection, production methods, and nano-biochar properties have to be understood for the optimization of production processes targeted for agriculture or environmental applications. On the basis of these factors, one can modulate the nano-biochars with targeted properties that make them highly efficient for plant growth promotion, contaminated soil remediation, or carbon sequestration (Abed Hussein et al., 2022; Lehmann & Joseph, 2024). The data in Table 1 summarizes how various feedstock types can impact nano-biochar properties.

2.2. Nano biochar production methods

Various nano biochar production methods are discussed below, and the key notes are depicted in Table 2.

Hydrothermal carbonization (HTC) is a thermochemical process that uses high pressure and temperature in water to convert biomass into carbon-rich materials (Bolan et al., 2022; Sandhya et al., 2024). It is also referred to as nano-hydrochar (Khosravi et al., 2022) that enables precise control over the final properties of nano-biochar by adjusting process parameters like temperature, pressure, and residence time. Higher temperatures and pressures enhance structural properties, while longer residence times can improve yield (Garg et al., 2024; Saraugi & Routray, 2024).

Table 1. Impact of feedstock types on Nano-biochar properties

Feedstock	Properties Affected	Potential Applications	Reference
Wood	High yield, good surface area, tailorable porosity	Adsorption, filtration, contaminant removal	Karinkanta et al. (2018)
Manure	High nutrient content, promotes plant growth	Soil amendment, nutrient delivery	Zhang et al. (2024)
Algae	High ash content (requires pre-treatment), potential energy production	Wastewater treatment, metal ion adsorption (after modification)	Yao et al. (2020)
Rice straw	Abundant, renewable, requires pre-treatment	Soil amendment, contaminant removal	Anupama and Khare (2021)
Fruit shells/pits	High lignin content, potential for aromatic structure	Soil stabilization, contaminant degradation	Anupama and Khare (2021)
Corn cobs	Cellulosic content, good porosity development	Adsorption, filtration, biocatalysis (after functionalization)	Xu et al. (2024)
Sewage sludge	Higher nutrient content, less adsorption capacity	Effective soil contaminant degradation (without pyrolysis)	Zhao et al. (2019)
Pulp mill sludge	Higher nutrient content, adsorption capacity differ with the types of heavy metal.	Higher adsorption affinities for Ni (II), Cu (II)	Islam et al. (2021)

The nano-biochar particles produced from this method had higher surface area, surface polarity, stability, surface functional groups, less energy input, and produced relatively smaller biochar particles compared to sonication or centrifugation (Behnam & Firouzi, 2023; Guo et al., 2020). This method proved to be a cost-effective, simple, and quick biochar nanoparticle-producing method (Guo et al., 2020). Studies on synthesizing nano-biochar using HTC are very meagre, which provides scope for research in this area.

Pyrolysis is one of the foundational methods for biochar production, which includes both slow and fast processes (Amusat et al., 2021; Xu et al., 2024). It involves the thermal decomposition of biomass in an oxygen-limited environment to produce biochar and its nanoscale derivatives. It is cost-effective for initial production but provides limited control over final properties. Parameters such as temperature, heating rate, and residence time significantly influence nano-biochar characteristics; for instance, higher temperatures increase surface area and porosity but reduce volatile organic content. Slow pyrolysis is the commonly used method for soil remediation and absorption of pollutants in wastewater, and is an eco-friendly process (Tomczyk et al., 2020; Zhang et al., 2017), whereas for biofuel production, fast pyrolysis is preferred. New approaches, such as microwave pyrolysis, can be employed for nano-biochar preparation as an alternative to conventional pyrolysis (Wallace et al., 2019; Yek et al., 2019). Microwave-assisted pyrolysis uses microwave irradiation to rapidly and uniformly heat biomass, forming nano-biochar more efficiently than traditional pyrolysis. This method can achieve higher porosity and better control over structural properties by optimizing microwave power. It results in a faster pyrolysis process with reduced energy consumption (Li et al., 2016; Motasemi & Afzal, 2013; Wang et al., 2022) and providing a greener, sustainable option (Dai et al., 2022; Xiao et al., 2013). A comparison study of microwave pyrolysis and traditional pyrolysis by Mašek et al. (2013) revealed that due to volumetric heating of the microwaves in microwave pyrolysis, increased surface area, micropore area are noticed resulting in rapid release of volatiles and development of new micropores (Wallace et al., 2019) over the traditional method. The fixed capital investment study of various nano-biochar production methods by Ramanayaka et al. (2020) analysis demonstrated that microwave pyrolysis results in a considerable increase in fixed capital investment due to high power consumption.

Ball milling is a mechanical process that uses high-energy grinding to reduce traditional biochar into nanoscale particles. It is an emerging and sustainable method for nano biochar production (Kumar et al., 2020; Song et al., 2022). This method is advantageous as it results in increased surface area, oxygen-containing surface functional groups, adsorption and reduced particle size (Lyu et al., 2018; Naghdi et al., 2017; Xiang et al., 2020). The grinding time and energy input control the final particle size, with extended milling potentially reducing porosity (Anupama & Khare, 2021; Raczkiewicz et al., 2024). Wet ball milling is more widely adopted for nano-biochar production due to its higher dispersity, surface functional group formation, labor savings, and sustainability compared to dry milling (Y. Yuan et al., 2020). Nano-biochar with a particle size less than 100 nm can be fabricated using the ball milling method. Ball milling produces nano-scale biodegradable products utilizing renewable resources and reducing the use of chemical procedures (Bhandari et al., 2023; Naghdi et al., 2015). Environmental impacts are minimal compared to other methods, making it a straightforward option for nano-biochar production (Xu et al., 2024).

Chemical activation enhances the surface reactivity of biochar through treatment with strong acids or bases, creating nano-biochar with highly functionalized surfaces. While effective for improving adsorption properties, this method incurs significant costs due to chemical use and disposal requirements. Parameters like the type and concentration of the activating agent influence the final properties but can introduce environmental concerns related to chemical handling and waste management (Sultan et al., 2024). Hydrothermal gasification combines hydrothermal carbonization with gasification to simultaneously produce

Table 2. Key considerations for Nano-biochar production methods

Sl.No.	Production Method	Description	Process Control Parameters & Influence on Properties	Reference
1	Hydrothermal Carbonization (HTC)	Thermochemical process using high pressure & temperature in water to convert biomass to carbon-rich materials	▪ **Temperature**: Higher temperatures generally increase surface area and porosity but can reduce functional groups (Tomczyk et al., 2020). ▪ **Pressure:** Higher pressure promotes the formation of aromatic structures and reduces ash content (Okolie et al., 2020). ▪ **Residence Time:** Longer residence times can enhance yield but might decrease surface area (Xu et al., 2024).	Titirici et al. (2007)
2	Pyrolysis	Thermal decomposition of biomass in an oxygen-limited environment	▪ **Temperature:** Higher temperatures lead to larger surface area and porosity but can decrease volatile organic matter content (Xu et al., 2024). ▪ **Heating Rate:** Slower heating rates promote the formation of ordered structures and higher surface area (Yu et al., 2021). ▪ * **Residence Time:** Longer residence times can increase yield but might reduce biochar stability (Lehmann & Joseph, 2024).	Xu et al. (2024)
3	Ball Milling	Mechanical process using high-energy grinding to reduce traditional biochar particle size to the nanoscale	▪ **Grinding Time/Energy Input:** Increased grinding time/energy can further reduce particle size but might decrease porosity (Xu et al., 2024).	Xu et al. (2024)
4	Chemical Activation	Treatment of biochar with strong acids or bases to enhance surface reactivity	▪ **Type of Activating Agent:** Choice of acid/base influences surface chemistry and functional groups (Sultan et al., 2024). ▪ **Concentration of Activating Agent:** Higher concentrations can create more surface defects but also raise disposal concerns (Ramadan et al., 2020).	Sultan et al. (2024)
5	Microwave-Assisted Pyrolysis	Uses microwave irradiation for faster & more uniform biochar formation at the nanoscale	▪ **Microwave Power:** Higher power can increase heating rate and porosity but might require optimization to avoid excessive energy consumption (Wang et al., 2022).	Wang et al. (2022)
6	Hydrothermal Gasification	Combines aspects of HTC & gasification to produce nano-biochar & valuable gaseous products (syngas)	▪ **Similar to HTC parameters** (temperature, pressure, residence time) for control over nano-biochar properties (Okolie et al., 2020). Additional parameters for syngas production optimization might be included.	Okolie et al. (2020)
7	Ultrasonic Treatment	Uses high-frequency sound waves to disrupt & fragment biochar particles	▪ **Sonication Time/Power:** Longer sonication or higher power can further reduce particle size but might require more energy input (Sarmah et al., 2023).	Sarmah et al. (2023)
8	Electrochemistry (Emerging)	Direct conversion of biomass into nano-biochar using electrochemical techniques	▪ **Electrolyte type and potential:** Choice	

nano-biochar and valuable gaseous products like syngas. This method is particularly suited for large-scale production with advancements in reactor design. Similar to HTC, parameters like temperature, pressure, and residence time influence nano-biochar properties. While complex to set up, the dual production of biochar and syngas makes this method an attractive option for integrated systems, albeit with similar environmental considerations as HTC (Okolie et al., 2020).

Ultrasonic treatment employs high-frequency sound waves to disrupt and fragment biochar particles, reducing them to the nanoscale, which improves their adsorption capacity (Liu et al., 2018; Oleszczuk et al., 2016). The two main advantages of this method are the homogeneity in nano-biochar surface and porosity development without any impediment (Yang et al., 2020). This technique is viable for small-scale production and offers precise control over particle size through adjustments to sonication time and power.

However, scaling up can be challenging due to increased energy requirements. Energy efficiency must be evaluated for broader applications, although it remains a promising method for niche uses (Sarmah et al., 2023). Electrochemical methods for nano-biochar production involve the direct conversion of biomass using electrochemical reactions, offering exceptional control over particle properties. This innovative approach is still in the experimental stage, limiting its current application. Further research is needed to establish optimal process parameters and evaluate environmental impacts, as this technique holds significant potential for future advancements.

2.3. Characterization techniques

Characterization techniques are imperative in understanding the physical and chemical properties of nano-biochar. Fourier-Transform Spectrometer (FTIR), X-ray Power Diffraction (XRD), and scanning electron microscopy (SEM) are some of the characterization techniques of nano-biochar. The functional group on the surface of biochar samples is determined using Fourier Transform Infrared spectroscopy. The higher surface phenolic and carboxylic group content in nano-biochar is confirmed by FTIR spectra (Song et al., 2019). The analysis of the surface area by Brunauer–Emmett–Teller expresses the quantitative measure of nano-biochar's total surface area accessible to gas molecules (Tomczyk et al., 2020). Given that the surface area is usually large, BET analysis can become very useful in estimating potential interactions of nano-biochar with many contaminants, nutrients, and soil components. Transmission electron microscopy (TEM) provides a direct visualization of nano-biochar particles with high magnification (Tomczyk et al., 2020). It provides information on their size, shape, and morphology, and their behaviour in soil environments.

XRD is applied for examining the crystalline structure of nano-biochar to provide information on the presence and relative abundance of mineral phases controlling their reactivity and environmental interactions for which it was designed (Tomczyk et al., 2020). Scanning electron microscopy (SEM) is used to visualize the surface morphology of the nano-biochar. SEM analysis provided visual evidence of coconut husk nano-biochar deposition, which was further confirmed by FTIR and XRD analysis (Geetha et al., 2024). The SEM images of rice husk nano-biochar showed cracked and disintegrated structures with scattered fragments, pore collapse, and destroyed carbon matrix due to high temperature and processing treatments (Aziz et al., 2023). These characterization techniques, therefore, will be of utmost help in elucidating the properties of nano-biochar and hence setting guidelines for its applications across a broad spectrum of environmental and agricultural contexts. It is within the realms of astute selection of feedstocks and modulation of parameters such as pyrolysis temperature, residence time, and heating rate in line with the target properties and applicability that the nano-biochar can be exploited to its full potential. Further research will tease out the variability of a much broader range of feedstocks and how these may affect the properties of nano-biochar, advancing our understanding of this exciting new material.

3. Potential Benefits of Nano-Biochar in Agriculture

3.1. Crop management and stress tolerance

Nano-biochar application promoted seed germination, plant height, stem diameter, leaf area, and crop yield through adsorption of organic compounds and facilitates the entry of nanoparticles into the plant by root hairs (Rajput et al., 2022). Additionally, its highly porous structure allows it to release adsorbed nutrients over time gradually (Xu et al., 2024), ensuring a steady supply of plant nutrients throughout the growing season. An increase in maize and wheat yield was noticed with the application of nano-biochar (Chaubey et al., 2024). Foliar application of nano-biochar improved primary and secondary metabolites in carrot leading to growth enhancements (Khaliq et al., 2023). Nano-biochar also contributed to increased water holding capacity in soil by 20-50% and reduces irrigation water requirements by 10-25% compared to conventional biochar, enabling crops to withstand dry periods better and potentially leading to higher yields (Dai et al., 2022; Naseri-Minabi et al., 2024; Wang et al., 2022). Conventional weed control methods often rely on herbicides, which can pose environmental and soil health concerns. Specific forms of nano-biochar, particularly those derived from feedstocks with allelopathic properties, have shown promising suppression of weed growth. Nano-biochar facilitates targeted release of allelopathic compounds into the soil environment at a rate of 10-20% of the total content within the first week, which creates a localized zone of weed suppression around the planted crop, offering a more sustainable alternative to herbicides (Bieser et al., 2022). Allelopathic effects of *Imperata cylindrica* on rice seedlings are ameliorated through soil application of nano-biochar and causing an increase in biomass, chlorophyll content, and reducing the Cd phytotoxicity (Shen et al., 2020; Yue et al., 2019). However, further research is needed to understand the mechanism involved in allelopathic weed suppression by nano-biochar and develop optimal application strategies.

Nanobiochar application also reduced physiological plant damage by causing an increase in chlorophyll *a* and *b* contents and a reduction in leaf membrane permeability, malondialdehyde, superoxide dismutase, peroxidase, and catalase levels (Ramzan et al., 2023; Shen et al., 2020). Application of nano-biochar triggers the plant systemic acquired resistance (SAR) against biotic stresses in plants by microbial colonization of plant growth-promoting bacteria or fungi, hormonal biosynthesis, and enzymatic activities (Dotaniya et al., 2024; Sani et al., 2023). Plants treated with rice straw nanobiochar had a significant reduction in disease incidence and severity due to upregulation of the innate immunity response of the plants against the pathogens (Aftab et al., 2022). Abiotic stresses such as drought, salinity and heat are ameliorated through nano-biochar applications by increasing the water use efficiency (Zheng et al., 2020). Application of nano-biochar reduced the sodium content in the vegetative parts of safflower, regulated soil pH and improved cation exchange capacity and thereby enhancing salinity stress tolerance (Zulfiqar et al., 2021). Research has demonstrated that nano-biochar enhances nitrogen availability in rhizosphere which is necessary to produce heat shock proteins and for building resistance to cellular damage caused by heat stress (Liu et al., 2019). Thus, nano-biochar aids in the tolerance of plants to biotic and abiotic stresses.

3.2. Soil health

Nano-biochar significantly improves soil physical properties such as soil structure through reduced bulk density and improved aeration, thus promoting root growth and plant health(Bai et al., 2023; Bieser et al., 2022). Studies using simulated rainfall demonstrated that amending soil with nano-biochar reduced surface runoff by 2–30.7%, showing greater effectiveness compared to bulk biochar (Ponnusamy et al., 2020; Ramadan et al., 2020). Nano-biochar also influences the soil chemical environment by enhancing the soil cation exchange capacity (CEC) (Bai et al., 2023; Zhang et al., 2024). Moreover, nano-biochar exhibits good pH buffering capacity, contributing to optimal soil pH levels, which is critical for maximizing plant growth and microbial activity (Naseri-Minabi et al., 2024). Nano-biochar creates a favourable environment for microbial activity in soil, essential for nutrient cycling, and organic matter decomposition (Dai et al., 2022; Wang et al., 2023), ultimately improving plant growth and overall soil health (Usharani et al., 2019). In a nutshell, the unique properties of nano-biochar offer a range of potential benefits for soil health, encompassing physical, chemical, and biological aspects.

Conventional fertilizers are prone to leaching, resulting in nutrient losses that can range from 30-80%, depending on soil type and fertilizer application methods (Zhang et al., 2024). Nano-biochar offers huge potential to reduce dependence on conventional fertilizers by facilitating the adsorption of essential nutrients, and controlled release of adsorbed nutrients (Pathak et al., 2024), thus ensuring a continuous supply of nutrients, plant growth and yield (Sultan et al., 2024; Xu et al., 2024; Zong et al., 2022). This shift benefits both farmers and the environment by increasing nutrient use efficiency, reducing fertilizer application rates by 10-20% and environmental pollution due to eutrophication by 20-40% (Dai et al., 2022). Nano-fertilizers provide a controlled approach tailored to plant needs, while nano-biochar enhances soil properties, offers slow nutrient release, and provides additional benefits over nano-fertilizers. However, further research is needed to fully understand the long-term effects of biochar on nutrient dynamics in various soil types and to optimize application strategies for different crop requirements.

3.3. Mitigation of greenhouse gases (GHGs) and environmental pollution

Agricultural activities are a major source of GHGs such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), thus mitigation of these gases is crucial. Nano-biochar is one of the options for reducing the GHGs as it affects numerous mechanisms such as an increase in adsorption of organic carbon, NH_3 and NH_4^+ in its nano-pores, aeration, nitrification process, and microbial activity, thus reducing the accumulation of nitrous oxide (Sultan et al., 2024) and increase in carbon sequestration in the soil (Bieser et al., 2022; Lehmann & Joseph, 2024; Pathak et al., 2024). The amount of CO_2 captured increases with the quantity of nano-biochar added to the soil (Abed Hussein et al., 2022; Ponnusamy et al., 2020), making it essential to develop standardized methods for the production and application of nano-biochar.

Traditional fertilizers contribute significantly to environmental pollution through nitrate and phosphate leaching into groundwater (Zhang et al., 2024). Nano-biochar presents a promising avenue for mitigating these issues compared to conventional biochar. The enhanced nutrient retention capacity of nano-biochar reduces leaching and thus assures groundwater quality (Saraugi & Routray, 2024). Additionally, nano-biochar acts as an effective sorbent for heavy metals (lead, cadmium), and organic pollutants (pesticides and herbicides), thereby reducing their mobility and uptake by plants (Dai et al., 2022; Pathak et al., 2024; Wang et al., 2023). This immobilization can help remediate contaminated soils and groundwater, aid in pest management and prevent the entry of heavy metals into the food chain, contributing to a safer food supply. Integration of nano-biochar with organic or inorganic fertilizers can alleviate the GHG emissions from the agricultural lands without compromising on the soil health, crop production, and productivity, and long-term studies on the mitigation of GHG emissions and their interactions with soils would strengthen the mitigation behaviour of nano-biochar.

Table 3. Comparison of conventional and nano-biochar in various aspects

Aspect	Conventional biochar	Nano-biochar	Citations
Carbon Sequestration	Promotes carbon storage in soil	Potentially higher carbon storage due to larger surface area and porosity	Lehmann and Joseph (2024)
Nutrient Availability & Retention	Improves nutrient adsorption	Greater nutrient adsorption and controlled release due to higher surface area and porosity	Dai et al. (2022); Sultan et al. (2024)
Water Retention & Soil Structure	Increases water holding capacity	Significantly improves water holding capacity and reduces bulk density	Bai et al. (2023); Dai et al. (2022)
Microbial Activity	May enhance microbial activity	Potentially greater stimulation of microbial activity due to increased surface area	Dai et al. (2022); Wang et al. (2023)
Weed Suppression	Limited effect	Certain types with allelopathic properties show promise for weed control	Bieser et al. (2022)
Reduced Environmental Impact	Reduces nutrient leaching	May offer greater reduction in leaching of nutrients and heavy metals	Zhang et al. (2024); Zong et al. (2022)

Table 4. Comparison of Biochar Impacts on Soil Properties, Plant Growth, and Environmental Sustainability

Factor	No Biochar	Conventional Biochar	Nano-Biochar	Reference
Physical Properties				
a) Soil Structure	Declining or variable	Moderate improvement (aggregation, porosity)	High potential for improvement (aggregation, porosity)	Wang et al. (2023)
b) Water Holding Capacity	Declining or variable	Moderate improvement	High potential for improvement	
Chemical Properties				
a) Nutrient Availability	Variable, prone to leaching	Moderate improvement (retention of P, K)	High improvement (retention of N, P, K)	Antonangelo et al. (2021)
b) Soil pH	Variable	May have a slight buffering effect	Potential for more pronounced buffering effect	
c) Cation Exchange Capacity (CEC)	Variable	May increase slightly	Potential for a significant increase	Hagemann et al. (2017)
Biological Properties				
a) Microbial Activity	Low or inconsistent	Moderate increase	Potential for a significant increase	Pathak et al. (2024)
b) Beneficial Microbes	Declining populations	May support beneficial populations	High potential to support beneficial populations	
Soil Health	Declining or variable	Moderate improvement	High potential for improvement	Wang et al. (2023)
Crop performance				
a) Growth	Variable, may be limited by nutrients and water	Moderate improvement (yield, root development)	High potential for improvement (yield, quality, stress tolerance)	Lehmann et al. (2006)
b) Yield	Variable	Moderate increase	Potential for significant increase	
c) Quality	Variable	May show some improvement	Potential for significant quality improvement	
Weed Suppression	Limited impact	May have some suppressive effects	Potential for enhanced weed suppression (competition for resources)	
Water Use Efficiency (WUE)	Variable	May improve slightly	Potential for significant improvement (better water retention)	
Nutrient Use Efficiency (NUE)	Low, prone to leaching losses	Moderate improvement (reduced leaching)	High improvement (enhanced nutrient retention & uptake)	Antonangelo et al. (2021)
Environmental Pollution				
a) Groundwater Contamination	Increased risk of nitrate leaching	Moderate reduction in leaching	High potential for reduced leaching of pollutants	Abed Hussein et al. (2022)
b) Heavy Metal Mobility	May increase mobility	May reduce mobility for some metals	High potential for immobilization of heavy metals	Pathak et al. (2024)
c) Greenhouse Gas (GHG) Emissions**	High (N2O from fertilizer)	Moderate reduction (improved N retention)	High potential for GHG reduction (improved N retention & C sequestration)	Rajput et al. (2022)
Sustainability	Limited	Moderate contribution	High potential contribution to sustainable agriculture	

However, further research is necessary to optimize application strategies and evaluate the cost-effectiveness of nano-biochar, as it has greater potential for sustainable agriculture and environmental remediation. A brief explanation of the comparison of various benefits from conventional and nano-biochar is mentioned in Tables 3 and 4.

4. Challenges and Considerations

While the potential benefits of nano-biochar for soil health and environmental remediation are enticing, a critical consideration for its agricultural application is its economic feasibility. One of the primary challenges lies in the potential for higher production costs compared to traditional biochar (Di Fraia et al., 2023; Neogi et al., 2022; Singh et al., 2022). Several factors contribute to this cost difference. Firstly, the production of nano-biochar often involves more complex and energy-intensive processes compared to traditional methods like pyrolysis (Neogi et al., 2022; Singh et al., 2022; Zhang et al., 2017). Traditional biochar production can utilize readily available technologies like slow pyrolysis at relatively low temperatures. In contrast, generating nano-biochar might require techniques like hydrothermal carbonization or advanced pyrolysis methods with stricter temperature control to achieve the desired particle size (Sarmah et al., 2023; Tomczyk et al., 2020; Xu et al., 2024). These more sophisticated processes can lead to higher energy consumption and the need for specialized equipment, ultimately inflating production costs (Ramanayaka et al., 2020). Secondly, the feedstock materials used for nano-biochar production can also influence economic viability. While traditional biochar can be produced from a wide range of biomass sources, optimizing nano-biochar properties for agricultural applications might necessitate specific feedstocks with desired chemical compositions (Ponnusamy et al., 2020; Radovic, 2008; Ramanayaka et al., 2020; Xu et al., 2024). Depending on the chosen feedstock and its availability, additional costs associated with acquisition and processing might come into play. While nano-biochar presents a promising avenue for enhancing soil health and crop production, there are aspects beyond production-related issues that require careful consideration. Here, we explore some potential downsides associated with nano-biochar application (Table 5).

Current research on nano-biochar primarily focuses on short-term effects on soil properties and plant growth (Jien & Wang, 2013; Pathak et al., 2024; Xie et al., 2016). More long-term studies are needed to evaluate the potential cumulative impacts of nano-biochar on soil health, crop performance, and potential environmental effects. The long-term fate and behavior of nano-biochar in the soil environment are crucial for understanding its sustainability and potential risks (Lehmann & Joseph, 2024; Neogi et al., 2022; Rajput et al., 2022). The small size and unique properties of nano-biochar raise potential environmental and health concerns. Concerns exist regarding the potential for nano-biochar particles to migrate through the soil and potentially enter groundwater or be taken up by plants and enter the food chain (Ponnusamy et al., 2020; Radovic, 2008; Ramanayaka et al., 2020; Xu et al., 2024). Additionally, inhalation of airborne nano-biochar particles during application or through wind erosion could pose health risks, although more research is needed to quantify these potential risks (Abed Hussein et al., 2022; Ponnusamy et al., 2020).

The current production methods for nano-biochar are often energy-intensive and require specialized equipment, making large-scale production more challenging and potentially less cost-effective compared to conventional biochar (Ponnusamy et al., 2020; Radovic, 2008; Ramanayaka et al., 2020).

Table 5. Key Research Areas in Biochar Development and Application

Research Area	Focus	Key Findings/Challenges	Citation
Environmental Applications	Soil health improvement (e.g., carbon sequestration) Contaminant remediation (e.g., heavy metal adsorption)	Effective for these purposes in initial studies, but long-term environmental fate remains unclear (Ponnusamy et al., 2020).	Ponnusamy et al. (2020)
Property Optimization	Tailoring surface chemistry, porosity, and surface area for specific applications (e.g., enhanced nutrient adsorption)	Improved nutrient adsorption and retention have been demonstrated, but cost-effective methods for specific functionalities are still under development (Antonangelo et al., 2021).	Antonangelo et al. (2021); Kumar et al. (2023)
Standardization	Consistent production and characterization protocols	Crucial for reliable comparisons across studies, but a lack of standards hinders risk assessment and wider adoption (Ponnusamy et al., 2020).	Pasumarthi et al. (2024); Ponnusamy et al. (2020)
Economic Feasibility	Cost-effective production methods * Life cycle impact assessment	Potential for economic benefits in agriculture, but energy-intensive production processes can be expensive (Sultan et al., 2024). Life cycle assessment needs further study (Zortea et al., 2018).	Kumar et al. (2024); Sultan et al. (2024); Zortea et al. (2018)
Long-Term Field Studies	Impact on soil properties and effectiveness across diverse landscapes	Promising for sustained soil health benefits, but limited data exists on long-term effects and effectiveness across different soil types (Ponnusamy et al., 2020; Sultan et al., 2024).	Ahmad et al. (2014); Ponnusamy et al. (2020); Sultan et al. (2024)
Risk Assessment	Characterization and potential environmental/health risks	Essential for safe and responsible application, but a lack of standardized protocols makes risk assessment challenging (Ponnusamy et al., 2020).	Ponnusamy et al. (2020)

Developing more scalable and environmentally friendly production methods is crucial for the wider adoption of nano-biochar in agricultural practices. While research suggests potential benefits of nano-biochar, there are still knowledge gaps regarding optimal application strategies for different soil types, crops, and climatic conditions. Understanding the appropriate application rates and potential interactions with other soil amendments is essential to maximize the benefits and minimize potential risks associated with nano-biochar use (Zong et al., 2022).

In conclusion, while nano-biochar holds promise for sustainable agriculture, a cautious and science-based approach is necessary. Addressing knowledge gaps regarding its long-term effects, potential environmental and health risks, upscaling challenges, and optimal application strategies is crucial for the responsible and sustainable implementation of nano-biochar technology.

4.1. Cost-Benefit Considerations

4.1.1. Balancing the Costs

While the production costs of nano-biochar are higher than conventional biochar, its potential economic benefits for farmers are significant. Nano-biochar's high surface area and adsorption capacity improve nutrient retention in soil, potentially reducing fertilizer application rates by 20-30% while maintaining or increasing crop yields (Bai et al., 2023). This efficiency translates to substantial cost savings on fertilizers. Improved soil health from nano-biochar can enhance crop yields and quality, leading to higher economic returns for farmers (Abed Hussein et al., 2022; Ponnusamy et al., 2020). Biochar amendments have shown yield increases ranging from 5-20% for various crops (Lehmann & Joseph, 2024; Neogi et al., 2022; Rajput et al., 2022). These benefits can offset the initial investment in nano-biochar, making it a profitable long-term choice. The economic feasibility of nano-biochar depends on a detailed cost-benefit analysis, considering production costs and long-term benefits. Further research is needed to develop cost-effective production methods and quantify economic advantages across various agricultural scenarios. By evaluating these factors, stakeholders can integrate nano-biochar into agricultural practices sustainably and profitably.

4.1.2. Environmental Risks

While the potential benefits of nano-biochar for agriculture and environmental remediation are promising, it is crucial to acknowledge the potential environmental risks associated with its application. One key concern is the potential release of nano-biochar particles into the environment. Due to their extremely small size, these particles can become airborne or migrate through soil pores, raising concerns about their impact on various environmental compartments (Bhandari et al., 2023; Di Fraia et al., 2023; Singh et al., 2022). One major concern is the impact of nano-biochar on soil organisms, which play a vital role in maintaining healthy soil ecosystems. These organisms include earthworms, nematodes, and beneficial bacteria, all of which contribute to nutrient cycling, decomposition, and soil aggregation (Bhandari et al., 2023; Singh et al., 2022). The small size and unique properties of nano-biochar particles could disrupt these organisms' behavior or cause physical harm through ingestion or physical contact. For example, some studies suggest that nano-biochar particles might block the respiratory systems of certain soil invertebrates (Singh et al., 2022). Additionally, the adsorption of nutrients or other essential elements onto nano-biochar particles could limit their bioavailability for soil microbes, potentially disrupting nutrient cycling processes.

The potential impact of nano-biochar on the broader ecosystem also warrants investigation. If nano-biochar particles become airborne, they could be inhaled by animals or humans, raising concerns about potential respiratory issues. The long-term fate and behavior of nano-biochar in the environment remain unclear. Understanding how these particles might interact with other environmental components, such as water bodies or plant tissues, is crucial to assessing potential ecological risks.

A critical knowledge gap remains regarding the long-term fate, behavior, and potential ecological risks of nano-biochar in soil environments (Antonangelo et al., 2021; Khosravi et al., 2022; Osman et al., 2022). Unlike traditional biochar, whose larger particle size limits its mobility, the minuscule size of nano-biochar raises concerns about its potential movement within the soil profile. Will it remain anchored in the soil, or could it migrate through soil layers and reach groundwater resources. Research is needed to investigate factors influencing nano-biochar mobility in various soil types, such as texture, organic matter content, and moisture conditions. Additionally, the unique properties of nano-biochar raise questions about its potential interactions with soil biota. Long-term studies are necessary to assess the potential impact of nano-biochar on soil microbial communities and their functioning within the ecosystem. By addressing these knowledge gaps, researchers can develop a more comprehensive understanding of the long-term behavior and potential ecological implications of nano-biochar in soil. This knowledge is critical for developing safe and sustainable application strategies for this promising technology.

4.2. Regulatory Uncertainty

The lack of established regulatory frameworks and standards for nano-biochar presents significant challenges. Unlike traditional biochar, which has been used for centuries and possesses well-understood properties, nano-biochar's unique characteristics raise novel questions regarding its safety and environmental impact. This regulatory uncertainty poses challenges for both researchers and potential users (Singh et al., 2024). Current agricultural regulations often focus on bulk materials, and nano-biochar, with its distinct size and properties, may not fall neatly into existing categories. Concerns regarding potential environmental risks associated with the release of nano-biochar particles into the environment are paramount (Lehmann & Joseph, 2024; Neogi et al., 2022; Pathak et al., 2024; Rajput et al., 2022).

The small size of nano-biochar particles allows them to potentially penetrate plant tissues, enter the food chain, or leach into groundwater, raising questions about their long-term effects on soil ecosystems and human health (Neogi et al., 2022; Singh et al., 2022). The lack of standardized protocols for nano-biochar production further complicates the regulatory landscape. Variations in feedstock materials, pyrolysis conditions, and post-processing techniques can significantly influence the properties of the final product (Kumar et al., 2023; Xu et al., 2024). Without standardized production methods, it becomes difficult to assess the safety and efficacy of different nano-biochar formulations consistently (Singh et al., 2024). This regulatory uncertainty creates barriers for researchers and potential users. The absence of clear guidelines can hinder research efforts and make it difficult to obtain necessary approvals for field trials. Additionally, potential users, such as farmers, may be hesitant to adopt nano-biochar due to concerns about potential liability or unforeseen consequences in the absence of established regulations (Singh et al., 2024).

To bridge this gap, collaborative efforts are needed from various stakeholders. Regulatory bodies can play a crucial role in developing risk assessment frameworks tailored to nano-biochar. This would involve establishing clear definitions for nano-biochar, outlining risk assessment protocols, and potentially setting standards for its production and application (Singh et al., 2024). Researchers have a vital role in conducting thorough studies on the environmental fate and potential risks associated with nano-biochar in various soil types and agricultural settings. Additionally, developing standardized production protocols would facilitate consistent characterization and evaluation of nano-biochar products (Xu et al., 2024). By working together, researchers, regulators, and industry stakeholders can pave the way for the responsible development and application of nano-biochar in agriculture. This collaborative approach is critical to ensure that the potential benefits of this novel material are harnessed while minimizing any potential environmental or health risks.

5. Current Research and Development

Nano-biochar typically has a surface area of 1-30 m^2/g, and nano-biochar boasts a significantly higher surface area, ranging from 5.6 to 472 m^2/g (Abed Hussein et al., 2022; Ramanayaka et al., 2020; Saraugi & Routray, 2024). This dramatic increase in surface area due to its nanoscale size is a key advantage, granting it superior potential for interaction with soil components.

Understanding these unique properties is essential. Researchers employ techniques like Brunauer-Emmett-Teller (BET) surface area analysis to quantify this crucial aspect. Beyond surface area, nano-biochar possesses a complex pore structure with micropores (less than 2 nm) and mesopores (2-50 nm) (Kumar et al., 2023; Xu et al., 2024). These pores, unlike bulk biochar's less developed pore structure, play a significant role in nutrient and water holding capacity. Optimizing the size and distribution of these pores is another area of active research, with techniques like controlling pyrolysis temperature showing promise (Garg et al., 2024; Ramadan et al., 2020).

The environmental applications of nano-biochar are particularly exciting. In agriculture, its high surface area and reactivity make it a prime candidate for enhancing soil fertility and plant growth. Studies suggest it can improve fertilizer and pesticide use efficiency (Abed Hussein et al., 2022; Antonangelo et al., 2021). Furthermore, its ability to adsorb and immobilize pollutants in soil offers a potential solution for remediating contaminated agricultural lands (Pathak et al., 2024).

6. Exploring Nano-Biochar Composites

Generation of agricultural tools with enhanced functionalities (Yi et al., 2020). This approach leverages the unique properties of nano-biochar, such as its high surface area, while introducing additional functionalities from the composite materials. Here, a comparison with traditional fertilizers helps illustrate the benefits. Traditional fertilizers can be prone to leaching, with studies suggesting losses ranging from 30% to 70% (Xiao et al., 2013). This leaching leads to nutrient loss for plants and can contribute to environmental pollution. By coating nano-biochar with slow-release fertilizer materials, researchers aim to create a more efficient nutrient delivery system (Yi et al., 2020). These composite materials could gradually release nutrients over time, with release rates potentially lasting weeks or even months (Xu et al., 2024). This synchronization of nutrient availability with plant needs and the minimization of leaching losses compared to traditional fertilizers (30-70%) highlight a significant potential advantage of nano-biochar composites.

Another promising avenue for nano-biochar composites lies in the integration of pollutant-degrading enzymes. Certain enzymes can break down environmental contaminants like organic pollutants or pesticides at remarkably high rates. For example, studies show some enzymes can degrade certain pesticides by up to 90% within a week (Pang et al., 2022). Immobilizing these enzymes onto nano-biochar creates a composite material with the potential to actively degrade pollutants in soil and promote bioremediation (Xie et al., 2016). The high surface area of nano-biochar, often exceeding 100 m^2/g compared to just 1-30 m^2/g for bulk biochar (Lehmann & Joseph, 2024), provides a superior platform for enzyme attachment. While the enzymes themselves offer the targeted degradation of specific contaminants at high rates (Pang et al., 2022), the increased surface area of nano-biochar composites enhances this capability.

Furthermore, research is ongoing to explore the incorporation of other functional materials into nano-biochar composites. These materials could include:

- Microbial inoculants: Introducing beneficial microbes like nitrogen-fixing bacteria or mycorrhizal fungi can enhance soil health and promote plant growth (Dai et al., 2022). Studies have shown that mycorrhizal fungi can increase plant nutrient uptake by up to 70% (Smith et al., 2003).
- Biostimulants: These naturally derived compounds can stimulate plant growth by promoting root development, enhancing nutrient uptake, or improving stress tolerance (Soltaniband et al., 2022).

By combining nano-biochar with these diverse materials, researchers are creating a new generation of targeted agricultural tools. These composites hold the potential to address multiple agricultural challenges simultaneously, promoting soil health through enhanced nutrient management and bioremediation, and boosting plant growth through improved nutrient uptake and stress tolerance. This ultimately contributes to sustainable food production systems by creating a healthier and more productive agricultural environment.

7. Critical Knowledge Gaps and Research Priorities

A crucial area of research lies in comprehending the long-term behavior of nano-biochar in the environment. While initial studies show promise for soil health improvement (Ponnusamy et al., 2020), the long-term fate and potential unintended consequences of nano-biochar particles remain under investigation. Research is needed to address questions about how nano-biochar interacts with soil components over extended periods. This includes investigating potential impacts on soil biota, the possibility of nano-biochar particles leaching into groundwater (Ponnusamy et al., 2020), and the potential for these particles to enter the food chain through plant uptake. A comprehensive understanding of these long-term effects is essential for ensuring the environmental safety of nano-biochar application in agriculture.

Optimizing the properties of nano-biochar for specific agricultural applications is another critical area of research. Current efforts focus on tailoring surface chemistry, porosity, and surface area to maximize benefits for plant growth and soil health. For instance, research on modifying surface chemistry explores methods to introduce specific functional groups that enhance the adsorption and retention of essential plant nutrients, like phosphorus and potassium, by a factor of several times compared to bulk biochar (Antonangelo et al., 2021). Optimizing the pore structure of nano biochar focuses on creating a more efficient platform for nutrient storage and promoting a suitable habitat for beneficial soil microbes (Ramadan et al., 2020). Finding for surface area is also crucial, ensuring sufficient interaction with nutrients and pollutants while avoiding excessive nutrient immobilization that could starve plants (Zheng et al., 2020). Further research in these areas will enable the development of tailored nano-biochar products for specific agricultural needs.

The lack of standardized protocols for producing and characterizing nano-biochar presents another challenge that requires further research. Currently, inconsistencies exist in the properties of nano-biochar across different studies due to the use of varying production methods and characterization techniques (Ponnusamy et al., 2020). Establishing standardized protocols for both production and characterization is crucial for ensuring the quality and effectiveness of nano-biochar products for agricultural applications. This will enable researchers to compare results across studies and develop reliable data on the performance of nano-biochar in various agricultural settings.

Economic feasibility is another crucial aspect that requires further research. Currently, the production of nano-biochar can be more expensive compared to traditional biochar due to the energy-intensive processes involved (Sultan et al., 2024). Developing cost-effective and scalable production methods for nano-biochar is essential for its wider adoption in agriculture. Additionally, conducting life cycle assessments is crucial to evaluate the environmental impact of nano-biochar production and application throughout its entire life cycle. This will help identify potential environmental hotspots and ensure the overall sustainability of nano-biochar use in agriculture. By addressing these key research areas, scientists and agricultural practitioners can work together to ensure the safe, effective, and sustainable application of nano-biochar in agriculture. This will pave the way for harnessing the full potential of nano-biochar to improve soil health, enhance crop productivity, and contribute to a more secure food supply for future generations.

8. Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) for Nano-Biochar

While the potential benefits of nano-biochar in agriculture and environmental remediation are enticing, a comprehensive understanding of its entire life cycle is crucial for its responsible implementation. This necessitates conducting two key analyses: Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA).

LCA provides a systematic framework for assessing the environmental impact of a product or process throughout its entire life cycle (Zortea et al., 2018). In the context of nano-biochar, LCA would involve evaluating the environmental footprint of its production, application, and ultimately, its end-of-life stage. This analysis would consider various factors.

The LCA would assess the energy and resources used during nano-biochar production, including feedstock acquisition, processing, and any required activation or modification steps (Sultan et al., 2024). This helps identify areas for potential environmental impact reduction. The analysis would quantify greenhouse gas emissions associated with nano-biochar production, such as those generated during pyrolysis or any necessary post-processing steps (Rajput et al., 2022). Understanding these emissions is crucial for assessing the overall carbon footprint of nano-biochar compared to traditional biochar or other soil amendments. LCA can also identify potential environmental risks associated with nano-biochar production and application. For instance, the analysis might consider the potential release of nanoparticles into the environment or the unintended consequences of using specific feedstocks (Ponnusamy et al., 2020). Identifying these risks early on allows for the development of mitigation strategies. By conducting a comprehensive LCA, researchers can gain valuable insights into the environmental trade-offs associated with nano-biochar production and application. This information can then be used to optimize production processes, minimize environmental burdens, and ensure the sustainability of nano-biochar as an agricultural tool.

Beyond environmental considerations, the economic viability of nano-biochar is crucial for its widespread adoption by farmers. Techno-Economic Analysis (TEA) plays a key role in assessing this aspect (Fawzy et al., 2022). In the context of nano-biochar, TEA focuses on analyzing the economic feasibility of its production and application. This includes evaluating production costs, such as feedstock acquisition, energy consumption during processing, specialized equipment needs, and labor costs (Sultan et al., 2024). Identifying these cost drivers is essential to determine the economic competitiveness of nano-biochar compared to traditional soil amendments. TEA also considers market potential by analyzing factors like farmer needs, perceived benefits of nano-biochar, and the potential market size in agriculture and environmental remediation. Understanding market demand helps determine the economic viability of large-scale nano-biochar production. Finally, a comprehensive TEA should consider life cycle costing, which includes not just production costs but also potential long-term benefits. This could involve factoring in potential cost savings for farmers due to reduced fertilizer needs or improved soil health brought about by nano-biochar application.

By conducting a thorough TEA, researchers can gain valuable insights into the economic feasibility of nano-biochar. This information can guide the development of cost-effective production methods, inform pricing strategies, and ultimately, influence the adoption of nano-biochar by agricultural stakeholders. Life Cycle Assessment and Techno-Economic Analysis are essential tools for evaluating the environmental and economic sustainability of nano-biochar. By conducting these analyses, researchers can ensure that the development and application of nano-biochar benefits both the environment and agricultural productivity, paving the way for a more sustainable future for our food systems. The major critical knowledge gaps and research priorities in nano-biochar for agriculture need to be known and addressed properly to achieve the full potential of nano-biochar applications.

9. Conclusion

While nano-biochar shows immense promise for enhancing soil health and advancing sustainable agriculture, its broader implementation relies on a nuanced understanding of its long-term effects, environmental implications, and economic viability. The integration of nano-biochar into agricultural practices offers several advantages, including improved nutrient retention, reduced fertilizer reliance, and increased crop yields. However, challenges such as economic feasibility, limited long-term studies, potential environmental and health risks, and regulatory uncertainties must be addressed effectively. To realize the full potential of nano-biochar, a cautious, science-based approach is essential. This involves conducting further research to fill existing knowledge gaps, particularly regarding optimal application strategies for various soil types and climates. Collaborating with regulatory bodies and stakeholders will be critical to establishing clear guidelines and standardized production methods, ensuring that nano-biochar can be safely and effectively utilized in agricultural systems. Ultimately, responsibly harnessing nano-biochar technology can lead to a more sustainable agricultural framework, contributing positively to environmental health while ensuring economic benefits for farmers and society at large.

Abbreviations

GHG, Green House Gas; **IPCC,** Inter-Governmental Panel on Climate Change; **HTC,** Hydrothermal Carbonization; **BET,** Brunauer–Emmett–Teller; **TEM,** Transmission Electron Microscopy; **XRD,** X Ray Diffraction; CEC, Cation Exchange Capacity; **NUE,** Nutrient Use Efficiency; **WUE,** Water Use Efficiency; **LCA,** Life Cycle Assessment; **SOM,** Soil Organic Matter; **TEA,** Techno-Economic Analysis; **WHC,** Water Holding Capacity.

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Author Contributions

This work was carried out in collaboration among all authors. This review paper has been prepared by the author NVK, under the conceptualization, direct supervision, and guidelines of the author's PKN, VDR, PR, TM, and BB for writing-original draft. The author's MSC, RK, and GNK were extensively involved in reviewing different source materials and writing-reviewing, and editing the original draft of this paper, whereas the author's RB and VDR made contributions in verifying and finalizing the manuscript. All authors have read and agreed to the published version of the manuscript.

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The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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