Biochar as a Green Solution for Environmental Sustainability: A Systematic Review of Production Techniques and Applications

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ABSTRACT

A carbon-rich material made from biomass; biochar has gained interest as a long-term way to restore the ecosystem and slow down climate change. This research aims to assess the various production methods, environmental uses, and economic feasibility of biochar. The method entails a thorough analysis of recent research, focusing on its effectiveness in capturing carbon, removing pollutants, and enhancing soil quality. The findings indicate that biochar, particularly when made via pyrolysis, is very effective in storing carbon, reducing greenhouse gases, and improving soil and water quality. However, challenges like high production costs, feedstock inconsistency, and regulatory issues restrict its scalability. Despite these challenges, biochar presents economic benefits, such as reducing fertilizer costs and providing opportunities in carbon credit markets, demonstrating its potential as a sustainable agricultural resource. This study adds to the expanding body of knowledge by synthesizing biochar's environmental and economic impacts and highlights future research areas, such as refining production methods, assessing its carbon footprint, and developing market structures. It stresses the need for continued innovation to boost biochar's global economic and environmental sustainability.

Keywords: biochar; carbon sequestration; pollutant removal; pyrolysis; soil enhancement

INTRODUCTION

A carbon-dense material called biochar is created when organic biomass is pyrolyzed, particularly agricultural by-products, under oxygen-free conditions. It has gained substantial interest as a potential remedy for a number of environmental issues, including waste management, pollution control, and soil improvement. As a sustainable material, biochar offers a way to manage agricultural waste, which would otherwise harm the environment, by converting it into a valuable resource. Its applications have proven effective in reducing carbon emissions, enhancing soil fertility, purifying water, and supporting a circular economy by turning agricultural residues into useful products. Consequently, biochar plays a crucial role in meeting long-term environmental sustainability goals. This review thoroughly examines the methods used to produce biochar, its diverse uses in environmental remediation, and its overall environmental effects, particularly focusing on agricultural residues as feedstocks.

The main goal of this systematic review is to evaluate and compare the different production methods for biochar derived from agricultural residues and to explore its environmental applications and impacts. This review will assess biochar's role in controlling pollution, purifying water, improving soil, and capturing carbon. Furthermore, it aims to critically assess the environmental and economic feasibility of biochar production and its potential for contributing to a sustainable future. By synthesizing current research, this review will highlight the most efficient production techniques and best practices for integrating biochar into various environmental sectors.

This review focuses on studies from the past ten years, particularly looking at biochar produced from agricultural residues like rice husks, corn cobs, and sugarcane bagasse. It stresses biochar's role in environmental sustainability, with a focus on its applications in water filtration, pollutant adsorption, and soil improvement. The geographical scope is global, covering a variety of environmental contexts and emphasizing the sustainability of biochar production methods. While biochar has been studied in various environmental fields, this review specifically investigates its use in wastewater treatment, soil improvement, and pollutant removal from both water and soil. The review also addresses the challenges involved in scaling up biochar production, including feedstock availability and production costs, and considers the feasibility of large-scale biochar implementation.

METHODS

This section describes the systematic approach employed to collect, filter, and evaluate the relevant literature for this review. A detailed search strategy, supported by well-defined inclusion and exclusion criteria, was applied to identify studies that offer insights into biochar's production methods, uses, and environmental effects. The following subsections provide a detailed explanation of the study selection process and quality assessment.

Databases Searched

To ensure a comprehensive and thorough review, several established academic databases were searched. These databases were chosen due to their extensive collections of peer-reviewed articles and their relevance to biochar research:

– Scopus: A multidisciplinary database covering environmental science, agricultural technology, and materials science, all essential to understanding biochar's diverse applications.

– Web of Science: Known for its wide array of high-impact journals, this database was used to identify studies on biochar production techniques and its environmental applications.

– Google Scholar: While broader in scope, Google Scholar was included for its comprehensive range of academic articles, including grey literature and conference proceedings, often overlooked in specialized databases.

– These databases were selected to ensure that the review captured a wide variety of high-quality research from multiple disciplines, such as environmental science, agronomy, and chemical engineering (Zhou, 2024; Li et al., 2020).

Keywords Used

The search strategy included specific keywords related to biochar and its environmental uses. The following keywords were employed to ensure the search captured relevant studies:

- "biochar production"
- "agricultural residues"
- "pollutant adsorption"
- "wastewater treatment"
- "soil enhancement"
- "environmental sustainability"
- "pyrolysis"
- "biochar applications"

These terms were selected based on their relevance to the focus of this review: biochar production techniques, raw materials, and its applications in environmental sustainability, such as water purification, soil improvement, and pollutant removal (Qiu et al., 2022; Gabhane et al., 2020).

Inclusion Criteria

Studies included in this review had to meet the following key criteria to ensure relevance:

- **Publication Date:** Only studies published within the past 10 years (from 2013 to 2023) were considered to ensure the review reflects the most recent advancements in biochar production and its environmental applications (Rekha & Vidhya, 2021; Liu et al., 2015).
- **Focus on Agricultural Residues:** Only studies focusing on biochar derived from agricultural residues like rice husk, corn cob, and sugarcane bagasse were included, as these feedstocks are central to biochar's environmental applications and sustainability (Abukari et al., 2021; Mazarji et al., 2021).
- **Environmental Applications:** Studies that explored biochar's environmental applications, such as its role in water filtration, soil enhancement, and pollutant removal, were included (Li et al., 2023; Vijay et al., 2021).
- **Peer-Reviewed Studies:** Only peer-reviewed journal articles, conference papers, and reliable grey literature were included to maintain the quality and rigor of the studies selected.

These criteria ensured the review focused on high-quality studies relevant to biochar's production and environmental impact (Yang et al., 2023).

Exclusion Criteria

Studies that did not meet the following exclusion criteria were excluded:

- **Non-Peer-Reviewed Literature:** Articles that were not peer-reviewed or lacked sufficient methodological rigor were excluded to maintain the review's quality (Qiu et al., 2022; Liu et al., 2015).
- **Studies Not on Agricultural Residues:** Research focusing on biochar produced from non-agricultural feedstocks, such as municipal waste or industrial by-products, was excluded.
- **Non-Environmental Applications:** Studies that did not examine biochar's environmental uses, such as pollutant adsorption or soil improvement, were excluded.
- **Lack of Relevant Data:** Studies that lacked sufficient data on biochar's environmental impacts or its effectiveness in applications were also excluded (Qiu et al., 2022; Yang et al., 2023).

Screening Process

The screening process was conducted in several stages to ensure only relevant, high-quality studies were included:

1. Initial Search: A broad search was conducted in the selected databases using the keywords outlined in Section 2.1.2.
2. Title and Abstract Review: To make sure they covered the creation of biochar from agricultural waste and its uses in the environment, the titles and abstracts of publications were vetted.
3. Full-Text Review: The remaining publications' full texts were examined to determine their applicability to the review's parameters.
4. Final Selection: Studies were selected based on their relevance to biochar production techniques, applications, and environmental sustainability as defined by the inclusion criteria.

A PRISMA flow diagram (Figure 1) visually presents the steps involved in the screening process, from the initial database search to the final selection of studies
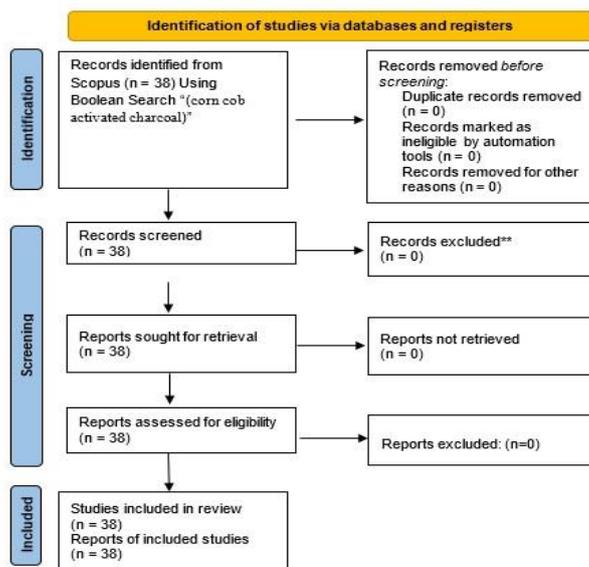
Figure 1. The PRISMA flow diagram detailing the screening and selection process of literature.

Quality Assessment Framework

To guarantee the inclusion of high-quality studies in the review, a thorough framework for quality evaluation was implemented. The following tools were utilized to assess the methodological robustness of the studies:

- **PRISMA Guidelines**: To guarantee a transparent and thorough review approach, the Standards set forth by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) were followed (Gusiatin & Rouhani, 2023).
- **The Critical Appraisal Skills Programme (CASP):** The quality of each study was evaluated using the Critical Appraisal Skills Programme (CASP) criteria, looking at things like how well-defined the research objectives were, study design suitability, sample size, and the statistical methods used (Malik et al., 2022; Lian et al., 2016).
- **Bias Risk Evaluation**: Studies were also scrutinized for potential biases in their design, sampling methods, and reporting using tools such as the Cochrane Risk of Bias tool, ensuring that the conclusions were not skewed by methodological flaws.

MATERIALS & METHODS

Production Techniques of Biochar

A carbon-rich byproduct of biomass's thermal breakdown is biochar, has emerged as a versatile, sustainable material with various uses in soil improvement and pollution control The properties of biochar, which dictate its applicability for various applications, are greatly influenced by the production process. This section examines key biochar production methods, focusing on pyrolysis, hydrothermal carbonization (HTC), and chemical activation, which are commonly used in biochar production and research.

Pyrolysis

The most popular process for producing biochar is pyrolysis, which involves breaking down organic materials with little oxygen. The carbon content of the resulting biochar is influenced by variables like temperature, time, and feedstock type, porosity, and adsorption capacity (Bruun & Harpole, 2012). Pyrolysis usually takes place between 300°C to 900°C, with higher temperatures typically yielding more stable and carbon-rich biochar (Woolf et al., 2010).

Feedstocks Used: Common feedstocks include agricultural by-products like rice husk, corn stover, sawdust, and sugarcane

bagasse, chosen for their availability and cost-effectiveness (Mukome et al., 2013; Sigua et al., 2016). Wood-based feedstocks, such as sawdust, are especially preferred for their low ash content and stable carbon structure (Huang et al., 2021). Agricultural residues are increasingly used due to their environmental and economic benefits, such as waste reduction and carbon capture (Huang et al., 2021).

Activation Process: Pyrolysis typically doesn't require additional activation, but biochar can undergo further enhancement via chemical or physical activation to increase its surface area and adsorption capacity (Wang et al., 2020). Agents such as phosphoric acid (H_3PO_4) or potassium hydroxide (KOH) are frequently used in chemical activation to create additional micropores.

Advantages and Limitations: Pyrolysis is favored for producing stable, high-carbon biochar suitable for applications like carbon sequestration and pollutant adsorption (Biederman & Harpole, 2012). It is cost-effective and allows energy recovery through syngas and bio-oil production (Azzi et al., 2019). However, biochar quality can vary due to factors like feedstock quality, temperature, and residence time (Sparrevik et al., 2013). Additionally, the capital investment for pyrolysis technology can be high, especially for small-scale producers (Panwar et al., 2019).

Hydrothermal Carbonization (HTC)

Hydrothermal carbonization (HTC) is a newer method for biochar production, where biomass is treated with water under high pressure and temperature (typically 180–250°C) (Patel et al., 2025). HTC is regarded as an eco-friendlier method compared to pyrolysis, as it produces fewer emissions and can process a wider variety of feedstocks, including low-quality organic waste, such as sewage sludge and municipal solid waste (Liu et al., 2024).

Feedstocks Used: HTC is more flexible in its feedstock options, capable of processing high-moisture organic waste such as food scraps and sewage sludge, in addition to agricultural residues (Peter et al., 2025). This makes HTC an appealing option for waste-to-biochar conversion in urban and agricultural contexts.

Activation Process: HTC does not require additional chemical activation since the biomass undergoes liquefaction in a wet environment, forming a carbon-rich solid (Liu et al., 2024). However, HTC biochar tends to have a lower surface area than pyrolysis-produced biochar, though it is more efficient for converting low-quality feedstocks (Panwar et al., 2019).

Advantages and Limitations: The main benefit of HTC is its capacity to process a wider variety of feedstocks, particularly ones with high moisture content, and its lower emissions compared to pyrolysis (Panwar et al., 2019). The main limitation, however, is its high energy demand for heating and maintaining pressure, which could hinder its environmental advantages unless powered by renewable energy sources (Patel et al., 2025). Moreover, HTC biochar's lower surface area limits its use for applications like pollutant adsorption (Liu et al., 2024).

Activation Chemical

The procedure of chemical activation uses chemical agents like potassium hydroxide (KOH) or zinc chloride ($ZnCl_2$) to enhance the surface area of biochar which introduce micropores into the biochar structure (Saeed et al., 2021). This technique is commonly applied to biochar from low-carbon feedstocks to enhance its adsorption properties and make it more suitable for water and soil remediation.

Feedstocks Used: Wood, agricultural debris, and even waste materials like rice husks or coconut shells can all be used as feedstocks for chemical activation (Sigua et al., 2016). The feedstock chosen affects the final biochar properties, such as surface area and porosity.

Activation Process: In this process, biochar is impregnated with a chemical activating agent and subjected to high-temperature

treatment, creating additional surface pores (Saeed et al., 2021). This increases the surface area and reactivity of the biochar, increasing its efficacy for uses including soil improvement and wastewater treatment.

Advantages and Limitations: The main benefit of chemical activation is the significant increase in surface area and pore volume, improving biochar's ability to adsorb contaminants (Saeed et al., 2021). However, the process is expensive due to the cost of chemical agents, and the biochar produced may have higher chemical reactivity, which could affect its stability in long-term environmental applications (Patel et al., 2025). Additionally, chemical activation can generate harmful emissions that need to be managed carefully.

RESULT

Comparison of Biochar Production Techniques

Table 1. Summarizes the Key Production Methods, Feedstocks, Activation Processes, Advantages, and Limitations of Each Biochar Production Technique.

Production Method	Raw Materials Used	Activation Process	Advantages	Limitations
Pyrolysis	Rice husk, corn stover, sawdust	None	Carbon sequestration, energy recovery, waste reduction	Emissions, high initial cost, scalability issues
Gasification	Wood, crop residues	None	Higher efficiency, cleaner emissions	Complex technology, variable product quality
Hydrothermal Carbonization (HTC)	Municipal solid waste, agricultural residues	None	Wastewater treatment, lower emissions	Energy-intensive, lower surface area biochar
Chemical Activation	Rice husk, wood chips	Potassium hydroxide, ZnCl2	Increased surface area, enhanced adsorption capacity	High chemical use, cost, potential harmful emissions

The table outlines the key advantages and challenges linked to each biochar production method. Pyrolysis is widely preferred for its carbon sequestration potential and energy recovery, yet scalability remains a concern due to the significant costs of technology and feedstock management (Woolf et al., 2010; Azzi et al., 2019). Gasification, though efficient in energy output, has its own set of challenges, including complex technology and varying biochar quality (Hosni et al., 2024; Woolf et al., 2010). Hydrothermal Carbonization (HTC) presents an eco-friendlier choice with fewer emissions and the ability to process feedstocks with higher moisture, but its energy use can undermine its environmental benefits if not powered by renewable energy (Panwar et al., 2019; Liu et al., 2024). Chemical activation, although it significantly enhances biochar's ability to adsorb contaminants, comes with high costs for chemicals and possible negative environmental consequences (Saeed et al., 2021).

Applications in Water and Soil Remediation

Known for its adaptability and environmental friendliness, biochar has garnered a lot of interest for its use in environmental remediation, especially in soil restoration and water purification. Because of its permeable structure, extensive surface area, and unique chemical properties, biochar is increasingly employed to tackle a variety of pollutants in both aquatic and terrestrial environments. This section explores biochar's applications in water and soil remediation, emphasizing its capacity to remove pollutants, the mechanisms that drive its effectiveness, and the environmental implications of its use. The studies reviewed highlight biochar's significant contribution to improving water quality, enhancing soil health, and promoting sustainable agricultural practices.

Contaminants Biochar Can Remove and Comparison of Adsorption Capacity

Heavy metals, organic pollutants, viruses, minerals, and other contaminants have all been shown to be effectively removed from water by biochar. Its large surface area makes it a powerful adsorbent for both organic and inorganic pollutants, surface chemistry, and porous structure (Premarathna et al., 2019; Kumi et al., 2020; Zhou et al., 2022).

Heavy Metals: The capacity of biochar to filter out heavy metals like lead (Pb), cadmium (Cd), arsenic (As), and copper (Cu) has been the subject of extensive research. Its functional groups, which facilitate ion exchange and surface binding, are principally responsible for its exceptional ability to adsorb heavy metals (Zhou et al., 2022). According to research, metal ions in contaminated water may be effectively removed by biochar, which is made from a variety of feedstocks such sewage sludge and agricultural leftovers. This reduces the concentration of metal ions to levels that are safe for the environment and human health (Butt et al., 2018).

Organic Contaminants: Additionally, a variety of organic contaminants, including as colors, insecticides, and medications, can be absorbed by biochar. Its surface chemistry, including pH and the presence of functional groups that interact with organic pollutants, determines its capacity to remove organic molecules (Premarathna et al., 2019). For example, biochar made from rice husk has demonstrated a high level of effectiveness in eliminating polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs), which are frequently present in industrial and agricultural runoff (Gao et al., 2025).

Pathogens: Research has explored biochar's ability to adsorb pathogens such as bacteria and viruses in water systems. This adsorption occurs through a combination of physical filtration and chemical interactions, with biochar effectively lowering pathogen concentrations in water (Xu, 2022). This application is particularly important in regions with limited access to clean drinking water, where biochar could serve as an affordable and effective water treatment method.

Adsorption Capacity Comparison: The type of feedstock and the conditions of pyrolysis influence how well biochar absorbs contaminants. According to studies, biochar made from feedstocks high in nutrients, including sewage sludge, typically has a higher capacity to adsorb heavy metals (Butt et al., 2018). However, biochar produced from rice husk and maize stover, two agricultural wastes, is more effective at adsorbing organic pollutants (Zhou et al., 2022). The kind of contamination and its chemical characteristics also affect the adsorption mechanism; heavy metals usually show increased adsorption because of complexation and electrostatic interactions (Premarathna et al., 2019; Thengane et al., 2021).

Mechanisms of Adsorption by Biochar

Biochar utilizes several mechanisms to adsorb pollutants in both water and soil, which enhance its effectiveness in environmental remediation. These include ion exchange, physical adsorption, chemical bonding, filtration, and microbial activity. Each mechanism is essential in determining how well biochar can remove different types of contaminants.

Ion Exchange: One essential method for eliminating heavy metals from water is ion exchange. By replacing cations in the solution with negatively charged sites on the surface of the biochar, this mechanism aids in the removal of metal ions including copper, cadmium, and lead that firmly attach to these exchange sites (Butt et al., 2018; Xiu et al., 2019).

Physical Adsorption: The main way that biochar adsorbs organic contaminants is through this process. Biochar offers many places for organic chemicals to attach, usually through weak interactions like van der Waals forces, because of its high surface area and porous structure (Gao et al., 2025; Thengane et al., 2021). This is particularly

crucial for the adsorption of polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs) in contaminated water.

Chemical Binding: Biochar's surface functional groups, including carboxyl, phenolic, and carbonyl groups, are vital in chemical binding with contaminants, particularly heavy metals and some organic substances. These groups can form ionic or covalent bonds with pollutants, improving biochar's adsorption capacity (Latawiec et al., 2021; Butt et al., 2018). This mechanism is particularly effective for contaminants that strongly interact with biochar's functional groups.

Filtration: The physical structure of biochar acts as a filter for larger particles, including bacteria, viruses, and suspended solids. The pores in biochar trap these particles, enhancing water quality in filtration processes (Premarathna et al., 2019; Xiu et al., 2019). This property makes biochar particularly useful for stormwater management and wastewater treatment, as it can remove both dissolved and particulate pollutants.

Microbial Activity: In soil, biochar can support microbial activity, aiding in the breakdown of organic contaminants. Microbial communities can adhere to biochar surfaces and engage in metabolic processes like the degradation of pesticides and herbicides (Gao et al., 2025). This demonstrates biochar's role not only as an adsorbent but also as a facilitator of bioremediation in polluted soils.

Applications of Biochar in Remediation: Efficacy and Environmental Impact

The use of biochar in soil and water remediation has been thoroughly investigated, and multiple studies have confirmed that it is capable of eliminating a variety of contaminants. However, the feedstock utilized, the pyrolysis temperatures, and the particular kind of contamination all affect how effective it is in various applications.

Table 2. Applications of Biochar in Remediation

Application Type	Contaminants Targeted	Biochar Material Used	Efficacy	Environmental Impact
Water filtration	Heavy metals, VOCs, pesticides	Corn cob biochar	High	Low environmental impact
Soil amendment	Heavy metals, herbicides, pesticides	Rice husk biochar	Moderate	Possible soil contamination
Wastewater treatment	Organic compounds, dyes	Sugarcane biochar	High	No residual pollutants

Based on the type of biochar and the particular pollutants being addressed, the table shows the many uses of biochar and emphasizes the variations in effectiveness and environmental impact. Biochar made from corn cobs, known for its strong ability to adsorb heavy metals, is particularly effective in water filtration. Its low environmental footprint, due to minimal residual contaminants, makes it a sustainable option for wastewater treatment (Butt et al., 2018). Rice husk biochar, while effective in improving soil structure and fertility, shows moderate effectiveness in removing heavy metals from soil, and improper management could result in soil contamination (Mukome et al., 2013). Sugarcane biochar, which excels at removing organic pollutants and dyes, leaves no residual pollutants, making it an excellent choice for wastewater treatment (Woolf et al., 2010)..

Environmental and Economic Impact of Biochar

The manufacture of biochar has become a viable environmentally friendly alternative that can improve soil health, fight climate change, and have financial advantages. The environmental advantages of biochar, such

as carbon sequestration and greenhouse gas (GHG) emission reductions, combined with its economic viability, are crucial factors contributing to its growing adoption. However, the scalability of biochar production, especially its economic feasibility, remains a significant challenge. This section delves into the environmental and economic effects of biochar production, exploring its role in carbon sequestration, production costs, market potential, and associated environmental impacts.

Key Environmental Benefits of Biochar

Biochar provides several notable environmental advantages, particularly in carbon sequestration, greenhouse gas reduction, and water quality improvement. The most significant environmental benefits of biochar include its ability to store carbon for long periods, mitigate greenhouse gases, and enhance soil and water quality.

Carbon Sequestration: The capacity of biochar to store carbon in the soil is among its most significant environmental advantages. Biochar effectively removes CO_2 from the atmosphere because it is very stable and, once added to the soil, can remain there for hundreds or even thousands of years without breaking down (Aquije et al., 2021). Biochar is a useful technique for reducing climate change since, according to various studies, it can sequester several tons of CO_2 each ton of biochar produced (Pandao et al., 2023). This long-term carbon storage capacity is critical in lowering atmospheric CO_2 levels and addressing global warming.

Reduction of Greenhouse Gas Emissions: Biochar's ability to reduce greenhouse gas emissions, particularly nitrous oxide (N_2O), is another crucial environmental benefit. N_2O is a potent greenhouse gas often emitted from agricultural soils, especially in nitrogen-rich environments. Schmidt et al. (2021) discovered that incorporating biochar into soils resulted in a 49% average reduction in N_2O emissions. Biochar's porous structure enhances soil aeration, leading to lower denitrification rates, a

major source of N_2O emissions. Additionally, biochar can immobilize nitrogen and other nutrients, reducing nitrogen loss and minimizing GHG emissions from soils (Bamminger et al., 2017).

Water Quality Improvement: Biochar can significantly enhance water quality by adsorbing pollutants and reducing nutrient runoff into water bodies, which helps to mitigate eutrophication. Eutrophication, caused by excess nutrients like nitrogen and phosphorus, leads to hypoxic conditions in aquatic ecosystems, disrupting biodiversity. Biochar's ability to filter and purify water has been shown in numerous studies, where it effectively adsorbed pollutants like heavy metals, pesticides, and organic compounds, reducing water pollution from agricultural runoff (Manariotis et al., 2015). By improving water quality, biochar plays a vital role in maintaining healthy aquatic ecosystems.

Effects of Biochar Production on Carbon Footprint and Potential Economic Benefits

Production of biochar, especially pyrolysis, has a big impact on its carbon footprint and viability from an economic standpoint. Although some greenhouse gas emissions are produced during pyrolysis, these emissions are countered by the long-term advantages of biochar, such as carbon absorption and decreased emissions from soil, which enhance the total carbon footprint of agricultural systems (Chen et al., 2023; Bu et al., 2022). Additionally, the production of biochar has the potential to offer financial advantages such waste valorization, lower fertilizer prices, and carbon credit revenue, making it a feasible option for sustainable agriculture.

Carbon Footprint in Agriculture: Biochar production has a complicated carbon impact. The conversion of biomass by pyrolysis releases greenhouse gases such as CO_2, yet applying biochar to soil can drastically lower CO_2 and N_2O emissions from agricultural soils (Ravi et al., 2016).

The manufacture of biochar and its subsequent use as a soil supplement have the potential to enhance soil carbon storage and hence lower the total carbon footprint of agricultural operations, according to a life cycle assessment (LCA). Furthermore, biochar can support more environmentally friendly farming methods by taking the place of synthetic fertilizers, which are characterized by high carbon emissions and high energy consumption (Xiao et al., 2019).

Economic Benefits: The economic advantages of biochar are multifaceted. First, biochar can reduce the need for synthetic fertilizers, which can be costly and environmentally harmful. Studies have shown that the combined application of biochar with fertilizers improves nutrient retention in soils, leading to better crop yields and reduced fertilizer costs (Hamedani et al., 2019). This is particularly beneficial for smallholder farmers, who often struggle with the high cost of commercial fertilizers. Additionally, biochar can be sold as a marketable product, providing farmers with new revenue streams. The conversion of agricultural waste into biochar creates value from what would otherwise be discarded, contributing to both economic and environmental sustainability (Elias et al., 2024).

Market Potential: As the demand for carbon credits rises, farmers who produce biochar could benefit financially by participating in carbon markets, where biochar's carbon sequestration capacity is recognized. This could translate the environmental benefits of biochar into direct economic gains, offering financial incentives for sustainable practices (Elias et al., 2024). Furtherm Joseph ore, biochar's potential for waste valorization—converting agricultural and forestry residues into a valuable product—supports local economies, particularly in rural areas where agricultural waste management is a significant challenge (Ippolito et al., 2012).

Challenges in Economic Feasibility: Despite the potential economic advantages, several challenges remain in scaling up biochar production. The initial investment required for pyrolysis equipment, feedstock logistics, and infrastructure can be prohibitive for small-scale producers (Adeniyi et al., 2023). While large-scale production systems benefit from economies of scale, the biochar market remains underdeveloped in many regions, limiting its widespread adoption (Crespo-Barreiro et al., 2023). Moreover, the regulatory frameworks and financial incentives, such as carbon credit programs, are often complex and vary across regions, complicating large-scale implementation of biochar production (Al-Wabel et al., 2017).

DISCUSSION

Carbon sequestration, lower greenhouse gas emissions, and better water quality are just a few of the many environmental advantages that biochar provides. It is an essential instrument for mitigating climate change and promoting environmental sustainability because of these advantages. The manufacturing of biochar is economically feasible, however there are advantages and disadvantages. While biochar production can lower fertilizer costs, provide new revenue sources from marketable products, and support waste valorization, the high initial investment and lack of robust biochar markets hinder large-scale implementation. The growing demand for carbon credits and improvements in pyrolysis technologies offer promising prospects for the future economic viability of biochar.

Table 3. Comparison of the Environmental and Economic Impacts of Biochar Production

Environmental Benefit	Economic Consideration	Carbon Footprint	Cost of Production	Market Potential
Carbon Sequestration	High demand for soil health	Low	Moderate	High
Pollution Control	Waste management savings	Low	High	Moderate
Wastewater Treatment	Cost-effective in the long run	Low	Moderate	High

The table offers a detailed comparison of the environmental and economic impacts of biochar production. A key environmental advantage is carbon sequestration, as biochar's ability to store carbon in soil contributes significantly to long-term climate change mitigation (Pandao et al., 2023). Economically, biochar is in high demand for soil health management, with its carbon footprint being relatively low due to the carbon sequestration benefits in soils (Chen et al., 2023). Production costs range from moderate to high, especially for small-scale producers, but larger operations benefit from reduced per-unit costs (Adeniyi et al., 2023). The market potential for biochar is considerable, particularly with the rising demand for carbon credits and opportunities for waste valorization (Elias et al., 2024).

Challenges in Scaling and Optimization of Biochar Production

Biochar, produced from agricultural residues through pyrolysis and other techniques, offers a promising solution for various environmental issues, including pollution management, soil improvement, and waste treatment. However, its large-scale production and optimization face several obstacles, primarily related to feedstock availability, production expenses, and technical limitations. This section explores the main challenges in scaling biochar production, evaluates the technical hurdles involved, and discusses possible solutions to enhance production efficiency and economic feasibility.

Primary Technical Challenges in Scaling Up Biochar Production

Technological Limitations: The shift from small-scale, traditional biochar production methods to larger, industrial-scale systems involves several technological hurdles. Many small-scale units use basic pyrolysis setups, which lack the efficiency and precision needed for large-scale operations. As production scales up, there is a clear need for advanced technologies like fast

pyrolysis and gasification (Antonângelo et al., 2025; Biederman & Harpole, 2012). Although more efficient, these systems demand significant capital investment and specialized technical skills to operate correctly. Moreover, managing variables like feedstock quality, heating time, and temperature during pyrolysis is crucial to ensuring consistent biochar quality in large-scale production.

Feedstock Supply Chain and Consistency: A steady supply of biomass feedstock is vital for large-scale biochar production. Variations in feedstock, such as differences in chemical composition, moisture content, and ash content, can significantly influence biochar quality (Liu et al., 2024). For example, feedstocks like rice husk, corn stover, or wood chips can vary in nutrient content, affecting the final biochar's adsorption properties and carbon content. A reliable feedstock supply chain, along with preprocessing methods like drying, grinding, and homogenization, is essential to ensure consistent biomass quality and improve biochar uniformity (Rezende et al., 2016; Haeldermans et al., 2023).

Environmental and Regulatory Compliance: Biochar production involves heating organic materials to high temperatures, which can generate greenhouse gases and particulate matter. With stricter environmental regulations, biochar producers must invest in emission control systems to comply with air quality standards. These additional costs can be particularly burdensome for smaller producers who lack the resources to adopt advanced technologies (Nelson et al., 2024). Furthermore, navigating the complex and region-specific regulatory frameworks surrounding biochar production may hinder investments, slowing the scaling process.

Economic Viability: High initial capital costs for setting up advanced biochar production systems pose a significant barrier to scaling production. The commercial success of biochar production depends largely on establishing sustainable markets for its use in agriculture, waste

management, and carbon credit markets. Fluctuating feedstock prices and uncertainty in the market for carbon credits and renewable energy credits complicate financial planning (Mota et al., 2021; Tang et al., 2023). Biochar's market potential remains underdeveloped in many areas, making it difficult for producers to secure long-term contracts and achieve economies of scale.

Table 4 Provides an Overview of the Key Challenges in Scaling Up Biochar Production, the Technical Barriers Associated with Each, Proposed Solutions, and Their Potential for Large-Scale Implementation.

Challenge	Technical Barrier	Proposed Solutions	Potential for Scale-Up	Global Implementation Feasibility
High Production Costs	Expensive equipment and operational costs	Optimized production processes; economies of scale	Low	Moderate
Feedstock Availability	Limited access to high-quality biomass	Use of diverse agricultural residues; feedstock preprocessing	Moderate	High
Environmental Regulations	Emission control requirements	Investment in emission control systems	Moderate	High
Market Development	Lack of established markets	Development of carbon credit markets; collaboration with agricultural sectors	High	Moderate

From Table 4, it is clear that high production costs remain a major barrier to scaling up biochar production. While economies of scale can help reduce per-unit costs, initial capital investment in advanced production technologies remains a significant challenge (Adeniyi et al., 2023). The feedstock availability issue can be addressed by diversifying feedstock sources and implementing preprocessing techniques to improve consistency and quality (Lee et al., 2021). The environmental regulations surrounding emissions from pyrolysis and gasification systems can be mitigated through investment in emission control technologies, though this will add to the production cost (Nelson et al., 2024). Finally, market development is crucial for the widespread adoption of biochar, with carbon credit markets offering a significant opportunity for biochar producers to secure revenue streams (Elias et al., 2024).

CONCLUSION
This study offers an in-depth evaluation of biochar's production methods, environmental uses, and economic viability, providing valuable insights into its capacity to tackle global issues like climate change, soil degradation, and water contamination.

The key findings show that biochar, especially when produced through pyrolysis, is highly effective for carbon storage, reducing greenhouse gases, and removing pollutants from water and soil. However, challenges such as high production costs, variability in feedstock, and regulatory hurdles impede its large-scale production.

The research emphasizes the need for advancements in production technology and feedstock preprocessing to enhance biochar consistency. Although large-scale biochar production faces economic challenges, opportunities arise from carbon credit markets and the increasing demand for sustainable agricultural practices.

This work enriches the current understanding by summarizing the environmental and economic impacts of biochar, revealing both its potential and the obstacles to its widespread adoption. Future studies should focus on assessing biochar's carbon footprint through life cycle analysis, exploring more cost-effective production methods, and developing strong market infrastructures to support its broader implementation. Additionally, field-based research is needed to evaluate the long-term effects of biochar on soil health and water

quality, which will be essential for promoting its role in sustainable agriculture and environmental management.

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