
Biochar for Environmental Remediation and Sustainable Agriculture: A Survey

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Abstract

Biochar, a carbon-rich material derived from biomass pyrolysis, plays a crucial role in environmental remediation and sustainable agriculture by enhancing soil health, fertility, and carbon sequestration. This survey paper comprehensively examines biochar's multifaceted applications, emphasizing its potential to improve soil structure, water retention, and nutrient dynamics, thereby boosting crop yields and reducing reliance on chemical fertilizers. The paper explores biochar's production methods, highlighting the impact of biomass types and processing parameters on its properties. Advanced characterization techniques and machine learning applications are discussed as tools for optimizing biochar production and ensuring quality. Furthermore, the survey addresses biochar's role in mitigating ecological risks, such as nutrient runoff and soil degradation, and its effectiveness in adsorbing pollutants, thereby improving water quality and reducing soil contamination. While biochar's benefits are significant, challenges such as variability in properties, ecological risks of contaminant release, and the need for standardized guidelines are acknowledged. The paper calls for continued research to overcome these barriers, emphasizing the importance of collaboration and innovation in advancing biochar technologies. By integrating biochar into agricultural practices, it is possible to enhance carbon sequestration, promote sustainable agriculture, and contribute to climate change mitigation. The survey concludes by advocating for comprehensive frameworks that address economic, social, and environmental considerations to optimize biochar's application and maximize its benefits.

1 Introduction

1.1 Concept of Biochar

Biochar is a carbon-rich material produced through the pyrolysis of biomass, a thermal decomposition process conducted under limited oxygen conditions. This stable carbon form, derived from carbon-rich biomass such as lignin, significantly enhances soil health and mitigates ecological risks. The pyrolysis process not only generates a stable solid but also increases the potential for carbon sequestration and contaminant remediation, positioning biochar as a valuable asset in tackling environmental challenges [1]. The global biochar industry has expanded notably, with production reaching 350,000 metric tons annually in 2023, underscoring its growing significance in sustainable agriculture and environmental remediation [2]. As a soil amendment, biochar improves soil health and agricultural productivity, emphasizing its multifaceted contributions to ecological and agricultural systems.

1.2 Relevance in Environmental Remediation and Sustainable Agriculture

Biochar is pivotal in addressing environmental and agricultural challenges by enhancing soil health, improving carbon sequestration, and supporting sustainable practices. Its incorporation into soil systems significantly increases soil organic carbon (SOC) storage, aligning with global initiatives

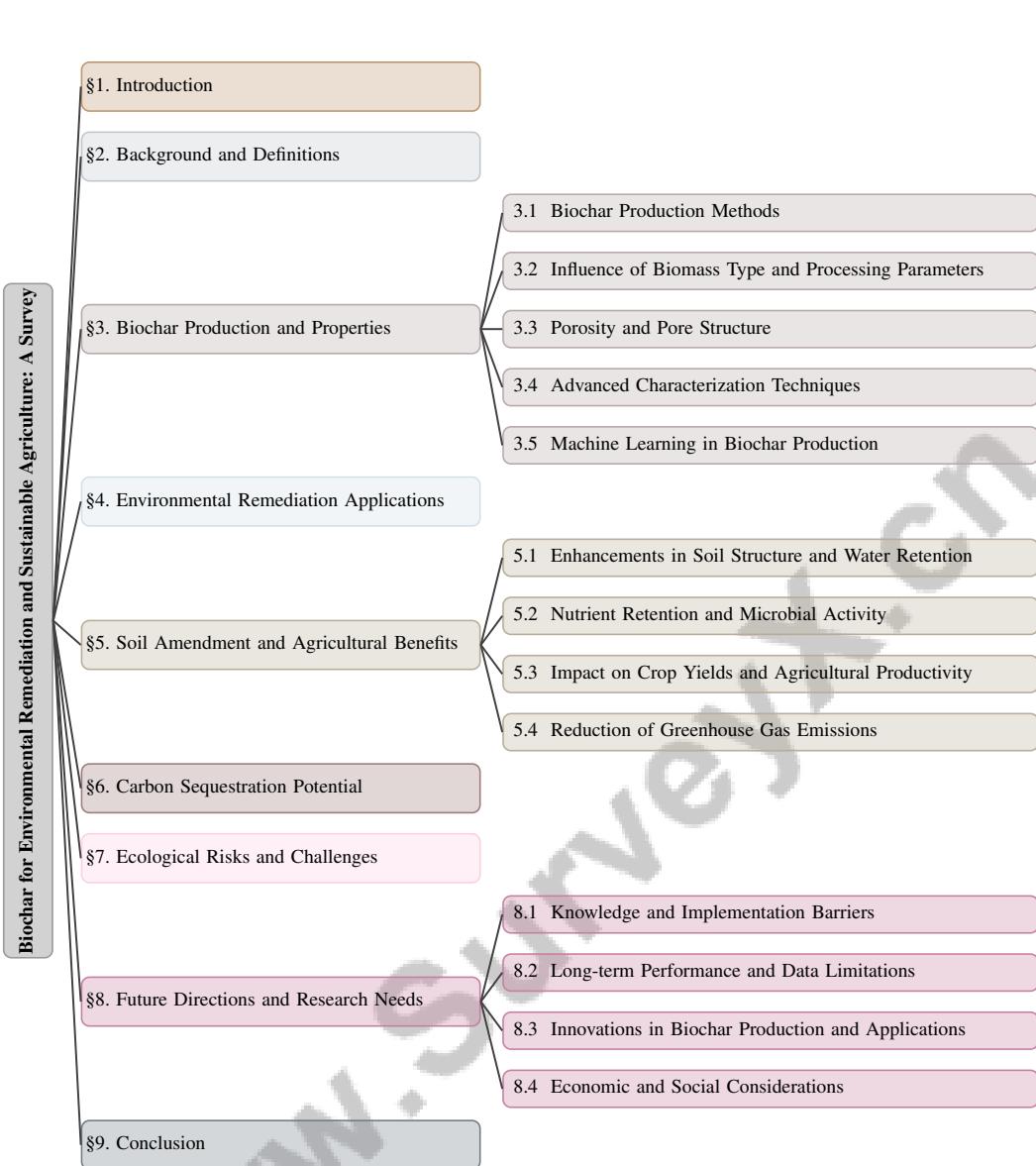


Figure 1: chapter structure

focused on climate change mitigation and food security through sustainable soil management. Transitioning agriculture from a carbon emitter to a carbon sink is essential, as highlighted by the need to enhance soil carbon sequestration via root exudates, which serve as a labile carbon source that boosts microbial activity and stabilizes carbon in ecosystems [3].

The agronomic advantages of biochar are evident in its capacity to improve soil fertility and structure, enhancing crop productivity and resilience to environmental stressors. Its role in nutrient retention and water management is critical for sustaining agricultural productivity and environmental quality, particularly in mitigating nutrient runoff and soil erosion. Moreover, biochar enhances financial profitability, biodiversity, and ecosystem services, solidifying its relevance in sustainable agriculture [4].

In environmental remediation, biochar's potential for soil and water purification is well recognized. Its effective application alongside solar energy technologies, such as visible light-responsive photocatalysts, enhances its ability to remove contaminants from the environment. This multifaceted utility positions biochar as an essential tool for advancing both environmental and agricultural sustainability, promoting a holistic approach to ecological challenges [5].

Accurate modeling of water infiltration in porous media is vital for improving irrigation practices and optimizing water use efficiency [6]. Understanding biochar's interactions within agroecosystems is crucial for enhancing sustainability and ensuring food security. Its capacity to sequester carbon and improve soil health renders biochar an integral component in the shift towards sustainable agricultural practices. This survey aims to explore biochar's role in enhancing soil organic carbon storage and its broader implications for environmental and agricultural sustainability.

1.3 Significance in Mitigating Ecological Risks

Biochar is instrumental in mitigating ecological risks associated with conventional agricultural practices by enhancing soil structure and reducing nutrient runoff, thus addressing the adverse effects of excessive reliance on synthetic fertilizers and pesticides. Its integration into agricultural systems promotes diversification, crucial for maintaining environmental sustainability and reducing the ecological footprint of farming activities [4]. By improving soil health and fertility, biochar helps combat soil degradation and biodiversity loss, significant challenges posed by conventional methods [7].

Beyond enhancing soil physical properties, biochar is vital for increasing soil carbon sequestration, a key process for capturing atmospheric CO₂ and mitigating climate change impacts [3]. This sequestration stabilizes the carbon cycle and alleviates the negative effects of climate change on nutrient availability and plant uptake, thereby supporting sustainable agricultural systems [8]. However, the effectiveness of biochar depends on overcoming the limitations of existing predictive methods, which often fail to explain causality and adapt to new environmental conditions [9]. Developing personalized, actionable strategies for farmers is essential, given the diverse responses of agricultural systems to various interventions [10]. Addressing these challenges will enable biochar to effectively mitigate ecological risks and foster resilient agricultural practices.

1.4 Structure of the Survey

This survey is systematically organized to provide a comprehensive examination of biochar's multifaceted role in environmental remediation and sustainable agriculture. It begins with an overview of biochar, detailing its definition, practical applications, and critical contributions to reducing ecological risks, particularly in enhancing soil fertility and promoting sustainable agricultural practices [11, 12, 13, 14]. Following this, the paper delves into the background and definitions essential for understanding biochar's applications, including its production, properties, and key terminologies.

Subsequent sections explore biochar production and properties, detailing various production methods, the influence of biomass types, and processing parameters on biochar characteristics. Advanced characterization techniques and the emerging role of machine learning in optimizing biochar production are also discussed.

The survey examines environmental remediation applications, highlighting biochar's adsorption capabilities, contributions to water quality improvement, and its role in reducing soil contamination. Practical applications and case studies demonstrate biochar's effectiveness in remediation efforts, showcasing its role as a soil amendment that enhances crop yields, reduces nutrient leaching, and improves soil biological properties, particularly in urban agriculture settings in West Africa. Research indicates that biochar can effectively adsorb contaminants in various contexts, such as in green roof systems, where it regulates fertilizer release and mitigates environmental impacts [12, 15, 16, 14, 17].

The analysis delves into the multifaceted advantages of biochar as a soil amendment, examining its significant effects on enhancing soil structure, improving nutrient retention, stimulating microbial activity, and ultimately increasing crop yields, as evidenced by various studies on its application in agricultural practices and urban farming systems in West Africa [18, 13, 14]. The potential for reducing greenhouse gas emissions through biochar application is also explored.

The investigation into biochar's carbon sequestration potential examines its mechanisms for carbon storage, integration into agricultural practices, and long-term implications for climate change mitigation. This includes a mathematical modeling framework analyzing how biochar interacts with soil to enhance carbon retention, identifying key factors such as soil type and climatic conditions that influence its effectiveness. The review highlights the multifaceted roles of soil as a major carbon reservoir and discusses the social and economic aspects affecting farmer adoption of biochar and

soil carbon sequestration practices, emphasizing the need for supportive policies and education to maximize its benefits in combating climate change [11, 14, 19, 20].

The ecological risks and challenges associated with biochar use, including the variability of its physicochemical properties and the necessity for standardized guidelines to ensure consistent application, are thoroughly evaluated in the context of its production, feedstock selection, and modification strategies. This evaluation highlights the importance of establishing clear correlations for effective utilization and predicting the potential environmental impacts of biochar [12, 13, 14, 21]. Finally, the survey outlines future directions and research needs, addressing knowledge barriers, data limitations, and innovations in biochar production and applications, alongside economic and social considerations.

The conclusion integrates the primary findings, emphasizing biochar's significant role in mitigating environmental issues and enhancing agricultural productivity while underscoring the necessity for ongoing research and collaborative efforts to optimize its application and effectiveness in various contexts [12, 22, 19, 14]. The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Key Terms and Definitions

Understanding key terms is crucial for comprehending biochar's diverse applications in environmental and agricultural systems. Biochar, a carbon-rich byproduct of biomass pyrolysis under limited oxygen conditions, primarily functions as a soil amendment and carbon sequestration tool [23]. This process contributes to carbon capture, enhances soil health, and mitigates ecological risks.

Biochar's impact on soil health is significant, influencing microbial diversity and ecosystem services, which are essential for nutrient cycling and soil structure. Its stable carbon structure supports carbon sequestration, crucial for climate change mitigation and enhancing plant nutrition through the stabilization of soil organic carbon [3, 8]. In environmental remediation, biochar's adsorption capabilities aid in pollutant removal from soil and water. Sustainable agriculture benefits from biochar's ability to reduce nutrient leaching and soil degradation, aligning with practices that maintain productivity while minimizing environmental impact [14].

Accurate biomass estimation is essential for assessing carbon balance, as inaccuracies can skew evaluations of carbon sequestration [24]. Understanding these terms and their interrelations is vital for advancing biochar applications in ecological and agricultural systems, promoting sustainable practices, and mitigating ecological risks.

2.2 Biochar's Role in Nutrient Transformation

Biochar plays a crucial role in nutrient transformation within soil ecosystems, significantly affecting the cycling and availability of essential macro and micronutrients. Incorporating biochar into soil impacts the dynamics of nitrogen (N), phosphorus (P), sulfur (S), and micronutrients like copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn), which are vital for soil fertility and sustainable agriculture [13].

Biochar's porous structure and high surface area enhance nutrient adsorption and retention, reducing leaching and improving nutrient use efficiency. This is particularly important in agricultural diversification, where maintaining nutrient balance is critical for crop productivity and ecosystem health [4]. Additionally, biochar interacts with soil organic matter and minerals, modifying the chemical environment to promote stable nutrient complexes and increase plant nutrient availability [25].

Emerging technologies, such as quantum algorithms, offer new approaches to optimizing nutrient transfer in soil ecosystems. Integrating quantum algorithms with mycorrhizal networks provides a framework for studying nutrient dynamics, facilitating more efficient management strategies in biochar-amended soils [26]. These innovations underscore biochar's potential to enhance agricultural sustainability by improving nutrient cycling and reducing reliance on chemical fertilizers.

Biochar's role in nutrient transformation is pivotal for enhancing soil health and agricultural productivity. By modulating nutrient dynamics, biochar serves as a vital soil amendment that supports the resilience and sustainability of agroecosystems. Its contributions to soil fertility and plant productivity align with broader goals of environmental remediation and sustainable agriculture, particularly

through increasing soil organic carbon levels, facilitating nutrient transformations, and promoting long-term carbon sequestration. This multifaceted role supports agricultural productivity while addressing climate change and fostering ecological balance within farming systems [27, 19, 13, 14].

3 Biochar Production and Properties

Category	Feature	Method
Biochar Production Methods	Chemical Enhancement Computational Optimization	LAC[28] e-TPPS[29]
Advanced Characterization Techniques	Structural Analysis	NMR-C[30]
Machine Learning in Biochar Production	Imaging and Structural Analysis Predictive and Optimization Strategies	XCT[31] MLCH[16], RFR[2], IMDA[21], CP-ML[32]

Table 1: This table provides a comprehensive overview of the various categories and methods utilized in biochar production, highlighting the integration of chemical enhancement, computational optimization, and machine learning techniques. The table delineates the specific features and methods employed within each category, offering insights into advanced characterization techniques and the role of machine learning in optimizing biochar production processes.

As the demand for sustainable agricultural practices and environmental remediation solutions grows, understanding the production and properties of biochar becomes increasingly critical. Table 1 presents a detailed examination of the different methodologies applied in biochar production, emphasizing the advancements in characterization techniques and the incorporation of machine learning strategies for enhanced production efficiency. Table 3 provides a comparative overview of various biochar production methods, detailing their processing techniques, optimization strategies, and applications, which are crucial for understanding their roles in sustainable agricultural and environmental practices. This section delves into the various methods of biochar production, highlighting the intricate processes that influence its characteristics and suitability for diverse applications. By examining the different production techniques, we can better appreciate how these methods affect the quality and functionality of biochar, setting the stage for a comprehensive discussion on the subsequent subsection regarding biochar production methods.

3.1 Biochar Production Methods

Method Name	Processing Techniques	Optimization Strategies	Functional Enhancements
LAC[28]	Mild Activation Agent	Optimizing Activation Process	Improved Electrochemical Properties
CP-ML[32]	Thermal Degradation	Machine Learning	Activation Processes
MLCH[16]	Hydrothermal Carbonization	Machine Learning	Activation
e-TPPS[29]	-	Advanced Simulation Methods	-

Table 2: Overview of biochar production methods highlighting the processing techniques, optimization strategies, and functional enhancements. The table summarizes various methods, including pyrolysis, co-pyrolysis, and hydrothermal carbonization, along with the integration of machine learning and advanced simulation methods to optimize biochar characteristics.

The production of biochar involves various methods, each with distinct processing parameters that influence the characteristics and quality of the resulting biochar. One of the primary methods is pyrolysis, which entails the thermal decomposition of biomass under limited oxygen conditions, leading to the formation of a carbon-rich solid product [28]. This process can be further optimized by co-pyrolysis, where different biomass types are blended to enhance biochar yield, a method that has been shown to benefit from machine learning techniques to predict optimal conditions [32].

Table 2 provides a comprehensive summary of different biochar production methods, detailing the processing techniques, optimization strategies, and functional enhancements that characterize each approach.

Hydrothermal carbonization (HTC) is another notable method, which converts wet biomass into hydrochar without the necessity for prior drying, making it an energy-efficient alternative [16]. This process occurs in a water medium at elevated temperatures and pressures, resulting in a versatile form of carbon that can be tailored for specific applications.

The activation of biochar is a crucial step that enhances its porosity and surface area, improving its utility in applications such as adsorption and soil amendment. For instance, lignin-derived activated carbon can be produced by activating lignin with KHCO₃, resulting in porous carbons suitable for use in supercapacitors and microbial fuel cells [28].

Advanced simulation methods for fluid and structure interactions in porous media provide insights into optimizing biomass processing, which is critical for enhancing the efficiency of biochar production methods [29]. These simulations enable the fine-tuning of processing parameters, ensuring that the biochar produced meets specific functional requirements.

3.2 Influence of Biomass Type and Processing Parameters

The properties of biochar are significantly influenced by the type of biomass used and the processing parameters employed during its production. Different types of biomass, including wood, agricultural residues, and manures, exhibit unique chemical compositions and structural characteristics that significantly influence the physicochemical properties of the resulting biochar. These variations arise from the inherent qualities of the feedstock, the specific biochar production processes employed, and the conditions under which these processes occur. Understanding these correlations is crucial for optimizing biochar production to meet the requirements of various applications, such as soil amendment, energy production, and pollutant adsorption. Comprehensive studies using advanced techniques, such as 3D imaging and machine learning, have demonstrated that factors like biomass composition, processing parameters, and pore structure play vital roles in determining the functionality and effectiveness of biochar in environmental and agricultural contexts [15, 12, 16]. These differences are crucial as they determine the biochar's suitability for specific applications, such as soil amendment or pollutant adsorption.

As illustrated in Figure 2, the primary factors influencing biochar properties can be categorized into biomass type, processing parameters, and optimization techniques. Each category includes specific examples or techniques, highlighting the diversity and complexity in biochar production and optimization. The porosity and pore size distribution of biochar are particularly affected by the type of biomass and the conditions under which it is processed. Studies have shown that biochars derived from different biomass sources exhibit significant variations in porosity and pore size distributions, which in turn impact their potential for soil water retention [15]. For instance, biochar produced from woody biomass tends to have a higher porosity and larger pore sizes compared to those derived from herbaceous materials, which is advantageous for applications requiring high water retention capacity.

Processing parameters, including pyrolysis temperature and residence time, significantly influence the physicochemical properties of biochar, as these factors determine the structural characteristics and chemical composition of the final product. Elevated pyrolysis temperatures can enhance certain properties, such as porosity, which is crucial for applications like water retention in agricultural settings. However, the impact of these parameters varies depending on the type of biomass feedstock used, necessitating a comprehensive understanding of their interactions to optimize biochar for specific applications [12, 16, 31]. Higher pyrolysis temperatures typically increase the carbon content and stability of biochar while reducing volatile matter and enhancing its adsorption capacity. However, these conditions can also decrease the yield and alter the pore structure, necessitating a careful balance to achieve the desired biochar characteristics.

Moreover, the use of co-pyrolysis, where multiple biomass types are processed together, can lead to synergistic effects that enhance biochar properties. This method, when integrated with sophisticated technologies such as machine learning, can significantly enhance the optimization of processing conditions, enabling the production of biochar with customized physicochemical properties. This is particularly beneficial for targeted environmental and agricultural applications, as machine learning algorithms can analyze diverse biomass sources and processing parameters to predict biochar yield and quality. For instance, studies have demonstrated that models like decision tree regression and support vector regression can effectively characterize biochar production, taking into account critical factors such as biomass composition and operating temperature. Furthermore, machine learning techniques have been successfully employed to streamline biochar production processes, improve regulatory compliance by minimizing emissions, and maximize output across various pyrolysis systems [32, 2, 16].

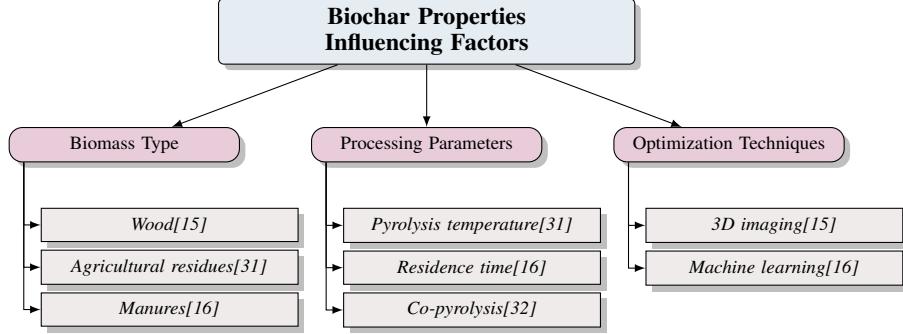


Figure 2: This figure illustrates the primary factors influencing biochar properties, categorized into biomass type, processing parameters, and optimization techniques. Each category includes specific examples or techniques, highlighting the diversity and complexity in biochar production and optimization.

3.3 Porosity and Pore Structure

The porosity and pore structure of biochar are critical determinants of its functionality, particularly in applications related to soil amendment and environmental remediation. The microstructure of biochar, including its porosity and pore size distribution, significantly influences its ability to retain water and nutrients, making it a valuable tool in enhancing soil health and fertility. For instance, the micrometre-range porosity of willow biochar has been identified as a key factor in its capacity to hold water for plant uptake, underscoring the importance of optimizing biochar's pore characteristics for agricultural applications [31].

Advanced characterization techniques, such as X-ray microtomography, have been employed to quantitatively analyze the pore structures of biochar, revealing substantial variations that impact their hydrological properties [15]. These variations are crucial as they determine the biochar's effectiveness in improving soil water retention and its potential to mitigate soil erosion and nutrient leaching.

The pore structure of biochar is influenced by several factors, including the type of biomass used and the conditions under which it is produced. The pyrolysis temperature significantly influences the porosity and pore size distribution of biochar, which in turn impacts its ability to adsorb pollutants and retain nutrients. Higher pyrolysis temperatures tend to increase the formation of pyrogenetic porosity, although the extent to which this change enhances the biochar's capacity to store plant-available water remains uncertain. Research utilizing advanced imaging techniques, such as X-ray tomography, has shown that the micrometer-range porosity is crucial for hydrological applications, yet the original structure of the feedstock plays a significant role in determining these properties. Therefore, optimizing biochar for specific uses requires careful consideration of both the pyrolysis conditions and the raw materials employed. [12, 15, 32, 31, 13]. Higher temperatures typically lead to increased porosity and larger pore sizes, which can enhance the biochar's adsorption capabilities but may also reduce its density and structural integrity.

Understanding the relationship between biochar's pore structure and its functional properties is essential for tailoring biochar to specific environmental and agricultural applications. By carefully optimizing the porosity and pore structure of biochar—characterized by factors such as raw material selection, pyrolysis temperature, and processing technology—it is possible to enhance its effectiveness in water management, nutrient retention, and pollutant adsorption. This optimization can significantly improve the water retention properties of biochar-amended soils, facilitate the regulation of fertilizer release in applications like green roofs, and increase the efficiency of contaminant adsorption. Consequently, these advancements contribute to sustainable agricultural practices and promote effective environmental remediation strategies. [15, 17, 31]

3.4 Advanced Characterization Techniques

Advanced characterization techniques, such as three-dimensional imaging and machine learning models, are crucial for understanding the intricate physicochemical properties of biochar. These properties, which vary significantly based on feedstock selection, production processes, and mod-

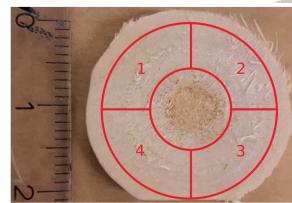
ifications, directly influence biochar's effectiveness in applications like soil enhancement, water retention in agricultural systems, and pollutant adsorption. By elucidating the relationships between biochar's molecular structure and its functional capabilities, researchers can optimize its use in environmental and agricultural contexts, thereby improving crop yields and promoting sustainable practices. [12, 15, 16, 14, 21]. The use of sophisticated analytical methods allows for a comprehensive understanding of biochar's physicochemical characteristics, including its surface morphology, porosity, and chemical composition.

One of the primary techniques employed in biochar characterization is nuclear magnetic resonance (NMR) crystallography, which provides detailed insights into the structural and chemical properties of biochar at the molecular level. This technique is particularly useful for identifying the presence of carbonates and other functional groups that influence biochar's reactivity and stability [30]. NMR crystallography enables the precise determination of biochar's molecular structure, aiding in the optimization of its properties for specific applications.

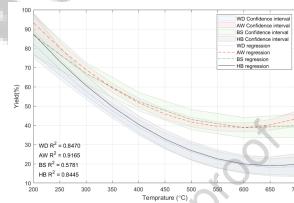
X-ray microtomography is another advanced technique that offers a non-destructive means of analyzing the internal pore structure of biochar. This method allows for the three-dimensional visualization of biochar's porosity and pore size distribution, providing critical information on its water retention and adsorption capabilities [15]. The ability to quantify these structural attributes is essential for tailoring biochar to enhance soil health and environmental remediation efforts.

Additionally, machine learning-based approaches have emerged as powerful tools for characterizing biochar properties. By integrating machine learning algorithms with traditional analytical techniques, researchers can predict biochar's performance in various applications, such as pollutant adsorption and soil amendment. These predictive models facilitate the optimization of biochar production processes, ensuring that the resulting material meets the desired specifications for its intended use [16].

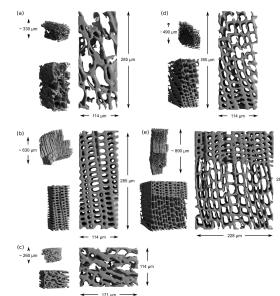
Overall, the integration of advanced characterization techniques with innovative analytical methods is crucial for advancing the understanding of biochar's properties. These approaches facilitate the targeted modification of biochar to meet the specific requirements of various environmental and agricultural applications, thereby improving its effectiveness in enhancing soil properties, increasing crop yields, and contributing to sustainable agricultural practices while addressing ecological challenges such as carbon sequestration and nutrient management. [19, 12, 16, 14]



(a) Cross-sectional View of a Wood Sample with Markings for Analysis[31]



(b) The image is a scatter plot graph showing the relationship between temperature and yield percentage for different regression models.[12]



(c) Microscopic Structures of Bone Tissue[15]

Figure 3: Examples of Advanced Characterization Techniques

As shown in Figure 3, In the exploration of biochar production and its properties, advanced characterization techniques play a crucial role in understanding and optimizing the material's potential applications. The provided examples illustrate the diversity of these techniques, showcasing different aspects of material analysis. The first example, a cross-sectional view of a wood sample, highlights the meticulous process of analyzing wood properties, where specific markings are used to facilitate precise measurements. This foundational analysis is essential for understanding the raw material that undergoes pyrolysis to produce biochar. The second example, a scatter plot graph, demonstrates the relationship between temperature and yield percentage across various regression

models, providing insights into the efficiency and outcomes of different pyrolysis conditions. Such data-driven analysis is vital for optimizing biochar production processes. Lastly, the depiction of microscopic structures of bone tissue exemplifies the intricate examination of material microstructures, akin to studying the porous nature of biochar. By employing these advanced characterization techniques, researchers can better understand the structural and functional properties of biochar, paving the way for its enhanced application in environmental and agricultural contexts. [? Jhyvluoma2018effectspyrolysistemperaturehydrologically,xie2022critical,hyvluoma2017quantitativecharacterizationporestructure)

3.5 Machine Learning in Biochar Production

Machine learning (ML) has emerged as a transformative tool in optimizing biochar production processes, offering innovative approaches to enhance efficiency and predict outcomes. By integrating ML algorithms with traditional production methods, researchers can achieve more precise control over biochar characteristics, tailored to specific environmental and agricultural applications. One significant advancement is the use of machine learning to predict the yield and quality of hydrochar from biomass hydrothermal carbonization. This approach leverages ML algorithms to analyze data and predict outcomes based on input parameters, thereby optimizing the production process for desired results [16].

As illustrated in Figure 4, the application of machine learning in biochar production encompasses several key areas, such as yield prediction, modeling, and advanced imaging techniques. This figure demonstrates how ML enhances the optimization of hydrochar yield, emission control, and co-pyrolysis effects, while also providing insights into biochar structure and soil health analysis. The application of machine learning in predicting emissions, such as NO_x during biochar production, represents a novel area of exploration. This innovation allows for the anticipation and mitigation of potential environmental impacts, ensuring that biochar production aligns with sustainable practices [2]. Furthermore, causal machine learning (Causal ML) integrates causal inference with machine learning to provide robust predictions and insights into cause-effect relationships, offering a deeper understanding of the factors influencing biochar production outcomes [9].

The construction of biochar models using basic structural units and virtual atoms is another area where machine learning contributes significantly. This method enables the realistic modeling of biochar structures and their properties, facilitating the design of biochars with specific porosity and functionality [21]. Additionally, machine learning techniques are employed to manage and analyze large datasets, addressing the critical need for scalable solutions in sustainable agriculture through tools like the SOC Copilot [27].

Moreover, the thermal degradation of blended biomass, such as algae and wood, is analyzed using machine learning algorithms to predict biochar yield. This process highlights the synergistic effects of co-pyrolysis, optimizing the conditions for enhanced biochar production [32]. The use of advanced imaging techniques, such as X-ray Computed Microtomography (XCT), in conjunction with machine learning, further enhances the ability to quantify and optimize the micrometre-range porosity of biochars produced at various pyrolysis temperatures [31].

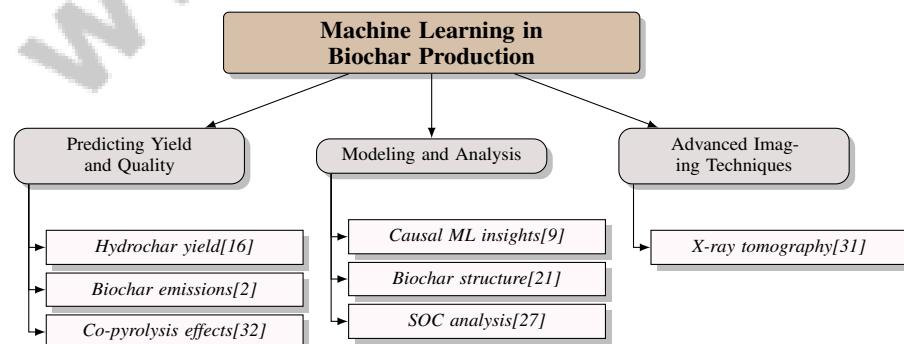


Figure 4: This figure illustrates the application of machine learning in biochar production, highlighting key areas such as yield prediction, modeling, and advanced imaging techniques. It demonstrates how ML enhances the optimization of hydrochar yield, emission control, and co-pyrolysis effects, alongside providing insights into biochar structure and soil health analysis.

Feature	Pyrolysis	Hydrothermal Carbonization (HTC)	Activation
Processing Method	Thermal Decomposition	Wet Biomass Conversion	Enhance Porosity
Optimization Strategy	Co-pyrolysis	Energy-efficient	Lignin Activation
Applications	Carbon-rich Product	Versatile Carbon	Adsorption, Supercapacitors

Table 3: Comparison of biochar production methods highlighting key features, optimization strategies, and applications. The table contrasts pyrolysis, hydrothermal carbonization, and activation processes, emphasizing their distinct processing methods and potential applications in environmental and agricultural contexts.

4 Environmental Remediation Applications

The exploration of environmental remediation applications encompasses a variety of innovative strategies aimed at mitigating the effects of contamination on ecosystems. Among these strategies, the utilization of biochar has emerged as a particularly effective approach due to its unique properties and capabilities. This section will delve into biochar's adsorption capabilities, highlighting its role in capturing and immobilizing pollutants within soil and water systems. By examining the mechanisms through which biochar operates, we can better understand its potential to enhance traditional remediation methods and contribute to sustainable environmental practices.

4.1 Biochar's Adsorption Capabilities

Biochar's adsorption capabilities are central to its application in environmental remediation, particularly in the adsorption and immobilization of contaminants within soil and water systems. The high surface area and porous structure of biochar enhance its effectiveness in capturing a wide range of pollutants, including heavy metals and organic compounds [1]. These properties make biochar a versatile tool in addressing the challenges of traditional contaminant remediation methods, which often struggle with efficiency and stability [1].

The adsorption efficiency of biochar is further influenced by the geometry of the porous medium and the activity of microbial communities within the soil, as demonstrated by studies on bacterial motility and its impact on pollutant dynamics [33]. This interaction highlights the potential for biochar to not only serve as a physical adsorbent but also to enhance the biological remediation processes by providing a conducive environment for microbial activity.

Innovative applications of biochar, such as its integration into Permeable Adsorptive Barriers, have shown promise in the removal of heavy metals like Pb²⁺ from groundwater. These barriers leverage the natural adsorption properties of biochar to effectively reduce contaminant concentrations, showcasing its potential in practical remediation efforts. Additionally, the development of defective metal-organic frameworks (MOFs), such as Zr-MOFs, with enhanced stability and catalytic activity, opens new avenues for biochar applications in catalysis and pollutant degradation [34].

The combination of biochar with advanced photocatalytic materials offers further opportunities for enhancing its pollutant removal capabilities. By integrating biochar with visible light-responsive photocatalysts, the degradation of organic pollutants can be significantly improved, addressing the limitations of conventional photocatalytic processes. This synergistic approach not only significantly improves the efficiency of pollutant removal from various environments but also broadens the range of potential applications for biochar in environmental remediation, including its use as a soil amendment to enhance crop yields and regulate nutrient leaching in urban agriculture, as well as its incorporation in green roof systems to mitigate contaminant transport and improve water quality. [12, 32, 19, 14, 17]

Overall, biochar's adsorption capabilities, coupled with advancements in catalytic and microbial technologies, underscore its effectiveness as a sustainable solution for mitigating environmental contamination. The unique physicochemical properties of biochar enable it to effectively adsorb a wide variety of pollutants, while also facilitating both biological and chemical remediation processes. This positions biochar as an essential element in the formulation of integrated environmental cleanup strategies, particularly as research continues to explore the optimal production methods, feedstock selection, and modification techniques that enhance its performance across diverse applications. [19, 12, 17, 14]

4.2 Role in Water Quality Improvement

Biochar plays a significant role in enhancing water quality through its ability to adsorb and immobilize contaminants, thereby reducing their mobility and bioavailability in aquatic environments. The high surface area and porous structure of biochar enable it to effectively capture a wide range of pollutants, including heavy metals and organic compounds, which are common in water bodies impacted by agricultural runoff and industrial discharges [1]. This adsorption capability is critical for preventing the leaching of harmful substances into groundwater and surface water, thereby protecting aquatic ecosystems and human health.

The integration of biochar into water treatment systems has been shown to improve the removal efficiency of various contaminants. For instance, biochar's ability to adsorb heavy metals such as lead (Pb), cadmium (Cd), and arsenic (As) is well-documented, making it a valuable tool in the remediation of polluted water sources [34]. Additionally, biochar can enhance the degradation of organic pollutants through its interaction with microbial communities, which can further break down complex organic molecules into less harmful substances [33]. This biological synergy is particularly beneficial in constructed wetlands and other natural treatment systems where biochar can serve as both a physical adsorbent and a habitat for pollutant-degrading microorganisms.

Moreover, the development of composite materials that combine biochar with advanced photocatalytic agents has opened new avenues for water purification. By leveraging the photocatalytic properties of materials such as titanium dioxide (TiO_2) and zinc oxide (ZnO), biochar composites can facilitate the photodegradation of organic contaminants under visible light, offering a sustainable and energy-efficient approach to water treatment [35]. These innovations not only enhance the removal of persistent organic pollutants but also expand the applicability of biochar in diverse environmental contexts.

4.3 Reduction of Soil Contamination

Biochar plays a pivotal role in mitigating soil contamination through its ability to adsorb and immobilize a wide range of pollutants, thereby reducing their bioavailability and mobility in soil environments. The porous structure and high surface area of biochar facilitate the adsorption of heavy metals, organic pollutants, and other contaminants, effectively sequestering them within the soil matrix and preventing their uptake by plants [17]. This adsorption capability is particularly beneficial in agricultural settings where the application of fertilizers and pesticides can lead to the accumulation of harmful substances in the soil.

One of the primary mechanisms by which biochar reduces soil contamination is through its ability to regulate nutrient release, thus minimizing the potential for nutrient leaching and subsequent environmental contamination [17]. By enhancing nutrient retention, biochar not only improves soil fertility but also mitigates the risk of nutrient runoff into adjacent water bodies, which can lead to eutrophication and other ecological disturbances.

Furthermore, biochar's interaction with soil microbial communities can enhance the degradation of organic pollutants, as it provides a conducive environment for pollutant-degrading microorganisms. This biological synergy enables the breakdown of complex organic compounds into less harmful substances, further reducing the contaminant load in the soil. The incorporation of biochar into soil significantly alters the chemical environment, facilitating the formation of stable complexes with heavy metals, which in turn decreases their solubility and mobility. This interaction not only enhances soil fertility and nutrient availability for plants but also plays a crucial role in mitigating environmental contamination by reducing the potential for heavy metal leaching into groundwater. Additionally, biochar's ability to sequester carbon contributes to long-term carbon storage in soil ecosystems, further promoting sustainable agricultural practices [17, 13, 19, 14].

In addition to its primary role in sequestering contaminants, biochar significantly enhances soil structure and improves water retention capabilities, both of which are essential for sustaining healthy soil ecosystems and promoting agricultural productivity. Studies indicate that biochar not only mitigates carbon dioxide release but also positively influences soil biological properties and nutrient management, thereby fostering a more resilient agricultural environment [19, 14]. By enhancing soil aeration and water-holding capacity, biochar supports the growth of beneficial soil organisms and promotes the natural attenuation of pollutants.

As illustrated in Figure 5, biochar plays a complex and significant role in mitigating soil contamination by employing a combination of physical adsorption mechanisms that capture pollutants and biological degradation processes that enhance the breakdown of contaminants, thereby improving soil health and fertility. This multifaceted approach not only aids in the retention of nutrients but also promotes sustainable agricultural practices, particularly in urban settings where soil quality is often compromised [13, 17, 14]. Its application in contaminated soils offers a sustainable approach to soil remediation, contributing to the restoration of soil health and the protection of environmental quality.

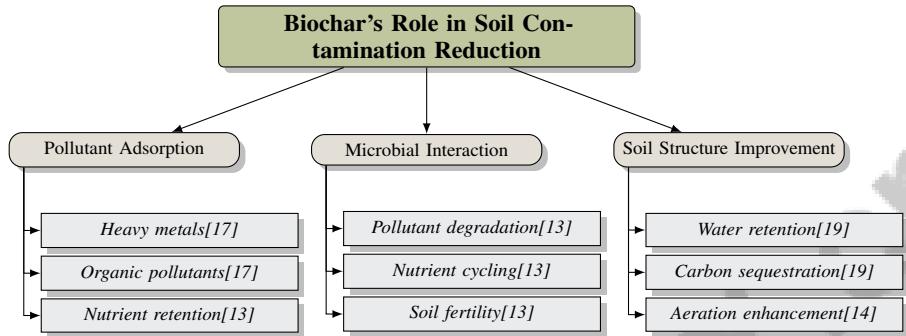


Figure 5: This figure illustrates the multifaceted role of biochar in reducing soil contamination, highlighting its capabilities in pollutant adsorption, microbial interaction, and soil structure improvement, which contribute to enhanced soil health and sustainable agricultural practices.

4.4 Case Studies and Practical Applications

Biochar's effectiveness in environmental remediation is well-documented through numerous case studies and practical applications, showcasing its potential to address various contamination challenges. One significant study highlights the role of biochar in stabilizing labile carbon from root exudates, which contributes to soil carbon sequestration and enhances ecosystem services [3]. This stabilization process is crucial for maintaining soil health and mitigating climate change impacts, demonstrating biochar's broader environmental benefits.

The successful application of biochar in enhancing ecosystem services is further exemplified by case studies that illustrate its role in improving soil fertility and crop productivity. Biochar filters have been shown to achieve pathogen removal rates comparable to traditional sand filters, while significantly enhancing crop biomass production [14]. This dual functionality underscores biochar's potential as a sustainable alternative in agricultural systems, promoting both environmental remediation and agricultural productivity.

In the context of biomass utilization, the integration of machine learning techniques with co-pyrolysis processes has been demonstrated to significantly improve biochar yield and quality. This approach not only optimizes the production process but also provides a pathway for sustainable biomass utilization, reinforcing biochar's role in circular economy initiatives [32].

Case studies from agricultural diversification projects have shown that biochar can enhance ecosystem services, providing valuable insights into its application in environmental remediation [4]. These studies highlight biochar's ability to support biodiversity, improve soil structure, and increase water retention, contributing to the resilience of agroecosystems.

The reviewed case studies and practical applications underscore the diverse and significant role of biochar in environmental remediation. These findings illustrate its potential as a sustainable and effective solution for mitigating contamination, enhancing soil health, and promoting ecological balance, particularly in urban agricultural contexts where biochar serves as a soil amendment and wastewater filtration medium, thereby improving crop yields and reducing nutrient leaching. [12, 17, 14, 16]. Through continued research and innovation, biochar can be further optimized to address a wide range of environmental challenges, contributing to the development of resilient and sustainable ecosystems.

As shown in Figure 6, The example "Environmental Remediation Applications; Case Studies and Practical Applications" provides a comprehensive overview of various innovative frameworks and

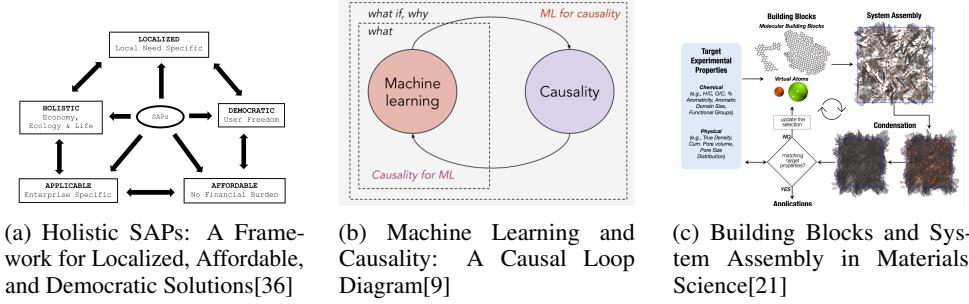


Figure 6: Examples of Case Studies and Practical Applications

methodologies used in addressing environmental challenges. The discussion is enriched by three illustrative case studies, each highlighting a unique approach. First, the "Holistic SAPs: A Framework for Localized, Affordable, and Democratic Solutions" showcases a flowchart detailing the interconnected components of sustainable applications, emphasizing the integration of economy, ecology, and democratic principles to ensure affordability and user freedom. This approach underscores the importance of localized and holistic strategies in environmental remediation. Second, the "Machine Learning and Causality: A Causal Loop Diagram" presents a visual representation of the interplay between machine learning and causality, highlighting how advanced computational techniques can enhance our understanding of causal relationships in environmental systems. Lastly, the "Building Blocks and System Assembly in Materials Science" case study delves into the molecular and systemic assembly processes, illustrating how careful selection of chemical and physical properties can lead to effective material solutions for environmental problems. Together, these examples provide valuable insights into practical and theoretical advancements in environmental remediation. [? Jmishra2022adoptionsustainableagriculturalpractices, sitokonstantinou2024causalmachinelearningsustainable, ngambia2024develop

5 Soil Amendment and Agricultural Benefits

The integration of biochar as a soil amendment offers substantial benefits for agricultural advancement by enhancing soil structure, water retention, and overall soil health, which are crucial for sustainable agriculture. This section delves into biochar's specific advantages, focusing on its role in improving soil structure and water retention, and its implications for agricultural productivity. Figure 7 illustrates the hierarchical structure of the benefits and applications of biochar in agriculture, highlighting its impact on soil structure, nutrient retention, crop yields, and greenhouse gas emissions reduction. The diagram categorizes biochar's roles, influencing factors, applications, and technological integrations, thereby emphasizing its contribution to sustainable agricultural practices and climate change mitigation.

5.1 Enhancements in Soil Structure and Water Retention

Biochar significantly enhances soil structure and water retention, which are vital for sustainable agriculture. By altering soil's physical and chemical properties, biochar improves nutrient transformation rates and overall soil health [13]. It increases soil porosity, thereby boosting water retention capacity, essential for maintaining soil moisture and supporting plant growth [37]. The raw material used in biochar production primarily determines its porosity, while pyrolysis temperature plays a lesser role in optimizing pore structure for water retention [31]. Biochar application supports improved soil management practices, especially in diversified agricultural systems where maintaining soil structure is crucial for crop success [4]. Additionally, biochar mitigates nutrient leaching and soil degradation, enhancing crop yields and soil health by increasing the soil's capacity to retain water and nutrients, thus bolstering agricultural ecosystems' resilience and productivity [14].

5.2 Nutrient Retention and Microbial Activity

Biochar plays a crucial role in enhancing nutrient retention and stimulating microbial activity within soil ecosystems, thereby improving soil fertility and agricultural productivity. Its high adsorptive surface area facilitates nutrient retention and reduces leaching, which is particularly beneficial in

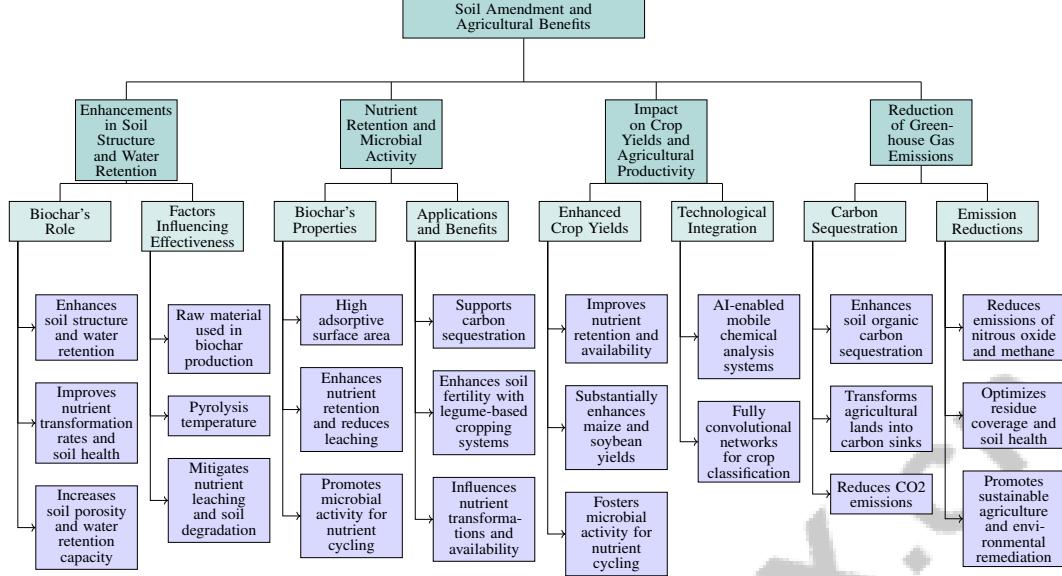


Figure 7: This figure illustrates the hierarchical structure of the benefits and applications of biochar in agriculture, highlighting its impact on soil structure, nutrient retention, crop yields, and greenhouse gas emissions reduction. The diagram categorizes biochar's roles, influencing factors, applications, and technological integrations, emphasizing its contribution to sustainable agricultural practices and climate change mitigation.

agricultural settings where nutrient loss can adversely affect crop yields and lead to environmental degradation [17]. Biochar enhances soil fertility by promoting microbial activity, critical for nutrient cycling and agricultural productivity [13]. Its porous structure provides habitats for soil microorganisms, fostering their growth and activity and enhancing nutrient cycling through organic matter decomposition and nutrient transformation into plant-available forms. Advanced imaging techniques, such as X-ray Computed Tomography (XCT), reveal biochar's micrometre-scale porosity, contributing to nutrient retention and microbial habitat [31]. Integrating biochar with legume-based cropping systems and inorganic fertilizers reduces nutrient loss and enhances soil fertility [18], leveraging the synergistic effects of biochar's nutrient retention and legumes' nitrogen-fixing capabilities. Biochar's unique properties contribute to sustainable soil management, influencing nutrient transformations and availability, thereby supporting carbon sequestration and long-term soil health [19, 12, 13, 14].

5.3 Impact on Crop Yields and Agricultural Productivity

Biochar significantly influences crop yields and agricultural productivity by enhancing soil fertility and promoting sustainable farming practices. Its application improves nutrient retention and availability, boosting crop yields, though its effectiveness depends on specific conditions such as biochar type and soil characteristics [13]. Research demonstrates that biochar can substantially enhance crop productivity by improving soil health and nutrient dynamics. Integrated management practices incorporating biochar with legume-based systems significantly reduce nutrient loss due to soil erosion, enhancing soil fertility and supporting higher crop yields [18]. This synergy improves nitrogen fixation and enriches the soil's overall nutrient profile, contributing to sustainable agricultural productivity. Empirical studies report substantial increases in maize and soybean yields by 12%

5.4 Reduction of Greenhouse Gas Emissions

Biochar application in agriculture offers a promising strategy for reducing greenhouse gas emissions, contributing to climate change mitigation. By enhancing soil organic carbon (SOC) sequestration, biochar improves soil quality and agricultural productivity while stabilizing carbon within the soil matrix, reducing CO₂ emissions [38]. This stabilization transforms agricultural lands into carbon sinks, mitigating farming's impact on global warming. Biochar integration aligns with broader environmental objectives aimed at enhancing quality and sustainability [36]. It significantly reduces

emissions of nitrous oxide (N_2O) and methane (CH_4)—potent greenhouse gases associated with conventional agriculture. The SOC Copilot exemplifies improved understanding of soil health dynamics, informing practices and policies aimed at curbing greenhouse gas emissions [27]. Biochar optimizes residue coverage and soil health, contributing to emission reductions by enhancing nutrient cycling and decreasing reliance on synthetic fertilizers, significant sources of N_2O emissions [39]. The use of biosorbents, such as pinecone with biochar, promotes sustainable agriculture and environmental remediation, recovering valuable metals and minimizing agriculture's environmental footprint [40]. Biochar's integration across sectors, like the British Columbia wine industry, illustrates its potential to enhance profitability while meeting sustainability goals, including greenhouse gas emission reductions [41]. Innovative biochar-related technologies, such as algae fillers in construction, further highlight its applicability in reducing emissions across industries [23]. The DRW algorithm enhances water management accuracy in agriculture, potentially improving crop yields and reducing reliance on traditional methods, indirectly contributing to greenhouse gas emission reductions [6]. Biochar in agriculture represents a comprehensive strategy for reducing greenhouse gas emissions, supporting sustainable practices, and contributing to global climate change mitigation by enhancing SOC sequestration and improving soil health.

6 Carbon Sequestration Potential

6.1 Mechanisms of Carbon Storage

Biochar plays a crucial role in carbon sequestration due to its stable carbon structure, formed through pyrolysis, which decomposes biomass under low oxygen conditions [24]. This structure resists microbial decomposition, serving as a long-term carbon sink in soil [42]. Its incorporation enhances carbon storage and soil fertility, supporting sustainable agriculture [8]. Biochar's porous structure and high surface area facilitate the adsorption of carbon compounds, immobilizing them within the soil matrix [20]. Interactions with soil minerals form stable complexes, minimizing carbon loss through microbial respiration [3], stabilizing soil organic carbon (SOC), and mitigating climate change. Biochar's influence extends to enhancing plant growth and organic matter accumulation, increasing SOC levels by boosting root biomass and microbial activity [8]. This transformation is significant in converting agricultural soils from carbon sources to sinks, reducing anthropogenic emissions. AI-based soil testing systems further assess biochar's impact on carbon sequestration, providing accurate soil analysis [43]. The mechanisms of carbon storage in biochar encompass direct sequestration and indirect effects on soil dynamics, enhancing the soil's capacity to capture atmospheric CO_2 , vital for climate change mitigation. Biochar also improves soil health by enhancing nutrient retention and promoting beneficial microbial activity [11, 14, 19, 20].

6.2 Integration with Agricultural Practices

Integrating biochar into agricultural systems enhances carbon sequestration and improves soil health and productivity. Its potential is amplified when combined with sustainable practices, such as afforestation in semi-arid regions, increasing carbon storage in agroecosystems [44]. Biochar stabilizes SOC and mitigates emissions when used with crop rotation, cover cropping, and reduced tillage, which improve soil structure and fertility [8, 38, 20, 11, 22]. Its porous structure aids moisture and nutrient retention, bolstering plant growth and increasing biomass contributing to SOC pools. Combining biochar with legume-based systems enhances nitrogen fixation and nutrient cycling, reducing synthetic fertilizer reliance and nitrous oxide emissions [4, 18, 19, 14]. Utilizing biochar in agroforestry systems, where trees and crops coexist, captures CO_2 through photosynthesis while enhancing carbon stabilization in the soil. This combination contributes to long-term sequestration, improves soil health, and creates a sustainable agricultural landscape [45, 19]. Integrating biochar offers a comprehensive strategy for enhancing carbon sequestration and supporting sustainable agriculture, achieving significant increases in soil quality, carbon storage, and ecosystem services [27, 8, 38, 4].

6.3 Long-term Implications for Climate Change Mitigation

Biochar's long-term implications for climate change mitigation are substantial, offering a multifaceted approach to reducing atmospheric CO_2 and enhancing soil health. Its stable carbon structure enables it to serve as a long-term carbon sink, crucial for mitigating climate change impacts by

reducing greenhouse gas emissions from agricultural systems [19, 38]. Integrating biochar into precision residue management optimizes carbon storage, supporting sustainable farming practices [39]. Economic incentives, such as those in the grape-growing industry, highlight biochar's potential for providing carbon offset benefits, driving widespread adoption [41]. In forest management, combining biochar with age-dependent logging strategies optimizes carbon storage, aligning economic objectives with environmental goals [46]. Advanced numerical methods, like the DRW algorithm, improve water management, indirectly supporting carbon sequestration by optimizing soil moisture and nutrient dynamics [6]. Biochar's potential for climate change mitigation involves direct sequestration and the enhancement of sustainable agricultural and forestry practices, contributing to initiatives like the 4p1000, supporting global efforts to mitigate climate change and enhance food security [38].

7 Ecological Risks and Challenges

The ecological risks and challenges of biochar are complex, primarily due to its variable properties, which affect its effectiveness and complicate its application across different environments. Understanding these variations is crucial for evaluating biochar's ecological impacts, especially concerning its interactions with soil matrices and potential contaminant release. The following subsections delve into the specifics of biochar property variability, the ecological risks of contaminant release, and the challenges in establishing standardized guidelines.

7.1 Variability in Biochar Properties

Biochar's variability in properties significantly influences its application in environmental and agricultural contexts. Variations in feedstock types and production methods result in differences in physicochemical characteristics like porosity, surface area, and nutrient content [12]. This inconsistency complicates the predictability of biochar performance, posing challenges for standardization in soil amendment and pollutant adsorption applications. The complexity of pyrolysis processes further exacerbates this variability, affecting biochar quality and consistency, and complicating emission control, such as NOx regulation [2]. Additionally, scalability issues in modified materials like metal-organic frameworks (MOFs) present challenges for consistent performance in diverse environments, complicating biochar's integration into remediation strategies [35].

Biochar's role in soil organic carbon (SOC) storage is also influenced by this variability, with biophysical limits and SOC dynamics complexity posing significant challenges [38]. Overcoming these constraints and socio-economic barriers is essential for enhancing SOC storage through biochar [22]. Furthermore, limitations in preconditioning methods, such as ILU preconditioners, reveal variability in effectiveness in complex multiphase flow scenarios, impacting ecological outcomes [1].

Comprehensive benchmarks and assessment methods are necessary to evaluate the ecological risks associated with biochar use, especially regarding heavy metal contamination and other environmental factors [47]. Current research often focuses narrowly on specific contaminants, lacking comprehensive data on emerging pollutants [48], and fails to address the long-term effects of exposure to heavy metals and pesticides, limiting the understanding of synergistic interactions [49].

Addressing variability in biochar properties requires standardizing production processes, developing advanced characterization techniques, and establishing guidelines for diverse applications. By tackling these challenges, biochar can enhance soil health by improving nutrient availability, reducing nutrient leaching, and promoting beneficial soil biological properties, supporting sustainable agricultural practices, particularly in urban agriculture contexts like West Africa [13, 12, 19, 14].

7.2 Ecological Risks of Contaminant Release

Biochar's application poses potential ecological risks related to contaminant release, despite its environmental and agricultural benefits. Variability in biochar properties can lead to inconsistent performance in contaminant adsorption and release, notably in zinc content near industrial activities, where significant ecological risks have been identified [47]. Biochar's interaction with complex soil matrices affects the mobility and bioavailability of contaminants, including heavy metals and organic pollutants. The effectiveness of biochar in adsorbing these contaminants varies with different transition metal dichalcogenides (TMDCs) and organic substrates, highlighting potential ecological

risks [50]. Understanding application conditions is crucial to ensure biochar's effectiveness in mitigating contaminant release.

The lack of comprehensive empirical data on the ecological effects of emerging contaminants, such as per- and polyfluoroalkyl substances (PFAS), complicates risk assessments related to biochar application [51]. Moreover, the movement of bacteria through heterogeneous three-dimensional porous media in biochar-amended soils presents challenges in predicting infection spread and microbial therapy development [33].

The ecological risks of contaminant release necessitate careful consideration of biochar's properties, interactions with environmental matrices, and the presence of emerging contaminants. To mitigate potential risks, extensive empirical research and standardized guidelines addressing biochar's specific properties, production processes, and interactions with soil and crops are essential. This comprehensive approach will enhance soil fertility, optimize nutrient transformations, and support sustainable agricultural practices [12, 13, 14].

7.3 Challenges in Standardization and Guidelines

Standardized guidelines for biochar production and application are crucial for maximizing its environmental and agricultural benefits while minimizing ecological risks. Variability in biochar properties, due to differences in feedstock types and production methods, presents significant challenges in establishing uniform standards. This inconsistency can lead to unpredictable outcomes in soil amendment and pollutant adsorption, necessitating a comprehensive framework for diverse applications [47].

Standardization efforts must address biochar's diverse characteristics, including porosity, nutrient content, and contaminant levels, influenced by feedstock selection, pyrolysis conditions, and modifications. Understanding these correlations is essential for optimizing biochar production for targeted applications [12, 31]. Establishing benchmarks for these properties ensures biochar products meet specific quality criteria, enhancing reliability and effectiveness.

Advanced characterization techniques, such as nuclear magnetic resonance (NMR) crystallography and X-ray microtomography, provide insights into biochar's physicochemical properties. These methods facilitate detailed analysis of pore structures, porosity, pore-size distribution, and structural anisotropy, critical for understanding biochar's functionality in applications like soil enhancement and water retention. By elucidating the relationships between biochar's molecular structure, processing temperature, and hydrological properties, these techniques support developing standardized assessment methods that optimize biochar's efficacy in environmental applications [15, 31, 21].

The ecological risks associated with contaminant release, such as heavy metals, emphasize the need for standardized guidelines. A comprehensive framework integrating multiple assessment methods can help identify and mitigate potential ecological impacts, ensuring biochar's safe and effective use in soil systems [47].

Establishing standardized guidelines for biochar production and application is essential for maximizing its agronomic benefits and enhancing soil properties while mitigating ecological risks. This requires a thorough understanding of the relationships between feedstock selection, production processes, and resulting biochar characteristics, informing stakeholders and end-users in making informed decisions regarding its utilization and effectiveness in various applications [12, 2, 14]. By addressing variability in biochar properties and incorporating advanced characterization techniques, these guidelines can facilitate the widespread adoption of biochar as a sustainable solution for environmental remediation and agricultural enhancement.

8 Future Directions and Research Needs

8.1 Knowledge and Implementation Barriers

Biochar technology adoption is hindered by significant knowledge and implementation barriers. A limited understanding of biochar's interaction with diverse soil types and its long-term impact on soil health and productivity is a primary challenge [13]. This knowledge gap is exacerbated by the lack of comprehensive life-cycle assessments essential for optimizing biochar's sustainable application [22]. Economic constraints, such as insufficient market infrastructure and awareness of economic models

promoting sustainability, further restrict biochar adoption [36]. Developing refined economic models and incentivizing strategies for farmers is crucial to overcoming these hurdles [22, 4].

Technological barriers, particularly in monitoring and predictive modeling, are critical for addressing ecological risks, especially concerning emerging contaminants like PFAS [51]. Current research is limited by challenges in synthesizing and characterizing defects, leading to inconsistent performance outcomes [34]. Future studies should optimize basalt application rates and explore the long-term effects of enhanced weathering on soil health and productivity [45]. Broader contaminant monitoring, including emerging pollutants, is necessary for effective water and waste management strategies [48].

Educational and cultural barriers, coupled with limited farmer engagement, impede the implementation of soil carbon sequestration practices [11]. Providing personalized insights based on local conditions and integrating causal analysis into agricultural decision-making can enhance biochar adoption [10]. Future research should explore biochar's long-term effects in various soil contexts and optimize its use in wastewater treatment [14]. Addressing these barriers requires enhancing farmer engagement, aligning economic viability with environmental sustainability, and developing comprehensive frameworks for biochar application. By overcoming these challenges, biochar can be effectively integrated into sustainable agricultural practices, contributing to climate change mitigation and improved soil health. Future research should prioritize optimizing extraction methods, developing stable formulations, understanding the ecological impacts of botanical insecticides, and addressing regulatory challenges to facilitate biochar adoption [52]. Understanding the synergistic effects of climate variables on nutrient dynamics and conducting site-specific studies are essential for assessing food security implications under climate change [8]. Improved data-driven approaches in agricultural practices are necessary to overcome barriers to effective hydrological modeling [6].

8.2 Long-term Performance and Data Limitations

Benchmark	Size	Domain	Task Format	Metric
C-SM[53]	1,000,000	Forestry	Carbon Sequestration Assessment	Pg C year 1, RMSE
BCWIB[41]	3,500	Agricultural Economics	Benefit-Cost Analysis	B/C Ratio, NPV
Biochar-3D[15]	1	Soil Science	Pore Structure Analysis	Porosity, Specific Surface Area
Yatir[44]	28	Forestry	Carbon Sequestration Measurement	g CO ₂ m ² yr ⁻¹
EW-CBM[45]	4,000	Agronomy	Carbon Dioxide Removal Assessment	CDR, N2O Mitigation
Zinc-Risk[47]	320	Soil Science	Ecological Risk Assessment	Potential Ecological Risk Index, Hazard Quotient
MCS[43]	805	Soil Chemistry	Soil PH Classification	Accuracy, Turnaround Time
GGP[42]	4,115	Carbon Sequestration	Carbon Stock Estimation	Tg C

Table 4: This table presents a comprehensive overview of various benchmarks used in biochar and related environmental studies, detailing their size, domain, task format, and evaluation metrics. The benchmarks cover diverse domains such as forestry, agricultural economics, soil science, and agronomy, highlighting the interdisciplinary nature of research in carbon sequestration and ecological risk assessment.

The long-term efficacy of biochar in environmental and agricultural applications is uncertain due to data limitations and the need for extended performance studies. Insufficient understanding of farmer satisfaction with current practices may hinder biochar adoption and other innovative methods [36]. This gap necessitates comprehensive assessments considering socio-economic factors influencing farmer decisions and potential benefits of biochar adoption. Current research often overlooks environmental factors affecting biochar's wettability and interactions with soil types, impacting efficacy [54]. Detailed studies on biochar-soil interactions under varying climatic conditions are needed. Table 4 provides a detailed overview of the representative benchmarks utilized in studies assessing the long-term performance and data limitations of biochar in environmental and agricultural contexts.

Long-term monitoring of carbon stocks and soil moisture dynamics is crucial for understanding biochar's sustained impacts on carbon sequestration and soil health [53]. Such monitoring should be complemented by studies on climate variability effects on biochar performance to inform adaptive management strategies. Future research should extend biochar treatment studies, incorporate

comprehensive data on agricultural practices, and conduct sensitivity analyses to enhance findings' robustness [10]. These efforts are essential for accurately assessing biochar's long-term impacts on soil health, crop productivity, and ecosystem services [18].

Additionally, variability in botanical extract efficacy and lack of commercially available biochar products challenge understanding of long-term ecological impacts [52]. Addressing these limitations requires developing stable formulations, improving product availability, and conducting extensive ecological assessments for sustainable biochar integration into agricultural and environmental management practices. A multidisciplinary approach incorporating socio-economic factors, environmental considerations, and technological innovations is essential to enhance long-term biochar performance studies. Research highlights biochar's agronomic benefits in urban agriculture and its potential to improve soil quality and support sustainable land management, exemplified by the "4 per 1000" initiative aimed at increasing soil organic carbon sequestration [38, 14]. Addressing data limitations and expanding research efforts can optimize biochar applications for enhanced sustainability and resilience in agricultural and environmental systems.

8.3 Innovations in Biochar Production and Applications

Innovations in biochar production and applications are crucial for maximizing its potential in environmental remediation and sustainable agriculture. Future research should prioritize participatory methods and geographic diversity to integrate farmer perspectives into policy design, enhancing the social implications of carbon markets [11]. Expanding research to include additional soil nutrients could significantly improve biochar applications, offering a more comprehensive approach to soil management [43].

To optimize biochar's role in carbon sequestration, future studies should focus on improving estimation methods by considering local conditions and integrating management practices' impacts [42]. This approach will yield a more accurate assessment of biochar's contribution to carbon storage, supporting its application in diverse environmental contexts. Innovations in production techniques can be informed by computational methods such as InfoSurf, enhancing the understanding of biological systems and aiding in the development of biochar formulations tailored to specific applications [55]. Additionally, *in situ* studies of root exudates in diverse ecosystems should be explored to understand their composition and effects on soil organic carbon (SOC) stabilization, as well as methods to enhance root exudation in native plant species [3].

Integrating machine learning (ML) into biochar production processes presents a promising avenue for innovation. By incorporating additional variables, such as biomass ash composition and solvent use, ML models can be refined to improve biochar characterization and optimize its applications [32]. These advancements align with broader efforts to explore innovations in biochar production, particularly in extending its application to more complex models and systems [1]. Advancing research in biochar production and applications should focus on refining existing models, considering complex interactions such as nutrient dynamics and environmental factors, and testing these innovations across diverse ecosystems. By exploring these research avenues, biochar can be optimized as a soil amendment and wastewater filtration medium, thereby supporting sustainable agricultural practices and environmental remediation efforts. This optimization will enhance crop yields and soil properties in regions like West Africa and play a significant role in global initiatives aimed at mitigating climate change and managing natural resources more efficiently [12, 19, 14, 22].

8.4 Economic and Social Considerations

Economic and social factors significantly influence biochar adoption and use in agricultural and environmental management. The demographic profile of farming communities, such as the average age and education level of farmers, suggests potential barriers to adopting innovative technologies like biochar [36]. Economic considerations, such as integrating economic factors into forest management strategies, highlight the need for policies that balance environmental goals with sustainable livelihoods [53]. This balance ensures biochar applications are economically viable and contribute to agricultural and forest ecosystems' resilience.

The broader ecological and socioeconomic impacts of initiatives like the Grain for Green Program (GGP) illustrate biochar's potential to enhance biodiversity and soil conservation while contributing to carbon sequestration [42]. These multifaceted benefits emphasize the importance of considering the

wider socioeconomic context when promoting biochar use, as it can lead to improved environmental outcomes and enhanced community well-being. To facilitate biochar adoption, it is imperative to develop economic models and strategies that align with the needs of farmers and other stakeholders. This includes providing incentives for sustainable practices, enhancing market infrastructure for biochar products, and fostering educational programs that increase awareness and understanding of biochar's benefits and applications. Addressing the economic and social factors associated with biochar utilization can more effectively incorporate it into sustainable agricultural and environmental practices. This integration enhances soil health and crop yields, as demonstrated in West African urban agriculture, and plays a significant role in climate change mitigation through soil carbon sequestration, ultimately supporting sustainable livelihoods and food security. Understanding farmers' perspectives on soil carbon sequestration can inform policy and incentivize adoption, maximizing the co-benefits of biochar application in diverse contexts [12, 19, 38, 14, 11].

9 Conclusion

This survey underscores biochar's pivotal role in addressing pressing environmental and agricultural challenges. Its ability to improve soil health, foster biodiversity, and enhance agricultural productivity marks it as a cornerstone of sustainable agriculture. The integration of biochar into soil systems not only augments carbon sequestration and nutrient retention but also aids in climate change mitigation and the enhancement of ecosystem services. Key findings emphasize the importance of soil biodiversity in boosting plant productivity and the adoption of sustainable practices to enhance soil health.

Innovative applications, such as the incorporation of biochar with emerging technologies like plant-protein-enabled bio-TENGs, demonstrate its potential to expand agricultural benefits. Additionally, advanced methodologies such as fully convolutional networks highlight the capacity for precision agriculture, reinforcing the importance of innovation in sustainable farming practices.

The survey also identifies the necessity for ongoing research and collaboration to fully exploit biochar's potential. Overcoming educational and cultural barriers, integrating co-benefits into policy frameworks, and increasing farmer engagement in soil carbon sequestration research are critical steps forward. Tools like the SOC Copilot exemplify how tailored insights can inform agricultural management and policy, emphasizing the need for continued exploration of sustainable practices.

While no significant human health risks from pharmaceuticals and personal care products in groundwater were found, moderate ecological risks for aquatic life necessitate thorough ecological assessments when applying biochar. Ultimately, biochar's transformative potential in fostering sustainable agricultural and environmental practices is clear, and ongoing research and collaboration are essential to optimize its application and maximize its benefits.

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