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Advances in biochar applications for enhancing soil fertility and carbon sequestration

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Abstract

Biochar, a stable carbon-rich material derived from the pyrolysis of biomass, has emerged as a promising solution for improving soil fertility and mitigating climate change. By enhancing nutrient retention, water-holding capacity, and microbial activity, biochar significantly improves soil productivity, especially in degraded and nutrient-poor soils. Concurrently, its high carbon stability enables long-term sequestration of atmospheric carbon when incorporated into soil, making it a valuable tool for reducing greenhouse gas emissions. Recent advances in biochar production, engineering, and functionalization have expanded its applications across various agroecosystems. However, site-specific responses, variable feedstock characteristics, and economic feasibility remain key challenges. This review explores the state-of-the-art in biochar science, including its properties, mechanisms of action, and role in carbon markets. It also identifies knowledge gaps and future research needs to optimize biochar for integrated soil management and climate resilience strategies.

Keywords: Biochar, soil fertility, carbon sequestration, pyrolysis technology, sustainable agriculture

1. Introduction

Global agriculture today faces a dual challenge: enhancing soil productivity to meet the growing food demands of an increasing population, while simultaneously addressing the urgent need to reduce greenhouse gas emissions and restore ecological balance. Conventional farming practices and unsustainable land use have contributed significantly to soil degradation, nutrient loss, and increased carbon emissions. This has spurred global interest in nature-based solutions that can rehabilitate soils and function as effective carbon sinks ^[1, 2]. Among these, biochar has emerged as a promising strategy that addresses both soil health and climate mitigation ^[2, 3].

Biochar is a porous, carbon-rich material produced through the thermal decomposition of organic biomass under limited oxygen conditions a process known as pyrolysis. Although its potential was first demonstrated in ancient Amazonian “terra preta” soils, modern scientific exploration has revealed a wide range of applications and benefits ^[2, 3]. When applied to soil, biochar enhances nutrient retention, improves water-holding capacity, buffers pH, and fosters microbial activity, leading to more resilient and fertile soils. In parallel, biochar’s stable carbon structure resists microbial decomposition, allowing carbon to remain sequestered in soil for hundreds to thousands of years, effectively removing CO₂ from the atmosphere ^[1, 3].

Recent advancements in biochar research have focused on optimizing its properties for specific soil types and crops, engineering biochars enriched with nutrients or microbial inoculants, and exploring its integration with other soil amendments. Studies have also begun to quantify its carbon sequestration potential and evaluate its role in climate policies and voluntary carbon markets ^[3, 4]. However, biochar’s performance varies widely based on feedstock type, pyrolysis conditions, soil characteristics, and climatic factors. Moreover, questions related to scalability, economic viability, long-term field performance, and potential environmental risks remain areas of active investigation ^[2, 3].

2. Biochar: Properties and Production Technologies

Biochar is produced through the thermochemical conversion of organic biomass under oxygen-limited conditions, a process most commonly referred to as pyrolysis. This process not only

reduces biomass to a stable carbon form but also yields co-products such as bio-oil and syngas, depending on the specific pyrolysis method employed ^[4, 5]. The properties of biochar are heavily influenced by both the type of feedstock used and the parameters of the thermal process, including temperature, heating rate, and residence time. Understanding these factors is crucial for optimizing biochar for different agronomic and environmental applications ^[5, 6].

The feedstocks used for biochar production are diverse, ranging from agricultural residues (such as rice husk, straw, and corn stalks), forestry waste (like sawdust and wood chips), and animal manures, to more novel materials like algae and municipal solid waste ^[8, 9]. Each feedstock contributes unique elemental and structural characteristics to the resulting biochar. For instance, woody biomass typically produces biochars with high carbon content and structural stability, while manure-derived biochars tend to be richer in nutrients such as nitrogen, phosphorus, and potassium ^[6, 7].

There are several pyrolysis techniques currently in use, including slow pyrolysis, fast pyrolysis, and intermediate pyrolysis ^[3, 7]. Slow pyrolysis, characterized by lower temperatures (300-500°C) and longer residence times, is widely used for producing high-yield, carbon-rich biochar with well-developed porosity. Fast pyrolysis, conducted at higher temperatures and rapid heating rates, produces more bio-oil and less solid biochar, making it more suitable for liquid fuel production. In addition to pyrolysis, other thermochemical processes such as gasification and hydrothermal carbonization are being explored for specific use cases. These processes can yield biochars with distinct properties, including varying pH levels, surface area, and chemical reactivity ^[6, 7].

The physicochemical properties of biochar, including its surface area, porosity, pH, cation exchange capacity (CEC), and elemental composition, are central to its function as a soil amendment and carbon sink ^[7, 8]. High surface area and porosity promote water retention and provide habitats for beneficial soil microorganisms. The alkalinity of most biochars can help neutralize acidic soils, while the CEC enables nutrient adsorption and exchange, reducing leaching losses. Biochar also contains a range of functional groups (e.g., carboxyl, hydroxyl) that influence its interactions with soil nutrients, organic matter, and pollutants ^[3, 9].

Recent advances in analytical techniques have enabled more precise characterization of biochar's structural and chemical features. Tools such as BET surface area analysis, Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), and X-ray diffraction (XRD) provide detailed insights into biochar morphology and reactivity ^[5, 9]. These methods support the development of engineered biochars, designed for specific applications such as nutrient delivery, contaminant adsorption, or enhanced microbial colonization ^[4, 9].

3. Biochar for Soil Fertility Enhancement

One of the most well-documented benefits of biochar is its ability to improve soil fertility, making it an effective amendment for degraded and nutrient-poor soils. Biochar's porous structure, high surface area, and chemical composition contribute to a range of soil improvements, both physical and chemical, that directly influence plant growth and productivity ^[7, 10]. Unlike conventional fertilizers that supply nutrients in a more transient form, biochar creates lasting changes to the soil matrix, offering both immediate and long-term benefits ^[10, 11].

A key mechanism through which biochar enhances fertility is its ability to retain nutrients and reduce leaching ^[12, 13]. Its high

cation exchange capacity (CEC) allows it to adsorb and hold essential nutrients like ammonium, potassium, calcium, and magnesium, which can then be slowly released to plants. This reduces the need for repeated fertilizer application and minimizes nutrient loss through runoff or percolation. In sandy soils, which are particularly prone to nutrient leaching, biochar application has shown significant improvement in nutrient retention. In acidic soils, the typically alkaline nature of biochar can also buffer pH, making micronutrients more bioavailable and creating a more favorable environment for crop roots ^[17, 18]. Biochar also contributes to the improvement of soil physical properties. Its porous structure enhances soil aeration and water infiltration while simultaneously increasing the water-holding capacity. This dual benefit is especially important in arid and semi-arid regions, where water scarcity is a major limitation to agriculture ^[12, 13]. Improved soil structure leads to better root penetration and microbial activity, which together facilitate healthier plant development ^[9, 11].

The biological impact of biochar is another dimension of its fertility-enhancing potential. Biochar provides a habitat for beneficial soil microbes due to its pore network, which protects microbial communities from predation and environmental stress ^[11, 12]. This results in increased microbial biomass and enhanced enzymatic activities critical for nutrient cycling. When co-applied with compost or microbial inoculants, biochar often acts synergistically to promote plant growth. This microbial boost also contributes to the suppression of soil-borne pathogens, supporting plant health ^[12, 13].

Numerous field and greenhouse studies have demonstrated increased crop yields following biochar application, though the extent of this effect varies by crop type, biochar characteristics, and soil condition. For example, studies have shown yield improvements in crops such as maize, wheat, rice, and vegetables, particularly in degraded or nutrient-poor soils. In addition, meta-analyses suggest that the benefits of biochar are more pronounced when used in conjunction with organic or inorganic fertilizers, as it enhances the efficiency of nutrient uptake ^[7, 9].

However, it is important to recognize that biochar is not universally beneficial across all soil types and conditions. In fertile, well-structured soils, the yield response may be minimal. Furthermore, excessive application or the use of poorly produced biochar can potentially immobilize nutrients or introduce contaminants. Thus, site-specific assessments and biochar quality control are critical for achieving optimal results ^[11, 14].

4. Biochar in Carbon Sequestration and Climate Change Mitigation

In addition to its role in improving soil fertility, biochar is increasingly recognized for its significant potential in long-term carbon sequestration and climate change mitigation. Unlike most organic matter applied to soils—such as compost or manure—which decompose relatively quickly and return carbon to the atmosphere, biochar is highly resistant to microbial degradation ^[11, 12]. This is due to its stable aromatic carbon structure formed during pyrolysis, which can persist in the soil for hundreds to thousands of years. As a result, biochar offers a unique opportunity to sequester atmospheric carbon dioxide in a solid, soil-stable form ^[14, 15].

The carbon sequestration capacity of biochar is determined by several factors including feedstock type, pyrolysis temperature, and post-production treatment ^[15, 16]. Biochars produced at higher temperatures generally exhibit greater aromaticity and

stability, though they may contain fewer plant-available nutrients. Researchers have developed metrics such as the carbon stability index and the H/C and O/C atomic ratios to assess the long-term permanence of biochar carbon in soils. Studies using radiocarbon dating and soil incubation methods have confirmed the long residence time of biochar-derived carbon, particularly under conditions that minimize oxidation and microbial attack [17, 18].

Beyond its role in stabilizing carbon in soil, biochar has been shown to influence greenhouse gas (GHG) emissions from soils. Numerous experiments have demonstrated that biochar application can reduce methane (CH₄) and nitrous oxide (N₂O) emissions, especially in flooded or high-nitrogen environments such as paddy fields and manure-treated soils. The mechanisms involved include improved soil aeration, enhanced microbial nitrogen cycling, and sorption of labile nitrogen compounds. These reductions can further contribute to the overall greenhouse gas mitigation potential of biochar-amended systems [19, 20].

Quantifying biochar's carbon mitigation effect requires life-cycle assessment (LCA), which considers emissions from feedstock collection, transportation, pyrolysis, and application, alongside the carbon sequestration and avoided emissions in soil. In most scenarios, especially when biochar is produced from agricultural or forestry waste, the net carbon balance is highly favorable. When co-products like bio-oil and syngas are used to displace fossil fuels, the climate benefits increase further, making biochar systems a strong candidate for inclusion in national and global carbon accounting frameworks [7, 19].

This has led to growing interest in integrating biochar into voluntary and compliance-based carbon markets. Standards such as Verra's VCS Methodology VM0044 and Gold Standard guidelines now provide methodologies for calculating and verifying carbon credits from biochar projects. These developments open new revenue streams for producers and landowners, while incentivizing climate-positive land management practices. However, standardization, robust monitoring, and third-party verification remain critical to building trust and ensuring environmental integrity in carbon markets [4, 20].

As countries seek to meet their Nationally Determined Contributions (NDCs) under the Paris Agreement, biochar offers a practical and scalable option for negative emissions. Its ability to deliver co-benefits in soil health and food security makes it especially attractive in the Global South, where sustainable agriculture and climate resilience must go hand in hand [6, 9].

5. Advances in Biochar Engineering and Functionalization

While traditional biochars have demonstrated significant benefits in both agriculture and carbon sequestration, recent innovations in biochar engineering and functionalization have further enhanced their performance, specificity, and versatility. Engineered biochars are produced by modifying feedstocks, altering pyrolysis conditions, or incorporating additional substances during or after production to tailor the biochar's properties for specific applications. These advances have expanded biochar's utility beyond soil amendment into areas such as nutrient delivery, pollution remediation, and targeted carbon capture [21, 22].

One of the most important developments is the creation of nutrient-enriched or loaded biochars. These are produced by infusing biochar with essential macro- and micronutrients—such as nitrogen, phosphorus, potassium, or iron—either by co-pyrolyzing biochar with nutrient-rich materials or by post-

treatment soaking [21, 22]. These engineered biochars act as slow-release fertilizers, improving nutrient use efficiency and minimizing leaching losses [25, 26]. Their porous structure not only retains nutrients but also facilitates microbial colonization, enhancing nutrient cycling and plant uptake. In nutrient-deficient or degraded soils, nutrient-enriched biochars have shown significant promise in improving crop yields while reducing reliance on synthetic fertilizers [23, 24].

Another emerging category is composite biochars, formed by combining biochar with other materials such as clays, zeolites, or composts. These composites offer synergistic benefits—for instance, improved sorption capacity for heavy metals or enhanced microbial habitat creation. Composite biochars are being tested for use in soil remediation, particularly in areas contaminated with industrial waste or pesticides. Additionally, blending biochar with organic matter like compost improves the bioavailability of nutrients and moderates biochar's high pH, making it more suitable for sensitive soils and crops [27, 28].

One of the most cutting-edge innovations in the field is the development of nano-biochar, which involves reducing biochar to nanoscale particles to exploit high surface area and reactivity. Nano-biochars are being researched for their ability to deliver nutrients or agrochemicals more efficiently, immobilize toxic metals, and influence soil-plant-microbe interactions at a micro-environmental scale [20, 21]. Similarly, magnetic biochars, produced by incorporating iron oxides or metallic nanoparticles, are gaining traction for environmental remediation applications. Their magnetic properties enable easy separation and recovery after use, particularly in wastewater treatment and soil decontamination [19, 20].

Engineered biochars are also being designed to support biological functions, such as inoculating them with beneficial microbes or enzymes. These biochar-based biofertilizers can stimulate soil microbial diversity, suppress pathogens, and promote plant health. Recent studies show that such biochars can significantly increase plant growth while reducing the need for chemical inputs, supporting more sustainable agricultural practices [23, 24].

Despite these advances, several challenges remain in scaling engineered biochars. The complexity and cost of functionalization processes, the need for specialized production facilities, and the lack of standardized performance metrics pose barriers to widespread adoption. Furthermore, while lab-scale and greenhouse studies have demonstrated the effectiveness of engineered biochars, more field-based trials are needed to evaluate their long-term impacts and agronomic viability under diverse environmental conditions [21, 25].

6. Case Study: Biochar for Soil Restoration and Food Security in Kenya

In Kenya, a country where agriculture supports over 70% of the population, declining soil fertility remains one of the biggest constraints to food production. Over-reliance on chemical fertilizers, coupled with deforestation and unsustainable land management, has led to widespread soil degradation, particularly in smallholder farming systems. In response, several non-governmental organizations, research institutions, and community cooperatives have begun piloting the use of biochar as a soil amendment to restore productivity and improve climate resilience [26, 27].

One prominent initiative is led by The International Centre for Tropical Agriculture (CIAT) and the World Agroforestry Centre (ICRAF), which have implemented biochar trials in central and western Kenya since the early 2010s. Using locally available

feedstocks such as maize cobs, coffee husks, and cow dung, farmers produce biochar through low-cost, open-pit pyrolysis or portable kilns. The biochar is then either applied directly to the soil or co-composted before application, especially for acidic and nutrient-depleted soils [27].

Results from field trials have shown significant increases in crop yields, particularly in maize and beans—staple crops in the region. In one study conducted in Kisumu and Vihiga counties, maize yields increased by 20-60% depending on the biochar type and application method, with the most notable improvements seen in soils that were previously acidic or low in organic matter (Kätterer *et al.*, 2019). The co-application of biochar with compost was especially effective, enhancing microbial biomass and nutrient availability [26, 27].

Furthermore, biochar has contributed to climate change mitigation and adaptation in these communities. Soils treated with biochar showed improved water retention, helping crops withstand erratic rainfall and drought spells, which are increasingly common due to climate variability. Farmers also reported improved fertilizer efficiency, allowing them to reduce dependency on expensive synthetic inputs. In some areas, biochar adoption has been linked to reforestation activities, as demand for biomass residues encourages tree planting and agroforestry practices [27].

Despite these successes, several challenges remain. The lack of standardized production methods and quality control often leads to inconsistent results. Many farmers are unfamiliar with the pyrolysis process or lack the tools to produce biochar safely and efficiently. Additionally, while initial yields are promising, long-term impacts on soil ecosystems are still under study. Institutional support, training, and microfinancing have proven crucial to scaling adoption among smallholders [26, 27].

The Kenyan experience illustrates how biochar, when contextually integrated with local knowledge and participatory models, can enhance food security, regenerate soils, and build resilience in vulnerable farming systems. It also underscores the importance of coupling technological solutions with education, capacity-building, and supportive policies [26, 27].

7. Environmental and Economic Considerations

While the environmental and agronomic benefits of biochar are increasingly recognized, its broader implications—both ecological and economic—require careful evaluation to ensure responsible and scalable adoption. A well-designed biochar system must not only enhance soil health and carbon sequestration but also avoid unintended environmental risks and prove economically viable for producers, farmers, and policy stakeholders [28, 29].

From an environmental standpoint, biochar production and application can offer multiple co-benefits when managed properly. The use of agricultural residues and waste biomass for biochar avoids open burning, a common practice in many developing regions that contributes to air pollution and greenhouse gas emissions [30, 31]. Furthermore, when applied to soil, biochar can reduce the mobility of heavy metals, pesticides, and other contaminants by adsorbing them on its surface, making it a useful tool for soil and water remediation. However, environmental concerns do arise depending on feedstock quality and pyrolysis conditions. If biochar is made from contaminated biomass (such as treated wood or industrial waste), it may introduce heavy metals or persistent organic pollutants into the soil. Likewise, low-temperature pyrolysis or incomplete combustion can produce biochars with high levels of volatile organic compounds or polycyclic aromatic hydrocarbons

(PAHs), which are harmful to soil biota and potentially toxic to plants [31, 32].

Additionally, large-scale production of biochar could trigger unsustainable biomass harvesting if not properly regulated. This risk is particularly relevant in forested or biodiversity-rich areas, where biomass demand may lead to deforestation or monoculture plantations. Thus, biochar sustainability must be assessed holistically, considering land use change, biodiversity impacts, water use, and energy balance [33, 34].

On the economic side, the feasibility of biochar adoption depends on factors such as production cost, labor requirements, yield gains, market incentives, and co-benefits. Smallholder farmers often face challenges in accessing pyrolysis equipment, learning production techniques, and affording the initial investment. In many cases, locally fabricated kilns or low-tech pyrolysis pits are employed, but these can be inefficient and labor-intensive. Moreover, biochar alone rarely delivers immediate, dramatic yield gains; instead, its benefits tend to accumulate over multiple growing seasons. This lag in returns can deter adoption without supportive policies or extension services [35, 36].

Economic analysis, however, has shown that biochar can be cost-effective when integrated into circular farming systems. For example, co-composting biochar with manure or plant waste not only improves its nutrient content but also reduces methane emissions and enhances compost quality. In such systems, farmers save on fertilizer costs, increase yield stability, and generate more marketable produce. Furthermore, biochar producers can benefit from emerging carbon credit markets, especially where certification frameworks like Verra's VM0044 methodology allow for the monetization of carbon sequestration [37, 38].

Beyond on-farm benefits, biochar production can stimulate rural employment, value-added biomass use, and local enterprise development. In regions with agricultural or forestry waste surpluses, community-scale biochar projects may offer new income streams and reduce waste management costs. Some regions, such as the European Union and parts of the United States, are also experimenting with policy subsidies, tax credits, and public-private partnerships to promote biochar deployment as part of broader climate action plans [39, 40].

8. Challenges and Research Gaps

Despite the growing interest in biochar and the substantial body of evidence supporting its multifunctional benefits, several challenges and research gaps continue to limit its large-scale application and mainstream acceptance. These challenges span across the scientific, technical, social, and policy domains, and addressing them is critical for the responsible and effective deployment of biochar technologies [37, 38].

One of the primary challenges is the lack of standardization in biochar production and characterization. Because biochar properties are highly sensitive to feedstock type and pyrolysis conditions, products vary widely in chemical composition, stability, nutrient content, and physical structure [339, 40]. This variability makes it difficult to predict biochar behavior in soils, compare study outcomes, and formulate universal application guidelines. While international standards like those developed by the International Biochar Initiative (IBI) and the European Biochar Certificate (EBC) offer some guidance, more work is needed to align definitions, testing protocols, and certification systems globally [31, 33].

Another persistent gap is the site-specific nature of biochar performance. Field trials have shown inconsistent results across

soil types, climatic zones, and crop systems. For instance, biochar may significantly improve yield in acidic or sandy soils but offer minimal benefit in fertile, well-structured soils. These discrepancies underscore the need for decision-support tools and region-specific recommendations that guide farmers and land managers in selecting the appropriate type and application rate of biochar for their local conditions ^[25, 26].

Long-term effects of biochar on soil biology, nutrient dynamics, and ecosystem functioning also remain poorly understood. While short-term studies show promising outcomes, the influence of biochar on soil food webs, microbial diversity, and nutrient cycling over years or decades has not been comprehensively documented. Similarly, the interaction of biochar with fertilizers, pesticides, and organic matter under real-world field conditions is still an evolving area of inquiry. To close this gap, more long-duration, multi-season field studies are needed, particularly in tropical and subtropical regions where adoption is most urgently needed ^[27, 28].

A further challenge lies in scaling production technologies sustainably and economically. Many pyrolysis units used today are either small and inefficient or large and capital-intensive, limiting access for smallholder farmers and decentralized communities. There is a pressing need for affordable, modular, and mobile pyrolysis technologies that can process diverse feedstocks and operate under variable energy conditions. This includes innovations in low-emission kilns, batch reactors, and energy-integrated systems that utilize by-products like bio-oil or syngas for on-site use ^[28, 31].

From a policy and institutional standpoint, biochar suffers from fragmented regulatory recognition and limited integration into national climate or soil health strategies. While some countries have acknowledged biochar in their climate mitigation plans, few have dedicated financial mechanisms, subsidies, or extension programs to promote its adoption. Moreover, the nascent carbon markets for biochar—though promising—are constrained by high verification costs, limited awareness among producers, and a lack of scalable methodologies for small projects. Bridging this gap requires interdisciplinary collaboration between scientists, policymakers, carbon accounting experts, and farmer cooperatives to build inclusive governance models ^[32, 33].

Finally, there is a knowledge gap in socio-economic dimensions of biochar adoption. Most research has focused on agronomic performance and environmental benefits, with less emphasis on user behavior, cultural acceptability, gender impacts, and equitable access to technology. Understanding these dimensions is vital to ensuring that biochar solutions are not only effective but also inclusive and empowering, especially in the Global South where marginalized communities stand to benefit the most ^[34, 35].

9. Future Directions and Recommendations

As the global demand for sustainable agricultural practices and climate change solutions intensifies, biochar stands at a promising intersection of soil health restoration and carbon sequestration. To fully harness its potential, future developments must emphasize scientific rigor, technological innovation, policy integration, and socio-economic inclusion. This section outlines key directions and actionable recommendations to guide researchers, practitioners, and decision-makers toward a more impactful and scalable biochar ecosystem ^[39, 40].

First and foremost, there is a need to develop site-specific and crop-specific biochar application frameworks. Given the heterogeneity in soil types, climates, and farming systems, a

“one-size-fits-all” approach is insufficient. Future research should focus on building predictive models and decision-support systems that can match specific biochar types to localized soil conditions and agricultural needs. Leveraging artificial intelligence (AI), remote sensing, and machine learning could play a critical role in guiding precise biochar recommendations tailored for small and large farms alike ^[41, 42].

Equally important is the advancement of low-cost, decentralized pyrolysis technologies that are efficient, safe, and accessible to smallholder farmers. Mobile pyrolysis units that can process diverse, locally available biomass could reduce logistics costs and promote circular biomass economies in rural areas. Governments and development organizations should invest in pilot projects and innovation hubs to scale such technologies through public-private partnerships and farmer cooperatives ^[43, 44].

To ensure environmental integrity, future directions must also prioritize biochar quality assurance and certification systems. Establishing regionally adapted, enforceable standards especially in developing countries will be key to maintaining trust among end-users and ensuring that biochar products are both safe and effective. Certification should include parameters such as carbon content, pH, nutrient availability, heavy metal content, and carbon stability, and should be made affordable and accessible to small producers ^[39, 41].

Another critical area is the integration of biochar into climate finance and carbon market mechanisms. While initiatives like Verra and Gold Standard have introduced biochar methodologies, broader policy support is necessary to mobilize climate finance at scale. Governments should include biochar in their Nationally Determined Contributions (NDCs) and carbon trading frameworks. Meanwhile, researchers should continue to refine monitoring, reporting, and verification (MRV) tools to make carbon credit generation from biochar more transparent, scalable, and farmer-friendly ^[43, 44].

Moreover, interdisciplinary and participatory research approaches must be strengthened. Collaborations between soil scientists, climate experts, economists, social scientists, and community stakeholders can ensure that biochar strategies are not only scientifically robust but also socially equitable and culturally appropriate. Participatory trials, farmer-led experiments, and gender-sensitive programs can enhance adoption rates and bring real-world feedback into the research loop ^[31, 34].

Educational outreach and capacity-building will also play a pivotal role in mainstreaming biochar. Universities, extension services, and NGOs should integrate biochar training into existing agricultural curricula and field programs. Demonstration plots, farmer field schools, and digital knowledge-sharing platforms can help build awareness and technical know-how at the grassroots level ^[36, 37].

Finally, future directions should align biochar deployment with broader regenerative and circular economy models. Biochar can play a transformative role when embedded in systems that integrate composting, agroforestry, cover cropping, and waste valorisation. Its co-benefits in reducing waste, improving soil organic matter, enhancing crop resilience, and stabilizing carbon make it a valuable tool for systemic agricultural transformation ^[41, 43].

10. Conclusion

Biochar has emerged as a powerful, multifaceted solution in the pursuit of sustainable agriculture and climate resilience. Its ability to simultaneously enhance soil fertility, improve water

retention, support microbial life, and sequester carbon makes it uniquely suited to address the intertwined challenges of food security and environmental degradation. Grounded in centuries-old practices and backed by modern science, biochar offers a compelling example of how traditional knowledge and innovation can intersect to create sustainable land management strategies.

This review has explored the evolving landscape of biochar—from its diverse feedstocks and production methods to its engineered enhancements and integration into soil and carbon systems. Evidence from laboratory experiments, field trials, and real-world case studies confirms its value as a soil amendment, particularly in low-fertility and degraded environments. Moreover, biochar's high carbon stability and ability to reduce greenhouse gas emissions position it as a critical tool in global efforts to mitigate climate change.

However, realizing biochar's full potential will require concerted efforts to overcome technical, economic, and policy-related barriers. Standardizing quality control, tailoring site-specific applications, scaling decentralized pyrolysis technologies, and integrating biochar into national carbon strategies are all essential next steps. Equally important is the inclusion of smallholder farmers, marginalized communities, and youth in biochar value chains, ensuring that its benefits are equitably distributed.

As the world moves toward regenerative agriculture and nature-based climate solutions, biochar represents not just a product, but a platform—one that bridges carbon management, soil health, and sustainable livelihoods. Its successful deployment will depend on interdisciplinary collaboration, long-term field research, and policy support that align environmental goals with social and economic realities.

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