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Biochar: Advancing Agriculture, Environmental Conservation, and Climate Resiliency with Carbon

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Abstract

Since the early 2000s, research on biochar, a carbon-rich material produced through the thermochemical conversion of organic waste, has surged, with over 30,000 peer-reviewed articles highlighting its diverse environmental benefits. Recognized by the Intergovernmental Panel on Climate Change as a negative emission technology, biochar can sequester carbon long-term, contributing to climate change mitigation. It improves soil health by enhancing soil structure, increasing water-holding capacity, and promoting nutrient cycling. Additionally, biochar applications significantly reduce greenhouse gas emissions, such as nitrous oxide (N2O) and ammonia (NH3), and decrease nitrate leaching, improving water quality. Despite these advantages, the widespread adoption of biochar remains limited due to market challenges and profitability concerns, particularly in the United States. Legislative and regulatory support is essential for broader adoption. Comprehensive cost-effectiveness analyses, controlled environment studies, long-term field monitoring, and standardized guidelines are necessary to demonstrate biochar's economic and environmental benefits. Education and outreach efforts are crucial to raise awareness among farmers and other stakeholders. This article aims to raise awareness of the need for education, research, and investment in biochar research to enhance ecological, environmental, and agricultural practices and better inform industry and policymakers. Collaboration among researchers, policymakers, and practitioners is vital to integrate biochar into sustainable agriculture and environmental conservation strategies, unlocking its full potential for ecological and economic benefits.

Keywords: Biochar; Terra Preta; Education; Ecology; Economics; Carbon Negative; Sustainability; Urban Forestry; Agriculture; Water Quality; Bioremediation; Green Carbon

Abbreviations: IPCC: Intergovernmental Panel on Climate Change; NET: Negative Emission Technologies; SOM: soil organic matter; SOC: soil organic carbon; BMP: Best Management Practice

Introduction

Since rediscovering Terra Preta soils, also known as "Dark Earth," in the Amazon Basin in the early 2000s [1], the international scientific community has published over 30,000 peer-reviewed articles on biochar. There has been a notable surge in publications over the past decade, with approximately 80% of these articles emerging in the last five years [2]. Despite significant progress in research, the widespread adoption of biochar applications remains limited. Nonetheless, numerous studies have highlighted biochar's significant environmental benefits. This research progress has brought global attention to biochar as a solution to various environmental challenges. This article aims to raise awareness about the significance of biochar as an environmental and agricultural amendment and emphasizes the critical need for collaboration and investment in this field. This article does not seek to cover all existing literature on the topic but rather to serve as a springboard for those wishing to learn more and for those seeking clear and concise information to support biochar initiatives.

Biochar, a durable carbon-rich material similar to charcoal, is produced through the thermochemical conversion of organic matter such as wood waste, green waste, biosolids, and manures in an oxygen-free environment. This ancient technique, initially used by Amazon Basin cultures to improve soil fertility, predates modern fertilizers. Unlike compost or other carbon sources, biochar remains stable in soil for thousands, potentially millions, of years, acting as a long-term carbon sink. The Intergovernmental Panel on Climate Change (IPCC) recognizes biochar as a negative emission technology alongside reforestation and soil restoration [3,4]. According to the IPCC, biochar has the potential to remove 2.6 billion tons of carbon dioxide (CO_2) annually globally. For context, other Negative Emission Technologies (NETs) include (but are not limited to) afforestation or reforestation, soil carbon sequestration, and enhanced rock weathering.

Various feedstock sources can be used to produce biochar using different technologies. The resulting biochar's properties depend on the feedstock type, temperature during pyrolysis, heating time, additives used, and other factors facilitating a custom-made biochar tailored to specific environmental and stakeholder needs. Not all biochar performs the same way; thus, selecting the appropriate source and processing and applying biochar in the correct place at the correct rate is crucial [5,6]. Despite a general agreement in the scientific community of great variability in types and uses of biochar, the primary literature generally agrees on the benefits of biochar for soil health and subsequent agricultural and ecosystem services [7].

Application and Use

The European Union uses biochar in various applications, including urban landscaping, stormwater management, structural soils, agriculture, animal feed, and building materials. With numerous production facilities across Europe, the demand for biochar has consistently grown, doubling annually for the past decade [8]. European markets also benefit from the energy generated during biochar production, which can be converted into high-value heat and electricity. Europe's voluntary carbon market is also thriving and expanding rapidly. In the United States, the biochar market has grown exponentially in recent years, primarily due to the recovery of biochar from existing biomass energy facilities and the development of new production facilities. However, obtaining reliable information on the volume of biochar produced is challenging, largely attributable to market competition. Unlike Europe, the US struggles to maintain profitability, as opportunities for heat repurposing are limited, and low electricity prices and waste tipping fees for organic feedstocks pose challenges.

Despite these obstacles, biochar sales in the US are increasing, with early-entry companies benefiting from growing voluntary carbon markets. Significant growth is seen in biomass energy facilities modifying their operations to extract high-carbon fly ash. Additionally, communities focused on climate resilience are considering biochar as a mechanism to meet carbon reduction commitments. Biochar, as a fixed carbon product, functions as a carbon sink and is classified by the Intergovernmental Panel on Climate Change (IPCC) as a negative emission technology (NET) [3]. Evaluations of biochar production facilities indicate that for each ton of biochar produced, there is a net reduction of 2-3 metric tons of CO_2 equivalent. This positions biochar as a carbon-negative, cost-effective absorbent with significant potential for climate change mitigation and various environmental benefits, including energy development [7]. In contrast to activated carbon, predominantly derived from bituminous coal, lignite coal, and coconut shells, biochar is a climate-friendly green carbon. Its production and utilization can substantially contribute to the circular economy [9-11].

Soil Health and Environmental Benefits

A meta-analysis by Omondi et al. [12] demonstrated that biochar application significantly enhances soil structure and functionality, decreasing soil bulk density by an average of 8% following biochar amendment. Additionally, soil porosity and aggregate stability were shown to increase by 8%, available water-holding capacity by 15%, and saturated hydraulic conductivity by 25% [13]. The impact of biochar on plant-available water varies with soil texture, showing the most significant improvements in coarse-textured (sandy) soils, with a 47% increase in available water, compared to a 9% increase in medium-textured soils and negligible effects in fine-textured (clayey) soils [14]. These findings suggest that using biochar based on soil texture can optimize water relations and maximize its benefits. Furthermore, biochar applications are associated with significant reductions in nitrous oxide (N_2O) emissions and nitrate (NO_3^-) leaching, addressing critical environmental concerns. Field studies reported an average 12.4% reduction in N_2O emissions, while a broader analysis of 88 studies observed a 38% reduction in N_2O emissions in the first year [15]. Bekchanova et al. [16] found that N_2O emissions decreased by 29% in sandy soils. Biochar also significantly reduces NO_3^- losses from soil, with reductions averaging 26% to 32% in studies with observation periods of at least 30 days [15].

The interaction between biochar and native soil organic matter (SOM), known as priming, affects the mineralization rates of SOM [17]. Biochar additions can result in positive priming, increasing SOM mineralization rates, and negative priming, slowing decomposition and contributing to SOM accumulation [18]. Positive priming effects are typically short-term (< 2 years) [19,20], followed by long-term negative priming (more than two years) [21]. These priming differentials substantially increase native soil organic carbon (SOC) content, with soils showing a 40% higher SOC content after three years of biochar application relative to untreated soils [20]. Bai et al. [22] found that biochar outperformed other climate-smart agricultural practices, resulting in a 39% increase in SOC. Biochar also significantly enhances nutrient cycling and efficiency, increasing soil phosphorus and nitrogen availability. A meta-analysis by Gao et al. [23] showed that biochar applications increased available phosphorus in the topsoil by 45% and phosphorus in microbial biomass by

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48%, which is especially beneficial in phosphorus-limited soils. The same study noted a 12% reduction NO_3^- and an 11% decrease in ammonium content in topsoil, indicating biochar's ability to improve nutrient use efficiency and reduce fertilizer requirements. A systematic review by Schmidt et al. [7] effectively delineated the multifaceted benefits of biochar in agriculture, highlighting its significant impact on soil properties, nutrient cycling, and carbon sequestration. These advantages enhance agricultural productivity and provide substantial ecological benefits, making biochar crucial in sustainable agricultural practices and environmental conservation efforts.

Progress in Government Policies and Initiatives

Government legislation, policies, and guidelines significantly influence environmental outcomes. For example, the United States federal government frequently leverages legislation to advance innovation, technology, and sustainable practices nationally, including biochar initiatives. Since approximately 2010, various federal agencies, including the US Forest Service, Department of Agriculture, Natural Resource Conservation Service, and the Department of Energy, have been actively engaged in biochar research and testing. Recent legislative activities include provisions for biochar in the Infrastructure Investment and Jobs Act (HR 3684 – 117th Congress 2021-2022), allocating $200 billion to the Secretary of Interior and Agriculture; the Biochar Act of 2021 (HR 2581 – 117th Congress 2021-2022); and the National Biochar Research Network Act of 2022 (S. 4895 by Grassley, Tester, Thune, and Brown). Additionally, the NRCS 808/336 Soil Carbon Amendments, USDA Climate-Smart Commodities, and the USFS Wood Innovations Program have been approved for use in all but six states. The state of Washington (US) has enacted SB/HR 5961 (2021-2022), incentivizing state and local governments to utilize biochar in government contracts, while Colorado State has passed HBN23-1069 (2021-2022) to investigate the use of biochar in capping abandoned gas and oil wells. Other states in the US, including Maine, New York, Vermont, and Nebraska, are also developing biochar legislation [24].

Recent and Needed Advancements

Recent investigations have demonstrated biochar's versatility as a compost additive, highlighting its effectiveness in mitigating odor emissions, enhancing nutrient cycling, improving compost quality, and increasing carbon sequestration in soil. Incorporating biochar into composting processes significantly influences nutrient dynamics, particularly concerning nitrogen and phosphorus. Nguyen et al. [25] emphasized biochar's role in reducing nutrient losses due to its adsorptive properties and ability to enhance microbial activity. Their research demonstrated that adding just 10% biochar to compost mixtures could reduce nitrogen loss by up to 50% and increase phosphorus availability for plants by 18%. Biochar's porous structure provides an optimal habitat for microorganisms, facilitating the transformation and stabilization of nutrients within the compost [26]. Similarly, Steiner and Harttung [27] reported a 64% reduction in ammonia (NH_3) emissions with a 20% biochar inclusion in compost. Biochar's unique properties, including high porosity, hydrophobicity, and substantial carbon content, make it an effective sorbent for odorous gases. Nguyen et al. [25] observed a 30-50% decrease in NH3 and hydrogen sulfide (H_2S) emissions with a 10% biochar amendment. Additionally, they reported a 45% reduction in overall odor emissions in biochar-amended composts compared to those without such amendments.

There is an ongoing need for comprehensive cost-effectiveness analyses of biochar amendments to answer questions about what kind to use, when to use it, how long it will last, and what to do with waste or saturated biochar. These details are crucial to advocating for biochar as a Best Management Practice (BMP) and quantifying the relatively small incremental costs and significant benefits for environmental and agricultural improvement. These analyses can build on previous research, similar to Price et al. [28], who synthesized previous research to estimate the costs of stormwater and agricultural practices for reducing nitrogen and phosphorus runoff in Maryland, US. Long-term field monitoring is critical to establish biochar applications' long-term benefits in agriculture, urban landscapes, and forests. Leveraging opportunities and partnerships with stakeholders, including state and local municipalities, non-profits, universities, and private industry, is also essential [29-31]. Expanding the reimbursement structure for biochar applications to include additional ecosystem service co-benefits is also needed to incentivize broader adoption. Providing multiple business case studies highlighting the circular economy benefits of biochar, such as job creation, energy production, and climate change mitigation, can also support this effort. Moreover, developing specific guidance and specifications for using biochar in treatment applications will address a critical gap in current regulatory processes [9,11,32]. Ultimately, educating end-users on current specifications, application methods, and purchasing options for biochar is vital for consumer acceptance and adoption.

Conclusion

The extensive body of research on biochar underscores its potential as a versatile and impactful tool in agricultural and environmental management. Despite the surge in scientific publications and the recognized benefits of biochar, its widespread adoption remains limited. Biochar production through the thermochemical conversion of organic waste materials provides a sustainable method of waste management while simultaneously generating a stable, carbon-rich product. Its stability in soil for thousands of years, or much longer, positions biochar as a crucial component in long-term carbon sequestration strategies. The IPCC's recognition of biochar as a negative emission technology (NET) further validates its role in mitigating climate change. Research consistently indicates that biochar improves soil health and agricultural crops by enhancing soil structure, increasing

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water-holding capacity, and promoting nutrient cycling, particularly in coarse-textured soils. Furthermore, biochar applications significantly reduce greenhouse gas emissions, such as nitrous oxide (N_2O) and ammonia (NH_3), and decrease nitrate (NO_3^-) leaching, thereby improving water quality in sensitive ecosystems.

Despite these benefits, the biochar market has numerous challenges, particularly in the United States, where profitability concerns arise from limited heat repurposing opportunities, low electricity prices, and low waste tipping fees for organic feedstocks. Legislative and regulatory support is critical to overcoming these barriers. Recent initiatives, such as the United States Infrastructure Investment and Jobs Act and the Biochar Act of 2021, reflect growing recognition of biochar's potential. For example, state-level efforts in Washington, Colorado, and other states exploring biochar applications in various contexts. However, comprehensive cost-effectiveness analyses, long-term field monitoring, and standardized guidelines based on biochar source, application rate, and soil type are necessary to enhance its adoption. Education and outreach efforts are crucial to raising awareness among farmers and potential users about biochar's benefits and application methods. To reveal biochar's full potential in promoting sustainable agriculture and environmental conservation, renewed and aggressive investment, incentives, and collaboration among researchers, policymakers, and practitioners are required.

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