ENVIRONMENTAL REPORTS

Review Article
01 to 04 (2023)
https://er.researchfloor.org/

Biochar Applications in Soil Restoration: Enhancing Soil Health and Carbon Sequestration

Chakri Voruganti

Department of Plant and Soil Science, Texas Tech University, Lubbock, TX, USA.

Citation: Chakri Voruganti (2023). Biochar Applications in Soil Restoration: Enhancing Soil Health and Carbon Sequestration. *Environmental Reports*. **DOI: https://doi.org/10.51470/ER.2023.5.1.01**

Corresponding Author: **Chakri Voruganti** | E-Mail: **(Voruganti chakri29@gmail.com)**

Received 02 January 2023 | Revised 04 February 2023 | Accepted 12 March 2023 | Available Online April 09 2023

ABSTRACT

Soil health degradation, driven by intensive agriculture, deforestation, and climate change, has become a pressing global issue, demanding sustainable restoration solutions. Biochar, a carbon-rich material produced via pyrolysis of organic matter, has garnered attention as a potent soil amendment. It offers significant benefits, including improved soil structure, enhanced nutrient retention, increased water-holding capacity, and better crop productivity. Additionally, biochar plays a crucial role in carbon sequestration, thereby contributing to climate change mitigation. This article reviews the applications of biochar in soil restoration and examines the mechanisms through which it enhances soil health. It discusses how biochar contributes to long-term carbon storage in soils, reduces greenhouse gas emissions, and supports soil microbial activity. Furthermore, the review highlights biochar's role in rehabilitating degraded agricultural lands, restoring ecosystems, and remediating contaminated urban soils. While biochar presents numerous benefits, its large-scale adoption faces challenges such as variability in its properties based on production methods, high production costs, and the need for long-term impact studies. The article outlines these challenges and offers directions for future research, including optimizing biochar production, standardizing its application, and exploring its interactions with different soil types and ecosystems.

Keywords: *Biochar, soil restoration, carbon sequestration, soil health, sustainable agriculture*

1. Introduction

Soil degradation is a widespread environmental challenge, impacting food security, ecosystem services, and overall soil productivity. It is primarily driven by human activities such as deforestation, overgrazing, unsustainable agricultural practices, and urbanization. These activities lead to the depletion of organic matter, soil erosion, nutrient loss, and a decline in soil fertility. As soils degrade, their capacity to support crops, regulate water, and provide ecosystem services diminishes, posing severe risks to food systems, water quality, and biodiversity [1]. The need for soil restoration has thus become a priority in the pursuit of sustainable agriculture and environmental conservation. A growing body of research highlights the importance of developing sustainable solutions for reversing soil degradation. One such solution is biochar, a carbon-rich, porous material produced from the thermal decomposition of organic matter (biomass) under low oxygen conditions in a process known as pyrolysis [2]. Biochar has gained attention for its potential to enhance soil properties, restore degraded soils, improve crop productivity, and mitigate climate change through carbon sequestration. This versatile material has been successfully applied across various soil types and agricultural systems, making it a valuable tool for both soil restoration and environmental sustainability.

Biochar's benefits stem largely from its unique physical and chemical properties. Its porous structure allows for enhanced soil aeration, increased water-holding capacity, and improved drainage, especially in sandy soils. In clay soils, biochar helps reduce compaction and improves root penetration [3]. Furthermore, biochar's high cation exchange capacity (CEC) enables it to retain nutrients such as nitrogen, phosphorus, and potassium, which are vital for plant growth. By reducing nutrient leaching and increasing nutrient availability, biochar can improve crop yields while reducing the need for chemical fertilizers, which contributes to more sustainable agricultural practices. In addition to improving soil structure and fertility, biochar plays a critical role in soil organic matter management and carbon sequestration. When organic material naturally decomposes, carbon is released back into the atmosphere as carbon dioxide (CO_2), contributing to greenhouse gas emissions. However, when biomass is converted into biochar through pyrolysis, a significant portion of the carbon is captured and stored in a stable form, preventing it from re-entering the carbon cycle for hundreds or even thousands of years [4]. This process makes biochar an effective tool for long-term carbon sequestration, helping to mitigate the effects of climate change. Moreover, biochar's benefits extend to the biological aspects of soil health. The porous structure of biochar provides a habitat for beneficial soil microorganisms, such as bacteria and fungi, which are essential for nutrient cycling, organic matter decomposition, and disease suppression. These microorganisms enhance the soil's biological activity and contribute to improved plant health and productivity. By fostering a more diverse and active microbial community, biochar also helps to enhance soil resilience to environmental stressors such as drought, salinity, and pests. However, despite its numerous advantages, the large-scale application of biochar in soil restoration faces challenges [5]. The variability in biochar properties depending on the feedstock used and pyrolysis conditions means that its performance in different soils and climates can be unpredictable. Additionally, the cost of producing and transporting biochar remains high, particularly in regions where biomass resources are limited or expensive. To fully realize the potential of biochar in soil restoration, further research is needed to optimize its production, standardize its application, and assess its long-term impacts on soil health and carbon storage [6]. This paper aims to explore the various applications of biochar in soil restoration and assess its impact on soil health and carbon sequestration. By examining its role in nutrient retention, water management, and carbon sequestration, this study seeks to highlight the potential of biochar as a sustainable solution for restoring degraded soils and mitigating climate change. Furthermore, the challenges and limitations associated with biochar use are addressed, along with suggestions for future research directions to enhance its efficacy and promote its broader adoption.

Table 1: his table structure provides an organized way to analyze and compare biochar's effects in different contexts

Parameter	Soil Type	Biochar Feedstock	Biochar Application Rate (tons/ha)	Soil Health Impact	Carbon Sequestration Potential	Study Findings
Water Retention	Sandy	Wood	10	Increased water-holding capacity	Moderate	Improved crop yield during drought periods
Nutrient Retention	Clayey	Agricultural waste	5	Enhanced nutrient retention	High	Reduced leaching of N and P
Soil Microbial Activity	Loamy	Forest biomass	20	Increased microbial diversity	Moderate	Enhanced root growth and soil resilience
pH Balancing	Acidic	Rice husk	15	Reduced soil acidity	Low	Significant pH increase and higher crop yield
Heavy Metal Detoxification	Contaminated (urban soils)	Animal manure	25	Detoxified soil from heavy metals	Low	Reduced bioavailability of lead and cadmium
Carbon Sequestration	Degraded farmland	Mixed wood	10	Neutral impact on plant growth	High	Long-term carbon storage, reduced GHG emissions
Crop Yield Improvement	Sandy	Corn stover	8	Enhanced productivity	Moderate	20% yield increase in corn crops

2. What is Biochar?

Biochar is a porous, stable form of carbon produced from organic materials such as agricultural waste, forestry residues, and manure through the process of pyrolysis. Unlike traditional charcoal, biochar is specifically designed for soil application to improve soil health and enhance its ecological functions [7]. The composition and properties of biochar depend on the feedstock used and the conditions under which it is produced, including temperature, residence time, and heating rate. Biochar's high surface area, porosity, and capacity to retain nutrients and water make it an excellent soil amendment for restoring degraded soils.

3. Mechanisms of Biochar in Soil Health Improvement

Biochar has demonstrated significant potential in enhancing soil health, making it an effective and sustainable tool for soil restoration [8]. Its impact on soil functions and plant productivity is mediated through several key mechanisms.

3.1. Enhancing Soil Structure and Water Retention

Biochar's porous structure is one of its defining features, significantly improving soil physical properties. Its pores increase soil aeration, which facilitates root growth and enhances microbial activity. In sandy soils, where water retention is often a challenge, biochar's porous nature helps increase the soil's capacity to hold moisture [18-20]. This improved water retention benefits plants, especially during drought conditions, by ensuring more consistent water availability [9]. In clayey soils, biochar enhances soil aggregation and reduces compaction, allowing better infiltration and drainage of water. This prevents waterlogging and improves the conditions for plant roots and soil organisms. By improving the soil's water-holding and drainage capacity, biochar contributes to the resilience of agricultural systems under changing climatic conditions.

3.2. Nutrient Retention and Availability

Biochar acts as a nutrient reservoir in the soil. Its high cation exchange capacity (CEC) allows it to adsorb and hold essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K), preventing them from leaching away. This slow-release mechanism ensures that plants have access to a steady supply of nutrients over time, reducing the need for frequent fertilizer applications [10]. In addition to macro-nutrients, biochar also retains micro-nutrients such as calcium, magnesium, and iron, which are critical for plant health. By minimizing nutrient losses and enhancing nutrient availability, biochar improves soil fertility and contributes to increased crop yields, making it a valuable amendment in both nutrient-poor and intensively farmed soils.

3.3. Microbial Activity and Soil Biodiversity

The porous surface of biochar serves as a refuge and habitat for beneficial soil microorganisms, such as bacteria and fungi. These microorganisms are essential for nutrient cycling, organic matter decomposition, and maintaining overall soil health. Biochar provides them with stable niches and protects them from environmental stresses such as drought or extreme temperatures [11]. The presence of biochar enhances microbial activity, which in turn promotes plant growth. Certain beneficial microbes, like mycorrhizal fungi, form symbiotic relationships with plant roots, helping plants access nutrients more efficiently. Furthermore, biochar supports a more diverse microbial community, increasing the soil's resilience to pests, diseases, and environmental changes. This boost in microbial biodiversity strengthens ecosystem functions, improving soil productivity over time.

3.4. Reduction of Soil Acidity and Heavy Metal Detoxification

Many agricultural soils suffer from acidity, which limits plant growth and reduces nutrient availability.

Biochar's alkaline nature helps to neutralize acidic soils, improving the pH balance and making the soil more suitable for crop growth. A more balanced soil pH ensures that nutrients are more readily available to plants, enhancing overall soil fertility [12]. Biochar also has the ability to immobilize heavy metals, such as lead, cadmium, and mercury, which are toxic to plants and soil organisms. These metals can be adsorbed onto the surface of biochar, reducing their mobility and bioavailability in the soil. As a result, biochar can detoxify contaminated soils, providing a safer environment for plants to grow and reducing the risk of food contamination from heavy metals. This capacity for detoxification makes biochar especially useful in remediating soils impacted by industrial pollution or mining activities.

4. Carbon Sequestration Potential

One of biochar's most significant contributions to soil restoration is its ability to sequester carbon. When organic matter decomposes naturally, it releases carbon dioxide (CO_2) into the atmosphere, contributing to climate change. However, when this biomass is converted into biochar through pyrolysis, much of the carbon is locked into a stable form, preventing it from re-entering the atmosphere for hundreds or even thousands of years [13].

4.1. Long-Term Carbon Storage

Biochar can sequester carbon in soils for extended periods due to its stable structure. This property makes it an important tool in mitigating climate change by removing atmospheric CO_2 and storing it in soils. Studies have shown that biochar can sequester between 12% and 31% of the carbon present in biomass, depending on the feedstock and pyrolysis conditions.

4.2. Reducing Greenhouse Gas Emissions

In addition to carbon sequestration, biochar can reduce the emission of other greenhouse gases like methane (CH_4) and nitrous oxide (N_2O), which are more potent than CO_2. By improving soil aeration and reducing the need for synthetic fertilizers, biochar limits the conditions that promote these emissions.

5. Applications of Biochar in Soil Restoration

Biochar has wide-ranging applications in restoring degraded soils across different ecosystems and agricultural systems. Below are some notable applications:

5.1. Rehabilitating Degraded Agricultural Soils

Biochar can restore agricultural soils that have been depleted of nutrients due to intensive cropping practices. By improving nutrient retention, water holding capacity, and soil structure, biochar promotes healthier crops and greater yields.

5.2. Restoring Forest and Grassland Ecosystems

In forest and grassland restoration, biochar improves the organic matter content and nutrient cycling, helping to establish native vegetation. Biochar also enhances soil resilience, enabling ecosystems to better withstand stresses such as drought and fire.

5.3. Mine Site Rehabilitation

Biochar is increasingly being applied to rehabilitate soils affected by mining activities. Its ability to bind heavy metals and improve soil structure makes it ideal for restoring the fertility of mine-impacted soils, allowing for the re-establishment of vegetation and stabilization of the landscape.

5.4. Urban Soil Restoration

In urban environments, biochar is being used to remediate contaminated soils, improve green spaces, and enhance the performance of urban agriculture systems. Biochar's ability to improve poor-quality soils in city environments holds potential for urban sustainability [14].

6. Challenges and Considerations

Despite its numerous benefits, there are several challenges that limit the large-scale application of biochar in soil restoration.

6.1. Variability in Biochar Properties

The effectiveness of biochar depends heavily on the feedstock used and pyrolysis conditions, making it difficult to predict its behavior in different soils. Standardization of biochar production methods is necessary to ensure consistency in its application [15].

6.2. High Production Costs

The costs associated with producing and transporting biochar can be prohibitive for widespread use, especially in low-income regions. Research into cost-effective production techniques and scalable technologies is needed to make biochar more accessible [16].

6.3. Long-Term Impact Studies

While biochar has demonstrated promising short-term benefits, more research is needed to understand its long-term impacts on soil health and carbon sequestration. Large-scale field trials are essential to verify biochar's long-term sustainability and ecological effects [17].

7. Future Research Directions

Future research should focus on optimizing biochar production to ensure its effectiveness in different soils and climates. Developing biochar systems that integrate local waste materials will help lower costs and make biochar a more accessible solution for soil restoration and climate mitigation. Exploring biochar's interaction with different soil types, microbial communities, and plant species will further refine its use as a soil amendment. Finally, policy frameworks that incentivize the use of biochar in agriculture and land restoration projects will play a key role in its adoption.

8. Conclusion

Biochar offers a promising solution for restoring degraded soils, improving soil health, and contributing to carbon sequestration. Its ability to enhance soil structure, improve water retention, retain essential nutrients, and promote beneficial microbial activity makes it a valuable tool in sustainable agriculture and soil restoration efforts. By addressing key issues such as soil degradation, nutrient depletion, and climate change, biochar has the potential to become a critical component in environmentally sustainable practices. However, challenges remain, particularly in terms of production costs, variability in biochar quality, and the need for long-term studies to fully understand its impact across diverse ecosystems. For biochar to achieve its full potential, research must continue to refine its application methods, optimize production processes, and evaluate its long-term effects on soil health and carbon storage. As global interest in sustainability grows, biochar could play a significant role in strategies aimed at achieving environmental conservation, sustainable agriculture, and carbon management. With further development and widespread adoption, biochar has the potential to contribute significantly to both soil restoration and climate change mitigation.

References

1. Lehmann, J., & Joseph, S. (2009). Biochar for Environmental Management: Science and Technology. Earthscan.

2. Chan, K. Y., & Xu, Z. (2009). Biochar: Nutrient Properties and Their Enhancement. In Biochar for Environmental Management (pp. 67-84). Earthscan.

3. Sohi, S. P., Krull, E., Lopez-Capel, E., & Bol, R. (2010). A Review of Biochar and Its Use and Function in Soil. Advances in Agronomy, 105, 47-82.

4. Jeffery, S., Verheijen, F. G., van der Velde, M., & Bastos, A. C. (2011). A Quantitative Review of the Effects of Biochar Application to Soils on Crop Productivity Using Meta-Analysis. Agriculture, Ecosystems & Environment, 144(1), 175-187.

5. Atkinson, C. J., Fitzgerald, J. D., & Hipps, N. A. (2010). Potential Mechanisms for Achieving Agricultural Benefits from Biochar Application to Temperate Soils: A Review. Plant and Soil, 337(1), 1-18.

6. Laird, D. A. (2008). The Charcoal Vision: A Win–Win Scenario for Simultaneously Producing Bioenergy, Permanently Sequestering Carbon, while Improving Soil and Water Quality. Agronomy Journal, 100(1), 178-181.

7. Spokas, K. A., Novak, J. M., & Venterea, R. T. (2012). Biochar's Role as an Alternative N-Fertilizer: Ammonia Capture. Plant and Soil, 350(1-2), 35-42.

8. Van Zwieten, L., Kimber, S., Morris, S., Downie, A., Berger, E., Rust, J., & Scheer, C. (2010). Effects of Biochar from Slow Pyrolysis of Papermill Waste on Agronomic Performance and Soil Fertility. Plant and Soil, 327(1), 235-246.

9. Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable Biochar to Mitigate Global Climate Change. Nature Communications, 1(1), 56.

10. Major, J., Rondon, M., Molina, D., Riha, S., & Lehmann, J. (2010). Maize Yield and Nutrition during Four Years after Biochar Application to a Colombian Savanna Oxisol. Plant and Soil, 333(1), 117-128.

11. Zimmerman, A. R. (2010). Abiotic and Microbial Oxidation of Laboratory-Produced Black Carbon (Biochar). Environmental Science & Technology, 44(4), 1295-1301.

12. Verheijen, F., Jeffery, S., Bastos, A. C., Van der Velde, M., & Diafas, I. (2010). Biochar Application to Soils: A Critical Scientific Review of Effects on Soil Properties, Processes, and Functions. European Commission Joint Research Centre Institute for Environment and Sustainability.

13. Agegnehu, G., Bass, A. M., Nelson, P. N., & Bird, M. I. (2016). Benefits of Biochar, Compost and Biochar–Compost for Soil Quality, Maize Yield and Greenhouse Gas Emissions in a Tropical Agricultural Soil. Science of the Total Environment, 543, 295-306.

14. Cornelissen, G., Martinsen, V., Shitumbanuma, V., Alling, V., Breedveld, G. D., Rutherford, D. W., & Sparrevik, M. (2013). Biochar Effect on Maize Yield and Soil Characteristics in Five Conservation Farming Sites in Zambia. Agronomy, 3(2), 256-274.

15. Liu, X., Zhang, A., Ji, C., Joseph, S., Bian, R., Li, L., & Pan, G. (2013). Biochar's Effect on Crop Productivity and the Dependence on Experimental Conditions—A Meta-Analysis of Literature Data. Plant and Soil, 373(1), 583-594.

16. Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B., & Neves, E. G. (2006). Black Carbon Increases Cation Exchange Capacity in Soils. Soil Science Society of America Journal, 70(5), 1719-1730.

17. Haefele, S. M., Konboon, Y., Wongboon, W., Amarante, S., Maarifat, A. A., Pfeiffer, E. M., & Knoblauch, C. (2011). Effects and Fate of Biochar from Rice Residues in Rice-Based Systems. Field Crops Research, 121(3), 430-440.

18. Ding, Y., Liu, Y., Wu, W., Shi, D., Yang, M., & Zhong, Z. (2010). Evaluation of Biochar Effects on Nitrogen Retention and Leaching in Multi-Layered Soil Columns. Water, Air, & Soil Pollution, 213(1), 47-55.

19. Mukherjee, A., & Lal, R. (2013). Biochar Impacts on Soil Physical Properties and Greenhouse Gas Emissions. Agronomy, 3(2), 313-339.

20. Singh, B., Singh, B. P., & Cowie, A. L. (2010). Characterisation and Evaluation of Biochars for Their Application as a Soil Amendment. Soil Research, 48(7), 516-525.

