STAC Biochar Literature Review

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Introduction

Biochar is defined by the US Department of Agriculture's Agricultural Research Service as black carbon produced from biomass sources for the purpose of transforming the biomass carbon into a more stable form. This stable form of carbon sequestration can be leveraged in a multi-pronged approach towards water/soil remediation and resilience building.

The research performed had four intertwined areas of focus whose nexus was the use of biochar to assist with reducing the TMDL of the Chesapeake Bay. These areas are Agriculture and Forestry, Toxins, Emerging Contaminants, and Stormwater Management, and Policy, Sustainability, Resiliency, and Economics.

This literature review assesses the remediation, soil improvement, and waste reuse capabilities of bio-charcoal (biochar) by coalescing and synthesizing the last decade of English-language research and reviews into a cohesive document made for decision makers to highlight the viability of biochar as a multipurpose soil and wetland amendment for the Chesapeake Bay watershed. Biochar's viability comes from its thoroughly documented ability to consistently boost phyto-agricultural output, sequester nutrients, neutralize toxins, improve water retention in soil, enable beneficial microorganism propagation, and be cost effective.

Biochar can be advantageous in that it has strong absorption, immobilization, aging properties, excellent electron transfer ability, and is a sustainable way to repurpose waste biomass. Biochar can effectively immobilize heavy metals and promote the circular economy.[1] However, biochar can be detrimental because the different feedstocks and pyrolysis temperatures lead to different properties of biochar which might induce toxicity inhibition in ADs and in soil.[2] This does not detract from its viability but should be noted moving forward as no soil amendment is perfect across the board.

[1] Sachdeva S, Kumar R, Sahoo PK, Nadda AK. Recent advances in biochar amendments for immobilization of heavy metals in an agricultural ecosystem: A systematic review. Environ Pollut. 2023 Feb 15;319:120937. doi: 10.1016/j.envpol.2022.120937. Epub 2023 Jan 3. PMID: 36608723.
[2] Xu, Xi-Jun, et al. "Enhanced Methane Production in Anaerobic Digestion: A Critical Review on Regulation Based on Electron Transfer." Bioresource Technology, vol. 364, 2022, https://doi.org/10.1016/j.biortech.2022

Research and Analysis: Agriculture and Forestry

Biochar has shown its ability to improve phyto-agricultural output, arboreal resilience, and the cost effectiveness of waste reuse in spades. Such indicators of biochar's performance enhancement within the agricultural and forestry sectors are its improvement of microorganism propagation in soil, its ability to decrease emissions and odors from vermicomposting if used sparingly, its enhancement of anaerobic digestion, and how it contributes to rural and urban economic circularity.

When biochar is pyrolyzed, the biomass' fuel derivatives are extracted, while a charcoal like husk remains. The improvement of microorganism propagation in the soil stems from this porous structural matrix that pyrolysis creates, which hosts a wide variety of microscopic life, which in turn help maintain healthy soils. The literature indicates this on the basis of biochar's large surface area given its structure, and capacity to adsorb soluble organic matter and inorganic nutrients, biochar is the ideal environment for microbes to thrive.[3] According to their physical and chemical characteristics, bacteria, rhizo-organisms, actinomycetes, and arbuscular mycorrhizal fungi can all preferentially colonize biochar. They claimed that the addition of biochar increased microbial abundance.[4] This applies to bacteria, rhizo-organisms, actinomycetes, and arbuscular mycorrhizal fungi, all of which have a preference for colonizing biochar depending on their physicochemical properties.[5] This is further built upon by the fact that plant rhizomes have an affinity for biochar amended soil because of the beneficial bacterial and nutrient load it sequesters.[6] The nutrient and pollutant sequestration, structure, and the recalcitrant nature of biochar enable it to remain in the soil and act in a remediative capacity for years depending on where it has been used.

It needs to be noted however that biochar has a variety of effects on soil properties, whether they be chemical, biological and physical, and this in turn affects the wellbeing and effectiveness of microbes and microscopic organisms. Increased soil pH and buffering capacity from biochar improve acidic soils. In order to do so, one needs to know the pH and salinity of the biochar one is using in acidic soils. In fine-grained soils, biochar can improve infiltration and hydraulic conductivity. In addition, it appears that biochar has a stronger impact on hydraulic conductivity in coarse-textured soils than in fine-textured soils. By adding biochar to the surface, one can enhance particle transport by both water and wind (dust). Factors such as the characteristics of the soil and biochar, the type of crop, and any potential costs all play a role in determining the rate at which biochar will be mixed into the soil. Use of biochar as an environmentally friendly sorbent for soil immobilization and agricultural soil improvement

[3] Thies JE, Rillig MC (2009) Characteristics of biochar: biological properties. In: Lehmann J, Joseph S (eds) Biochar for environmental management: science and technology. Earthscan, London, UK, pp 85–105

[4] Abujabhah IS, Bound SA, Doyle R, Bowman JP (2016) Effects of biochar and compost amendments on soil physico-chemical properties and the total community within a temperate agricultural soil. Appl Soil Ecol 98:243–253

[5] Karabulut, F., Shameem, N., Shafi, N., Parray, J.A., Hashem, A., Abd-Allah, E.F. (2023). Over View of Symbiosis Mechanisms and Soil Quality Management Practices to Combat Environmental Changes. In: Parray, J.A. (eds) Climate Change and Microbiome Dynamics. Climate Change Management. Springer, Cham. https://doi.org/10.1007/978-3-031-21079-2_14

[6] Karabulut et al., (2023)

is critical. Pyrolysis conditions, biochar precursors, and soil properties all have an impact on its utility. The pH changes caused by biochar application, as well as the potential toxicity of biochar due to volatile pyrolysis product emissions, have a big impact on the way soil microbial communities work and what they eat.[7] The complexities of biochar's effect on soil, as well as differences in soil properties, can lead to conflicting data, making it difficult to compare experiment results. Biochar's action on soil and microorganisms requires more research.

Notwithstanding, while more research is needed as to different biochars' effects on soil health, there are other indications that biochar research has reached maturity to the point where using it actively as a soil amendment and remediation measure is advantageous. Such an indicator is how biochar improves vermicomposting. Co-composting agricultural waste with biochar markedly reduces the combination's odor/GHG emissions, and increases nutrient capture.[8] The ratios for the agricultural waste co-composting are at least 20:1, but should not exceed 5:1 (biomass:biochar); the reason for this is that earthworms and other detritivores produce the best compost at the 20:1 mark, while going over 5:1 reduces compost quality markedly.[9]

These clear delineations on what amount of biochar works for enabling improved soil health clearly indicate the maturity and depth of available research, and thus requires decision makers to act with celerity to integrate biochar into their approaches of reducing, valorizing, and reusing waste.

Furthermore, when it pertains to waste reuse, anaerobic digestion (AD) and biochar's improvement of it are very key to creating economic circularity. AD, when converting biomass into usable gas/liquified fuels, needs conductive materials (CMs) to facilitate electron transfers between the microbes breaking down the digestate and the microbes producing the fuels.[10]

The supplementation of iron/carbon-based conductive materials (CMs), but in this case specifically biochar, to the AD process has been shown to effectively enhance the methane production, shorten lag phase and accelerate the organics degradation. The underlying mechanism was possibly due to the promoted DIET (direct interspecies electron transfer) between anaerobic microbes and methanogens by using CMs as electron conduits.[11] Of the CMs used in the literature, biochar has the least explicit disadvantages when added to the AD process.[12]

In all three of the aforementioned cases, biochar serves as an process enhancer, and the improvement of such process hinges on the manner in which and sources from which it is produced. Therefore, tweaking the chemical composition, pyrolization, and feedstocks of engineered biochars

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[7] Karabulut et al., (2023)
[8] Wu, Y., Li, Q., Zheng, Y. et al. Optimizing biochar addition for vermicomposting: a comprehensive evaluation of earthworms' activity, N2O emissions and compost quality. Biochar 5, 4 (2023). https://doi.org/10.1007/s42773-022-00203-9
[9] Wu et al., (2023)
[10] Xu et al., (2022)
[11] Xu et al., (2022)
[12] Xu et al., (2022)

(EBCs), is key to ensuring that they have the desired effects when put into soil. The potential environmental risks and preparation cost of EBCs should be fully taken into account. With the popularization and application of EBCs, extensive use of EBCs in alkaline soil may lead to extreme lime effect in soil, resulting in a threat to the survival of biota.[13] Besides, EBCs that interact with contaminants in the soil during application can migrate in the soil through surface runoff and infiltration, causing a potential impact to soil biota and humans.[14] Therefore, how to reduce the possible environmental risks and developing low-cost, high-efficiency, green, and environmentally friendly EBCs for soil remediation and amendment needs to be an area of focus in the future.

Nonetheless, EBCs can be applied to the soil to promote stability, which ensures that the physical structure of the soil is protected, thereby improving soil fertility.[15] EBCs are generally recommended based on the literature as soil amendments to improve soil water retention, especially in dry climates where water is scarce. The literature points to the fact that increased water retention and the increase in diversity of the microbial community indicate that the presence of EBCs strengthens soil resilience and biodiversity when used within reason.

Compounding upon the multi-faceted uses of biochar is the fact that in all of its uses, it builds into economic circularity. Biochar manufacturing promotes a circular bioeconomy for agricultural waste in that the biomass, when it is tested and pyrolyzed, with its fuel and charcoal derivatives extracted, feeds into itself by way of having the biochar fertilize crops and the biofuels power equipment, the former's waste being used for further pyrolysis and fuel.[16] Waste has enormous amounts of value that is otherwise going to the landfill, and this repurposing imparts ecological and economic value to what was once discarded. Lifecycle assessments of biochar production processes showed that it can consistently impart its environmental benefits. Even if the biochar market prices become low farmers can apply it on farms and accrue the ecological benefits. Biochar's influence in numerous applications is well proven, and the need of the hour is to build a continuous supply chain to commercialize biochar's use in these fields is what the research strongly indicates.[17]

[13] Tang, Hui, et al. "Engineered Biochar Effects on Soil Physicochemical Properties and Biota Communities: A Critical Review." Chemosphere, vol. 311, 2023, https://doi.org/10.1016/j.chemosphere.2022.137025.
[14] Tang et al., (2023)
[15] Tang et al., (2023)
[16] D. Phadtare, Prajakta, and S. R. Kalbande. "Biochar Production Technologies from Agricultural Waste, Its Utilization in Agriculture and Current Global Biochar Market: A Comprehensive Review." International Journal of Environment and Climate Change, 2022, pp. 1010–1031, https://doi.org/10.9734/ijecc/2022/v12i1131078.
[17] Phadtare, Prajakta and Kalbande, (2022)

Research and Analysis: Toxins, Emerging Contaminants, and Stormwater Management

Biochar has the ability to immobilize toxins such as heavy metals and ”forever chemicals”, so EBCs, in concert with bacterial breakdown and phytoremediation, can accomplish a wide variety of toxin and waste management duties. This is made evident by the outstanding redox property of biochar, which promotes microbial remediation by accelerating electron transfer. Biochar can also be used as an excellent carrier for loaded strains to better promote the process of bioremediation of pollution.[18]

Adequately mitigating soil pollution is acknowledging not only the presence of a single pollutant, but the coexistence and intermingling of multiple pollutants. Researchers can select or cultivate microorganisms that are resistant to coexisting pollutants, and effectively combine them with biochar to boost the treatment efficiency of combined pollution.[19] It is necessary to reduce the presence of harmful substances such as heavy metals, PAHs, and VOCs that exist in biochar as much as possible before adding the amendment to any soil.[20] Systematic studies and summaries of the methods for reducing the potential risk of biochar on microorganisms are required.[21] As is described in the Agriculture and Forestry section, this need is met by being precise when engineering biochars for desired qualities such that soil biota and abiotic factors are accounted for, and the former enabled to thrive. Pertaining to selecting properties of EBC for which to engineer, the nonmetal functional groups (NFGs) must be accounted for and structured accordingly.[22] The NFGs in EBCs include OFGs (oxygen functional groups), NFGs (nitrogen functional groups), SFGs (sulfurous functional groups), PFGs (phosphoric functional groups) and SiFGs (silicate functional groups), most of them in their inorganic and organic states. The regulation of functional groups has certain rules:(i) compared with BC prepared from plants, the biomass of biological precursors contains more nitrogen content; (ii) the increase of pyrolysis temperature makes the inorganic functional groups tend to convert into organic states; (iii) chemical modification of reagents containing specific elements is an effective modification idea. At present, the attention in the application of BC to remove pollutants is the performance effect. In the future, the reaction mechanism of BC to remove pollutants and the role of functional groups in it should be focused on, and economical and convenient preparation and modification methods should be vigorously developed, thereby expanding the prospect of BC in practical applications. What is more, in the process of soil bioremediation, whether to add key microbial species that are loaded on the biochar to the soil or to influence the selection of soil key microbial species through the addition of biochar to achieve the best treatment and economic effect, researchers need to further explore.

[18] Zheng, Xuemei, et al. “The Effects of Biochar and Its Applications in the Microbial Remediation of Contaminated Soil: A Review.” Journal of Hazardous Materials, vol. 438, 25 Sept. 2022, https://doi.org/10.1016/j.jhazmat.2022.129557.
[19] Zheng, Xuemei, et al., (2022)
[20] Zheng, Xuemei, et al., (2022)
[21] Zheng, Xuemei, et al., (2022)
[22] Yang, Yadong, et al. “Nonmetal Function Groups of Biochar for Pollutants Removal: A Review.” Journal of Hazardous Materials Advances, vol. 8, Nov. 2022, https://doi.org/10.1016/j.hazadv.2022.100171.

Some strains in soil, such as sulfate-reducing bacteria and methanogens, also respond positively to the amendment of biochar, which will create competition for electrons used for microbial reduction of pollutants and inhibit pollutant reduction. Hence, there is a requirement for researchers to explore the exact inhibition mechanism of pollutant reduction and ways to maximize the availability of electrons for pollutant reduction.[23] It is necessary to select an appropriate modification method according to the characteristics of the EBCs' raw materials and the application purpose to control the physical and chemical properties of the end product, including pretreatment methods, activation methods and N doping methods.[24] The appropriate modification methods such as ball milling, microwave pyrolysis, and redox-active metal preloading for biochar can effectively improve its corresponding properties.[25] Hence, researchers need to select suitable modification methods that can fully exploit the characteristics of biochar as a microbial carrier and electron transporter to promote microbial degradation of pollutants.

Additionally, biochar can be used as a substitute for materials such as cement and sand to enhance the mechanical properties and durability of biochar-concrete composites in green/blue infrastructure. It improves the functionality of construction materials, such as hydrothermal and acoustic properties.[26] Biochar mainly acts synergistically with external carbonation by promoting the generation of hydration products inside the concrete, and its own pore structure and high surface properties are decisive factors for the adsorption and storage of CO2.[27] The incorporation of biochar can effectively reduce the net carbon emissions of composite materials and improve the carbon sequestration performance of cementitious composites.[28] Overall, biochar has a very high potential as a carbon capture material in concrete and has good environmental and economic benefits for the industry if adopted at scale.

[23] Zheng, Xuemei, et al., (2022)
[24] Gao, Wenran, et al. "A Review on N-Doped Biochar for Enhanced Water Treatment and Emerging Applications." Fuel Processing Technology, vol. 237, 1 Dec. 2022, p. 107468, https://doi.org/10.1016/j.fuproc.2022.107468.
[25] Zheng, Xuemei, et al., (2022)
[26] Liu, Jun, et al. "Application Potential Analysis of Biochar as a Carbon Capture Material in Cementitious Composites: A Review." Construction and Building Materials, vol. 350, 3 Oct. 2022, https://doi.org/10.1016/j.conbuildmat.2022.128715.
[27] Liu, Jun, et al., (2022)
[28] Liu, Jun, et al., (2022)

Biochar remaining recalcitrant, soil compatible, and effective are cornerstones of what impedes it from being adopted.

According to the most recent literature, the effects of aging on biochar properties have been revealed: (1) increasing oxygen content, CEC (cation exchange capacity), SSA (specific surface area), and formation of OFGs; and (2) decreasing carbon content, aromatic components, ash content, and pH value. The enhanced adsorption of heavy metals by aged biochar is mainly due to the increase of OFGs.[29] The inhibition of adsorption is dependent on the reduction of ash in aged biochar.[30] This is a reminder to carefully use high-ash biochar for long-term remediation of heavy metals.[31] Specifically for the adsorption of organic pollutants, the aging poses a negative effect on the sorption capacity of biochar derived from high pyrolysis temperature (>500 °C). It is mainly due to the reduction of aromatic components and the formation of three-dimensional water clusters caused by proliferation of OFGs. It indicated that the adsorbed organics on these high-temperature biochars could be released into the environment after long-term aging. In the soil amendment, biochar inevitably contacts the soil components. The existing research has revealed that soil minerals (kaolinite, FeCl3, AlCl3, and CaCl2) could enhance the oxidation resistance of biochar, due to forming a physical barrier and decreasing the biochar reactivity.[32]

As for biochar standardization, it was found that the optimum pyrolysis temperature must be around 400 and 600 °C according to the literature.[33] It was also emphasized that biochar can be amended to construct wetlands as a waste treatment enhancement for sequestering heavy metals, VOCs, excess nutrients, and malignant biota.[34]

[29] Liu Y, Chen J. Effect of aging on biochar properties and pollutant management. Chemosphere. 2022 Apr;292:133427. doi: 10.1016/j.chemosphere.2021.133427. Epub 2021 Dec 23. PMID: 34954191.
[30] Liu and Chen, (2021)
[31] Liu and Chen, (2021)
[32] Liu and Chen, (2021)
[33] El Barkaoui, Sofiane, et al. "A Critical Review on Using Biochar as Constructed Wetland Substrate: Characteristics, Feedstock, Design and Pollutants Removal Mechanisms." Ecological Engineering, vol. 190, May 2023, p. 106927, https://doi.org/10.1016/j.ecoleng.2023.106927.
[34] El Barkaoui, Sofiane, et al., (2023)

Conclusion

Exploration of the wide applicability of biochar through bibliometric analysis suggested that global research on biochar has increased tremendously in the recent past. Biochar could be produced from a wide variety of waste biomass, which enables waste management. Biochar could enable food security management by augmenting soil fertility and plant productivity, mitigate climate change by sequestering carbon and minimizing greenhouse gas emission, produce bio-energy (i.e. bio-oil and syngas), and remediate contaminants from soil, water, and air. The wide applicability suggests the key role biochar could play in sustainable development worldwide. Artificial intelligence, data-driven machine learning and artificial neural network modeling could play a critical role in producing and screening application-specific biochar.[35] Moreover, it is crucial to incorporate life cycle assessment (LCA) for assuring environmental sustainability and determining the fate of biochar along with probable ecological and health consequences.

[35] Kumar, A., Bhattacharya, T., Shaikh, W.A. et al. Multifaceted applications of biochar in environmental management: a bibliometric profile. Biochar 5, 11 (2023). https://doi.org/10.1007/s42773-023-00207-z

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