Review Article

Biochar's effects and operations on microbial life within the soil ecosystem- A review

Abstract

This review explores the multifaceted impacts of biochar on soil ecosystems honing in on its capacity to improve soil characteristics and modify microbial behavior. Biochar is a carbon-rich substance generated through pyrolysis of biomass which has gained escalating interest within the scientific community due to its potential for boosting soil carbon sequestration enhancing soil fertility and mitigating soil pollutants. The improvements brought about by biochar extend to influencing the metabolic activities and community structures of soil microorganisms. Our investigation delves into the effects of biochar on soil physical and chemical properties, its influence on enzymatic activities, nutrient availability and its role in contaminant transformation. Notably, we also study the interplay between biochar and microbial entities elucidating possible mechanisms underpinning this interaction. Alongside the benefits of biochar use this review underscores potential risks, fostering a comprehensive understanding of the broader implications of biochar applications. By amalgamating current knowledge, we strive to lay the groundwork for future explorations in this field.

Keywords: *Biochar, Microorganisms, Soil, Pollutants, Interactions*

Introduction

Biochar is a carbon-rich, porous material produced by thermochemical conversion of organic materials under limited oxygen conditions, a process known as pyrolysis [1]. The resulting product has high stability and the potential to sequester carbon in the soil for hundreds to thousands of years, contributing significantly to climate change mitigation [2]. Biochar is recognized for its significant potential to improve soil health, increase crop yields and provide other environmental benefits [3]. Biochar is defined as a carbonaceous product obtained when organic material, usually plant matter is heated in a limited oxygen environment, a process known as pyrolysis. The pyrolysis process can take place at various temperatures, generally between 300 and 600^{o}C [4]. The result is a stable form of carbon with a structure that is rich in aromatic carbon and highly resistant to microbial decomposition making it an excellent candidate for long-term carbon sequestration [5]. The production of biochar occurs via the pyrolysis process which involves heating organic material to high temperatures in a low oxygen environment. The heat causes the organic matter to break down releasing gases and leaving behind a carbon-rich residue known as biochar [6]. The exact properties of biochar including its porosity, nutrient content and stability depend on the type of feedstock used and the specific conditions of the pyrolysis process [7]. Feedstocks can range from agricultural wastes like straw and manure to forestry residues, to purpose-grown energy crops [8]. The gases produced during pyrolysis can be captured and used as a source of renewable energy adding another dimension to the environmental benefits of biochar production [9].

The aim of this review is to delve into the multifaceted impacts of biochar on soil ecosystems. The specific focus will be on its ability to enhance soil attributes and alter microbial dynamics. It has garnered significant attention within the scientific community due to its potential to boost soil carbon storage, enrich soil fertility and mitigate soil pollutants. The advancements made by biochar extend to influencing the metabolic functions and community compositions of soil microorganisms. This review will provide a comprehensive understanding of biochar's broader implications and strive to lay the groundwork for future investigations in this field.

Biochar's Role in Soil Ecosystem

The soil ecosystem often referred to as the 'skin of the earth,' is a complex and dynamic system teeming with diverse physical, chemical and biological components [10]. Soils serve as the nexus of the biosphere, atmosphere and hydrosphere playing a pivotal role in critical processes such as nutrient cycling, water filtration and carbon sequestration [11]. A healthy soil ecosystem facilitates plant growth affects water quality influences the concentration of greenhouse gases in the atmosphere and supports a diverse array of organisms [12]. Given the centrality of soils to environmental health, it is of paramount importance to develop strategies that improve soil quality and sustainability. One promising strategy is the addition of biochar to soil, a practice that has received considerable attention for its potential to enhance soil properties and processes [13]. Biochar's potential benefits to soils are manifold, spanning from enhancing soil carbon storage and fertility to mitigating pollutants. Its unique physical and chemical characteristics such as high porosity, large surface area and diverse functional groups impart a variety of beneficial soil amendments [14].

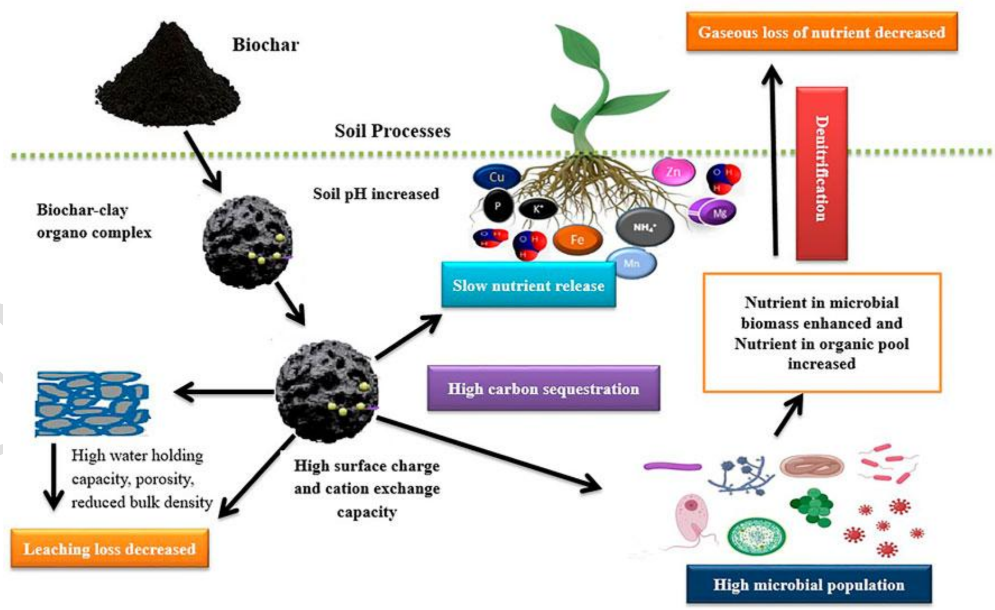

Image: Biochar-Soil-Plant interactions (Source- https://www.frontiersin.org/)

Impact on Soil Carbon Sequestration

Soil represents the largest terrestrial carbon sink and the management of soil carbon is a crucial element in strategies to mitigate climate change [15]. The highly recalcitrant nature of biochar means it can persist in the soil for centuries effectively sequestering carbon and reducing greenhouse gas emissions [16]. Various studies have indicated that it's application to soil significantly increases soil carbon content. For instance, a meta-analysis demonstrated that biochar amendment increased soil organic carbon by 25% on average [17]. This capacity for long-term carbon storage not only contributes to climate change mitigation but also can improve soil properties related to fertility and structure [18].

Influence on Soil Fertility

Biochar has been shown to improve soil fertility in several ways. Its porous structure and high surface area provide a habitat for soil microbes and improve soil structure enhancing soil water holding capacity and aeration [19]. It contains considerable amounts of nutrients such as nitrogen, phosphorus, and potassium and its high cation exchange capacity can improve the retention and availability of these nutrients in the soil [20]. Numerous studies have demonstrated the positive impact of biochar on soil nutrient status and crop productivity. It's amendment significantly increased soil phosphorus availability and wheat yield in a low-fertility soil [21].

Role in Soil Pollutant Mitigation

The high sorption capacity of biochar makes it a powerful tool for mitigating various soil pollutants including heavy metals and organic contaminants [22]. By adsorbing these pollutants onto its surface, biochar reduces their bioavailability and potential toxicity to plants and soil organisms [23]. Biochar amendment reduced the availability and plant uptake of heavy metals in an industrially contaminated soil [24]. Recent studies have shown that biochar can promote the degradation of organic contaminants by serving as a habitat and energy source for degrading microorganisms [25].

Biochar's Interaction with Microbial Life

Microbial metabolic activities refer to the biological processes undertaken by soil microorganisms to convert nutrients into energy which in turn supports their growth and reproduction [26]. Such activities include decomposition of organic matter, nutrient cycling and the formation and stabilization of soil structure [27]. These microbial processes are central to soil health and productivity driving key ecosystem services such as nutrient availability, organic matter turnover and greenhouse gas emissions [28]. It has been found to have considerable effects on the metabolic activities of soil microorganisms either directly through influencing microbial physiology or indirectly by modifying soil physicochemical properties [29]. It can directly affect microbial metabolic activities by altering the availability of nutrients and energy sources [30]. The high carbon content of biochar provides a potential energy source for heterotrophic microorganisms while the nutrients embedded within the biochar matrix can serve as essential growth factors [31]. The porous structure of biochar provides a physical habitat for microorganisms, protecting them from predation and environmental stresses which can enhance microbial activity and growth [32]. Studies have shown that biochar amendment can increase microbial biomass and activity as indicated by measures such as microbial biomass carbon and soil enzyme activities [33]. It can also indirectly influence microbial metabolic activities by improving soil physicochemical properties. By enhancing soil structure, nutrient availability and water holding capacity, biochar creates a more favorable environment for microbial activity [34]. For example, biochar amendment improved soil structure and water holding capacity which in turn increased soil microbial biomass and activity [35].

Impact of Biochar on Microbial Community Structure

In addition to affecting microbial activity, biochar can also shape the community structure of soil microorganisms influencing both their diversity and dominance. An important attribute of soil health it has been shown to increase the diversity of soil microorganisms [36]. The increase in microbial diversity may be due to the addition of new microhabitat niches within the porous structure of biochar as well as the provision of diverse carbon and nutrient sources [37]. The effects of biochar on microbial diversity can be influenced by various factors, including biochar properties, soil type and climatic conditions [38]. It can also alter the dominance of certain microbial species. Some studies have shown that biochar amendment can increase the abundance of beneficial microorganisms such as mycorrhizal fungi and nitrogen-fixing bacteria which can enhance plant nutrient acquisition and growth [39]. It can also potentially increase the abundance of pathogenic microorganisms although more research is needed in this area [40].

Biochar's Influence on Soil Properties

Biochar's beneficial impacts on soil environments primarily stem from its influence on soil physical and chemical properties. Its unique structure and composition can dramatically alter these properties thereby influencing various soil processes and phenomena. It influences on the physical properties of soil are significant with notable impacts on water-holding capacity and soil structure. Water-holding capacity is a critical determinant of soil productivity affecting plant availability to water and nutrients as well as microbial activity [41]. Biochar's porous structure and large surface area can increase the water-holding capacity of soils particularly sandy soils by providing additional space for water storage [42]. The addition of biochar to a sandy soil increased its water-holding capacity by up to 18% [43]. Such improvements in water availability can enhance plant growth and reduce irrigation needs contributing to sustainable agriculture [44].

Soil Structure and Compaction

Biochar can also improve soil structure including porosity, aggregation and compaction [45]. Its rigid, porous structure can introduce additional pore spaces in the soil improving aeration and reducing compaction [46]. Biochar can also promote the formation of stable soil aggregates which enhance soil structure and erosion resistance [47]. For example, biochar amendment improved soil structure and reduced soil erosion in a field experiment [48].

Soil Chemical Properties

In addition to its physical properties, it can also substantially alter the chemical properties of soils. The most pronounced effects are observed in soil pH and cation exchange capacity. It is often alkaline and its addition can increase soil pH, making it particularly useful for ameliorating acidic soils [49]. Elevated soil pH can improve nutrient availability and microbial activity leading to improved soil fertility [50]. Biochar amendment increased soil pH and nutrient availability in an acidic soil [51]. It's high cation exchange capacity (CEC) is another of its key attributes. CEC is a measure of soil's ability to retain and supply cations to plant roots which is vital for nutrient availability [52]. The high CEC of biochar can improve nutrient retention in the soil, reducing nutrient leaching and increasing nutrient use efficiency [53]. Demonstrated that biochar amendment significantly increased soil CEC leading to increased nutrient retention and plant growth [54].

Biochar's Role in Nutrient Availability and Enzymatic Activities

A key advantage of biochar application in soils lies in its ability to enhance nutrient availability and promote enzymatic activities both crucial to soil fertility and the overall health of the soil ecosystem. It has been proven to positively impact the availability of essential nutrients within soil profiles. As mentioned previously, it's high cation exchange capacity can enhance nutrient retention, reducing nutrient leaching and increasing the supply of nutrients to plant. Biochar often contains considerable amounts of nutrients , including nitrogen, phosphorus and potassium which can be slowly released into the soil over time [55]. The pH-ameliorating effects of biochar can improve the availability of nutrients that are sensitive to soil pH. By increasing soil pH, it can enhance the solubility and thus the availability of certain nutrients particularly phosphorus and micronutrients such as zinc and manganese [56]. For example, Biochar amendment increased soil pH and phosphorus availability in an acidic Ultisol [57]. It can affect nutrient availability indirectly by influencing microbial activity and nutrient cycling processes which will be discussed in the following section.

Impact on Enzymatic Activities and Nutrient Cycling

Biochar can promote soil enzymatic activities which play a pivotal role in the cycling of soil nutrients. Soil enzymes produced predominantly by microorganisms are involved in various soil processes including the decomposition of organic matter, the cycling of nitrogen, phosphorus, sulfur and the transformation of pollutants [58]. Biochar's porous structure and nutrient content can provide a habitat and energy source for microorganisms enhancing their growth and enzymatic activities [59]. The high surface area of biochar can provide physical sites for enzyme adsorption, protecting enzymes from degradation and stabilizing their activities [60]. It's amendment increased the activities of several enzymes involved in the nitrogen and phosphorus cycles [61]. Biochar can influence the cycling of specific nutrients by promoting the activities of specific groups of microorganisms. For example, the stimulation of nitrogen-fixing bacteria and mycorrhizal fungi by biochar can enhance the cycling of nitrogen and phosphorus, respectively [62]. Through enhancing nutrient availability and promoting enzymatic activities, it can contribute to improved soil fertility and productivity.

Potential hazard

The potential hazards of inherent biochar pollutants to soil microorganisms' range across various categories of pollutants (Table 1). One such category is heavy metals including Lead (Pb), Cadmium (Cd) and Zinc (Zn). These metals can pose significant threats to soil microorganisms. They are known to inhibit microbial growth, reduce biomass and disrupt the activity of microbial enzymes [87]. Organic contaminants such as polycyclic aromatic hydrocarbons and volatile organic compounds are also a source of concern. These compounds can exert genotoxic impacts on microorganisms suppressing their activities and altering the composition of the microbial community in the soil [88]. Environmentally Persistent Free Radicals (EPFRs) such as hydroxy and alkoxy radicals can be produced during the pyrolysis process and incorporated into biochar. These radicals can impair enzymatic activity within cells, induce oxidative stress and bring about significant alterations to microbial community patterns [89]. Other pollutants like perfluorinated compounds, perfluorooctane sulfonate and pentadecafluorooctanoic acid can also have adverse effects. They are known to induce changes in the diversity and abundance of soil bacterial communities and inhibit enzyme activity [90].

Table 1: Potential Risks of Inherent Biochar Pollutants to Soil Microorganisms

Pollutant Type	**Examples**	**Possible Risks**	**References**
Heavy Metals	Lead (Pb), Cadmium (Cd), Zinc (Zn)	Impediment of microbial growth, decrease in biomass, disruption of microbial enzyme activity	[87]
Organic Contaminants	Polycyclic aromatic hydrocarbons, volatile organic compounds	Genotoxic impacts on microorganisms, suppression of microbial activities, modification of microbial community composition	[88]
EPFRs	Hydroxy radicals, Alkoxy radicals	Impairment of enzymatic activity within cells, oxidative stress induction, alteration of microbial community patterns	[89]
Other Pollutants	Perfluorinated compounds, Perfluorooctane sulfonate, Pentadecafluorooctanoic acid	Changes in the diversity and abundance of soil bacterial communities, inhibition of enzyme activity	[90]

Biochar's Role in Contaminant Transformation

The application of biochar in soil has emerged as a promising technique for soil remediation, capable of immobilizing a wide range of contaminants including heavy metals, organic pollutants and excess nutrients. It's role in pollutant fixation and transformation can be attributed to several mechanisms including sorption, precipitation, complexation and microbial transformation [63]. Sorption is one of the most significant mechanisms where contaminants are bound onto the surfaces of biochar via physical or chemical interactions [64]. The large surface area and the presence of functional groups on biochar surfaces contribute to its high sorption capacity [65]. It effectively sorbed heavy metals from contaminated soil [66]. Precipitation and complexation, largely driven by the alkaline nature of biochar. It can also play a role in immobilizing heavy metals [67]. When biochar is added to an acidic soil, the increase in pH can lead to the precipitation of heavy metals as less soluble hydroxides or carbonates or the complexation of heavy metals with organic matter or carbonate ions reducing their mobility and bioavailability [68]. It can facilitate microbial transformation of contaminants. For instance, It has been shown to stimulate the microbial degradation of organic pollutants such as polycyclic aromatic hydrocarbons due to its ability to provide a habitat and carbon source for microorganisms [69].

Impact on Bioavailability of Contaminants

Biochar amendment can significantly reduce the bioavailability of contaminants, i.e., the fraction that is available for uptake by organisms [70]. This is a crucial aspect of soil remediation as it is the bioavailable fraction rather than the total concentration that determines the toxicity of contaminants [71]. By sorbing contaminants onto its surfaces, biochar can reduce the desorption and diffusion of contaminants, lowering their bioavailability [72]. The alkaline nature of biochar can further reduce the bioavailability of heavy metals by inducing their precipitation or complexation [73]. It’s amendment reduced the bioavailability of cadmium and lead in a contaminated soil [74]. It can promote the transformation of contaminants into less bioavailable forms. For example, the microbial degradation of organic pollutants facilitated by biochar can result in the formation of less toxic and less bioavailable metabolites [75].

Possible Mechanisms of Biochar-Microorganism Interactions

Biochar's impacts on soil ecosystems are strongly linked to its interactions with soil microorganisms. Unraveling the mechanisms behind these interactions can provide a more holistic understanding of the biochar-soil-microorganism nexus. Biochar-microorganism interactions can be complex and multifaceted with several mechanisms potentially at play. These mechanisms can be broadly categorized into direct and indirect effects [76]. Direct effects refer to the effects of biochar on microorganisms due to physical or chemical interactions. For instance, biochar can provide a habitat for microorganisms due to its porous structure protecting them from predators and harsh environmental conditions [77]. It can also serve as a carbon and energy source for microorganisms stimulating their growth and activity [78]. Moreover, biochar can directly influence microbial metabolism by adsorbing extracellular enzymes or substrates, which can have implications for nutrient cycling [79]. Indirect effects refer to the effects of biochar on microorganisms mediated through changes in soil properties. As previously discussed, it can alter soil physical and chemical properties such as water-holding capacity, pH, and nutrient availability which can influence microbial activity and community structure [80].

Interaction of Biochar with Various Types of Soil Microorganisms

Different types of soil microorganisms can respond differently to biochar amendment due to their distinct ecological niches and metabolic capabilities. Bacteria is the most abundant and diverse group of soil microorganisms which shows varied responses to biochar amendment [81]. Some studies have reported increased bacterial abundance and diversity due to biochar amendment, possibly due to the provision of habitats and nutrients [82]. Other studies have reported no significant changes or even decreases in bacterial abundance, which could be due to the adsorption of substrates or changes in soil properties [83]. Fungi particularly mycorrhizal fungi can also be influenced by biochar amendment. Several studies have shown that biochar can stimulate mycorrhizal fungi enhancing their symbiosis with plants and their contribution to nutrient cycling [84]. The mechanisms behind these effects could involve the provision of habitats, changes in soil properties or the presence of signaling compounds in biochar [85]. Other groups of soil microorganisms such as archaea, protozoa and viruses have been less studied in the context of biochar but could also be influenced by biochar amendment in various ways [86]. The mechanisms of biochar-microorganism interactions can be complex and diverse and can depend on various factors including the type of biochar, the type of soil and the type of microorganisms. Further research is needed to fully elucidate these mechanisms and their implications for soil health and productivity.

Conclusion

Biochar is a carbon-rich material produced from biomass pyrolysis holds significant promise for enhancing soil ecosystems improving soil properties and aiding in contaminant transformation. By interacting with soil microorganisms it can influence microbial activities and community structures with implications for soil health and productivity. These interactions are multifaceted, involving both direct and indirect effects and can depend on various factors. Despite the existing body of research, further studies are required to elucidate the complex mechanisms underlying biochar's effects in soil particularly its interactions with different types of soil microorganisms. By advancing our understanding of these aspects, we can optimize the use of biochar for sustainable soil management.

References

1. Yadav, K., & Jagadevan, S. (2019). Influence of process parameters on synthesis of biochar by pyrolysis of biomass: an alternative source of energy. In *Recent advances in pyrolysis*. IntechOpen.
2. Lorenz, K., & Lal, R. (2014). Biochar application to soil for climate change mitigation by soil organic carbon sequestration. *Journal of Plant Nutrition and Soil Science*, *177*(5), 651-670.
3. Das, S., Mohanty, S., Sahu, G., Rana, M., & Pilli, K. (2021). Biochar: A sustainable approach for improving soil health and environment. *Soil erosion-current challenges and future perspectives in a changing world*, *1*, 5772.
4. McBeath, A. V., Wurster, C. M., & Bird, M. I. (2015). Influence of feedstock properties and pyrolysis conditions on biochar carbon stability as determined by hydrogen pyrolysis. *Biomass and Bioenergy*, *73*, 155-173.
5. Dynarski, K. A., Bossio, D. A., & Scow, K. M. (2020). Dynamic stability of soil carbon: reassessing the "permanence" of soil carbon sequestration. *Frontiers in Environmental Science*, *8*, 514701.
6. Lehmann, J., & Joseph, S. (2009). Biochar for environmental management: an introduction. *Biochar for environmental management: science and technology*, *1*, 1-12.

7. Oni, B. A., Oziegbe, O., & Olawole, O. O. (2019). Significance of biochar application to the environment and economy. *Annals of Agricultural Sciences*, *64*(2), 222-236.
8. McKendry, P. (2002). Energy production from biomass (part 1): overview of biomass. *Bioresource technology*, *83*(1), 37-46.
9. Lee, J. W., Hawkins, B., Day, D. M., & Reicosky, D. C. (2010). Sustainability: the capacity of smokeless biomass pyrolysis for energy production, global carbon capture and sequestration. *Energy & environmental science*, *3*(11), 1695-1705.
10. Hartemink, A. E. (2016). The definition of soil since the early 1800s. *Advances in Agronomy*, *137*, 73-126.
11. Lal, R., Mohtar, R. H., Assi, A. T., Ray, R., Baybil, H., & Jahn, M. (2017). Soil as a basic nexus tool: soils at the center of the food–energy–water nexus. *Current Sustainable/Renewable Energy Reports*, *4*, 117-129.
12. Cavicchioli, R., Ripple, W. J., Timmis, K. N., Azam, F., Bakken, L. R., Baylis, M., ... & Webster, N. S. (2019). Scientists' warning to humanity: microorganisms and climate change. *Nature Reviews Microbiology*, *17*(9), 569-586.
13. Cara, I. G., Țopa, D., Puiu, I., & Jităreanu, G. (2022). Biochar a promising strategy for pesticide-contaminated soils. *Agriculture*, *12*(10), 1579.
14. Leng, L., Xiong, Q., Yang, L., Li, H., Zhou, Y., Zhang, W., ... & Huang, H. (2021). An overview on engineering the surface area and porosity of biochar. *Science of the total Environment*, *763*, 144204.
15. Elbasiouny, H., El-Ramady, H., Elbehiry, F., Rajput, V. D., Minkina, T., & Mandzhieva, S. (2022). Plant nutrition under climate change and soil carbon sequestration. *Sustainability*, *14*(2), 914.
16. Al-Wabel, M. I., Ahmad, M., Usman, A. R., Akanji, M., & Rafique, M. I. (2020). Advances in pyrolytic technologies with improved carbon capture and storage to combat climate change. *Environment, climate, plant and vegetation growth*, 535-575.
17. Liu, S., Zhang, Y., Zong, Y., Hu, Z., Wu, S., Zhou, J. I. E., ... & Zou, J. (2016). Response of soil carbon dioxide fluxes, soil organic carbon and microbial biomass carbon to biochar amendment: a meta-analysis. *Gcb Bioenergy*, *8*(2), 392-406.
18. Lorenz, K., & Lal, R. (2014). Biochar application to soil for climate change mitigation by soil organic carbon sequestration. *Journal of Plant Nutrition and Soil Science*, *177*(5), 651-670.
19. Fischer, D., & Glaser, B. (2012). Synergisms between compost and biochar for sustainable soil amelioration. *Management of organic waste*, *1*, 167-198.
20. Hossain, M. Z., Bahar, M. M., Sarkar, B., Donne, S. W., Ok, Y. S., Palansooriya, K. N., ... & Bolan, N. (2020). Biochar and its importance on nutrient dynamics in soil and plant. *Biochar*, *2*, 379-420.
21. Alburquerque, J. A., Calero, J. M., Barrón, V., Torrent, J., del Campillo, M. C., Gallardo, A., & Villar, R. (2014). Effects of biochars produced from different feedstocks on soil

properties and sunflower growth. *Journal of plant nutrition and soil science*, *177*(1), 16-25.
22. Derakhshan Nejad, Z., Jung, M. C., & Kim, K. H. (2018). Remediation of soils contaminated with heavy metals with an emphasis on immobilization technology. *Environmental geochemistry and health*, *40*, 927-953.
23. Lin, Q., Tan, X., Almatrafi, E., Yang, Y., Wang, W., Luo, H., ... & Zhang, C. (2022). Effects of biochar-based materials on the bioavailability of soil organic pollutants and their biological impacts. *Science of The Total Environment*, *826*, 153956.
24. Chen, D., Liu, X., Bian, R., Cheng, K., Zhang, X., Zheng, J., ... & Li, L. (2018). Effects of biochar on availability and plant uptake of heavy metals–A meta-analysis. *Journal of Environmental Management*, *222*, 76-85.
25. Xiang, L., Harindintwali, J. D., Wang, F., Redmile-Gordon, M., Chang, S. X., Fu, Y., ... & Xing, B. (2022). Integrating biochar, bacteria, and plants for sustainable remediation of soils contaminated with organic pollutants. *Environmental Science & Technology*, *56*(23), 16546-16566.
26. Aislabie, J., Deslippe, J. R., & Dymond, J. (2013). Soil microbes and their contribution to soil services. *Ecosystem services in New Zealand–conditions and trends. Manaaki Whenua Press, Lincoln, New Zealand*, *1*(12), 143-161.
27. Juma, N. G. (1994). A conceptual framework to link carbon and nitrogen cycling to soil structure formation. *Agriculture, ecosystems & environment*, *51*(1-2), 257-267.
28. Hartmann, M., & Six, J. (2023). Soil structure and microbiome functions in agroecosystems. *Nature Reviews Earth & Environment*, *4*(1), 4-18.
29. Thies, J. E., & Rillig, M. C. (2009). Characteristics of biochar: biological properties. *Biochar for environmental management: Science and technology*, *1*, 85-105.
30. Thies, J. E., & Rillig, M. C. (2009). Characteristics of biochar: biological properties. *Biochar for environmental management: Science and technology*, *1*, 85-105.
31. Fagbohungbe, M. O., Herbert, B. M., Hurst, L., Ibeto, C. N., Li, H., Usmani, S. Q., & Semple, K. T. (2017). The challenges of anaerobic digestion and the role of biochar in optimizing anaerobic digestion. *Waste management*, *61*, 236-249.
32. Xiang, L., Harindintwali, J. D., Wang, F., Redmile-Gordon, M., Chang, S. X., Fu, Y., ... & Xing, B. (2022). Integrating biochar, bacteria, and plants for sustainable remediation of soils contaminated with organic pollutants. *Environmental Science & Technology*, *56*(23), 16546-16566.
33. Irfan, M., Hussain, Q., Khan, K. S., Akmal, M., Ijaz, S. S., Hayat, R., ... & Rashid, M. (2019). Response of soil microbial biomass and enzymatic activity to biochar amendment in the organic carbon deficient arid soil: a 2-year field study. *Arabian Journal of Geosciences*, *12*, 1-9.
34. Siedt, M., Schäffer, A., Smith, K. E., Nabel, M., Roß-Nickoll, M., & van Dongen, J. T. (2021). Comparing straw, compost, and biochar regarding their suitability as agricultural

soil amendments to affect soil structure, nutrient leaching, microbial communities, and the fate of pesticides. *Science of the Total Environment*, *751*, 141607.

35. Rahman, M. T., Zhu, Q. H., Zhang, Z. B., Zhou, H., & Peng, X. (2017). The roles of organic amendments and microbial community in the improvement of soil structure of a Vertisol. *Applied Soil Ecology*, *111*, 84-93.
36. Agegnehu, G., Srivastava, A. K., & Bird, M. I. (2017). The role of biochar and biochar-compost in improving soil quality and crop performance: A review. *Applied soil ecology*, *119*, 156-170.
37. 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*, 1-18.
38. Singh, H., Northup, B. K., Rice, C. W., & Prasad, P. V. (2022). Biochar applications influence soil physical and chemical properties, microbial diversity, and crop productivity: a meta-analysis. *Biochar*, *4*(1), 8.
39. Cao, H., Jia, M., Xun, M., Wang, X., Chen, K., & Yang, H. (2021). Nitrogen transformation and microbial community structure varied in apple rhizosphere and rhizoplane soils under biochar amendment. *Journal of Soils and Sediments*, *21*, 853-868.
40. Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., & Crowley, D. (2011). Biochar effects on soil biota–a review. *Soil biology and biochemistry*, *43*(9), 1812-1836.
41. Doran, J. W., Jones, A. J., Arshad, M. A., & Gilley, J. E. (1999). Determinants of soil quality and health. *Soil quality and soil erosion*, *36*.
42. Mohamed, B. A., Ellis, N., Kim, C. S., Bi, X., & Emam, A. E. R. (2016). Engineered biochar from microwave-assisted catalytic pyrolysis of switchgrass for increasing water-holding capacity and fertility of sandy soil. *Science of the Total Environment*, *566*, 387-397.
43. Artiola, J. F., Rasmussen, C., & Freitas, R. (2012). Effects of a biochar-amended alkaline soil on the growth of romaine lettuce and bermudagrass. *Soil Science*, *177*(9), 561-570.
44. Qadir, M., & Oster, J. D. (2004). Crop and irrigation management strategies for saline-sodic soils and waters aimed at environmentally sustainable agriculture. *Science of the total environment*, *323*(1-3), 1-19.
45. Du, Z., Chen, X., Qi, X., Li, Z., Nan, J., & Deng, J. (2016). The effects of biochar and hoggery biogas slurry on fluvo-aquic soil physical and hydraulic properties: a field study of four consecutive wheat–maize rotations. *Journal of soils and sediments*, *16*, 2050-2058.
46. Keller, T., Lamandé, M., Peth, S., Berli, M., Delenne, J. Y., Baumgarten, W., ... & Or, D. (2013). An interdisciplinary approach towards improved understanding of soil deformation during compaction. *Soil and Tillage Research*, *128*, 61-80.

47. Lee, M. H., Chang, E. H., Lee, C. H., Chen, J. Y., & Jien, S. H. (2021). Effects of biochar on soil aggregation and distribution of organic carbon fractions in aggregates. *Processes*, *9*(8), 1431.
48. Siedt, M., Schäffer, A., Smith, K. E., Nabel, M., Roß-Nickoll, M., & van Dongen, J. T. (2021). Comparing straw, compost, and biochar regarding their suitability as agricultural soil amendments to affect soil structure, nutrient leaching, microbial communities, and the fate of pesticides. *Science of the Total Environment*, *751*, 141607.
49. Yuan, J. H., Xu, R. K., Qian, W., & Wang, R. H. (2011). Comparison of the ameliorating effects on an acidic ultisol between four crop straws and their biochars. *Journal of soils and sediments*, *11*, 741-750.
50. Sheoran, V., Sheoran, A. S., & Poonia, P. (2010). Soil reclamation of abandoned mine land by revegetation: a review. *International journal of soil, sediment and water*, *3*(2), 13.
51. Novak, J. M., Busscher, W. J., Laird, D. L., Ahmedna, M., Watts, D. W., & Niandou, M. A. (2009). Impact of biochar amendment on fertility of a southeastern coastal plain soil. *Soil science*, *174*(2), 105-112.
52. Luo, X., Liu, G., Xia, Y., Chen, L., Jiang, Z., Zheng, H., & Wang, Z. (2017). Use of biochar-compost to improve properties and productivity of the degraded coastal soil in the Yellow River Delta, China. *Journal of Soils and Sediments*, *17*, 780-789.
53. Cheng, H., Jones, D. L., Hill, P., Bastami, M. S., & Tu, C. L. (2018). Influence of biochar produced from different pyrolysis temperature on nutrient retention and leaching. *Archives of Agronomy and Soil Science*, *64*(6), 850-859.
54. Major, J., Rondon, M., Molina, D., Riha, S. J., & Lehmann, J. (2010). Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. *Plant and soil*, *333*, 117-128.
55. Osman, A. I., Fawzy, S., Farghali, M., El-Azazy, M., Elgarahy, A. M., Fahim, R. A., ... & Rooney, D. W. (2022). Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: a review. *Environmental Chemistry Letters*, *20*(4), 2385-2485.
56. Labanya, R., Srivastava, P. C., Pachauri, S. P., Shukla, A. K., Shrivastava, M., & Srivastava, P. (2022). Valorisation of phyto-biochars as slow release micronutrients and sulphur carrier for agriculture. *Environmental Technology*, 1-10.
57. Kamran, M. A., Jiang, J., Li, J. Y., Shi, R. Y., Mehmood, K., Baquy, M. A. A., & Xu, R. K. (2018). Amelioration of soil acidity, Olsen-P, and phosphatase activity by manure-and peat-derived biochars in different acidic soils. *Arabian Journal of Geosciences*, *11*, 1-15.
58. Huang, P. M., Wang, M. K., & Chiu, C. Y. (2005). Soil mineral–organic matter–microbe interactions: impacts on biogeochemical processes and biodiversity in soils. *Pedobiologia*, *49*(6), 609-635.

59. Palansooriya, K. N., Wong, J. T. F., Hashimoto, Y., Huang, L., Rinklebe, J., Chang, S. X., ... & Ok, Y. S. (2019). Response of microbial communities to biochar-amended soils: a critical review. *Biochar*, *1*, 3-22.
60. Foster, E. J., Fogle, E. J., & Cotrufo, M. F. (2018). Sorption to biochar impacts β-glucosidase and phosphatase enzyme activities. *Agriculture*, *8*(10), 158.
61. Elzobair, K. A., Stromberger, M. E., Ippolito, J. A., & Lentz, R. D. (2016). Contrasting effects of biochar versus manure on soil microbial communities and enzyme activities in an Aridisol. *Chemosphere*, *142*, 145-152.
62. Aggangan, N. S., Cortes, A. D., Opulencia, R. B., Jomao-as, J. G., & Yecyec, R. P. (2019). Effects of mycorrhizal fungi and bamboo biochar on the rhizosphere bacterial population and nutrient uptake of cacao (Theobroma cacao L.) Seedlings. *Philippine Journal of Crop Science (PJCS)*, *44*(1), 1-9.
63. Wang, S., Zhao, M., Zhou, M., Li, Y. C., Wang, J., Gao, B., ... & Ok, Y. S. (2019). Biochar-supported nZVI (nZVI/BC) for contaminant removal from soil and water: a critical review. *Journal of Hazardous Materials*, *373*, 820-834.
64. Fang, Q., Chen, B., Lin, Y., & Guan, Y. (2014). Aromatic and hydrophobic surfaces of wood-derived biochar enhance perchlorate adsorption via hydrogen bonding to oxygen-containing organic groups. *Environmental science & technology*, *48*(1), 279-288.
65. Fahmi, A. H., Jol, H., & Singh, D. (2018). Physical modification of biochar to expose the inner pores and their functional groups to enhance lead adsorption. *RSC advances*, *8*(67), 38270-38280.
66. Zhang, X., Wang, H., He, L., Lu, K., Sarmah, A., Li, J., ... & Huang, H. (2013). Using biochar for remediation of soils contaminated with heavy metals and organic pollutants. *Environmental Science and Pollution Research*, *20*, 8472-8483.
67. Yang, F., Wang, B., Shi, Z., Li, L., Li, Y., Mao, Z., ... & Wu, Y. (2021). Immobilization of heavy metals (Cd, Zn, and Pb) in different contaminated soils with swine manure biochar. *Environmental Pollutants and Bioavailability*, *33*(1), 55-65.
68. Dai, S., Li, H., Yang, Z., Dai, M., Dong, X., Ge, X., ... & Shi, L. (2018). Effects of biochar amendments on speciation and bioavailability of heavy metals in coal-mine-contaminated soil. *Human and Ecological Risk Assessment: An International Journal*, *24*(7), 1887-1900.
69. Mukherjee, S., Sarkar, B., Aralappanavar, V. K., Mukhopadhyay, R., Basak, B. B., Srivastava, P., ... & Bolan, N. (2022). Biochar-microorganism interactions for organic pollutant remediation: Challenges and perspectives. *Environmental Pollution*, *308*, 119609.
70. Zhang, C., Shan, B., Zhu, Y., & Tang, W. (2018). Remediation effectiveness of Phyllostachys pubescens biochar in reducing the bioavailability and bioaccumulation of metals in sediments. *Environmental Pollution*, *242*, 1768-1776.
71. Beesley, L., Moreno-Jiménez, E., & Gomez-Eyles, J. L. (2010). Effects of biochar and greenwaste compost amendments on mobility, bioavailability and toxicity of inorganic

and organic contaminants in a multi-element polluted soil. *Environmental pollution*, *158*(6), 2282-2287.

72. Kookana, R. S. (2010). The role of biochar in modifying the environmental fate, bioavailability, and efficacy of pesticides in soils: a review. *Soil Research*, *48*(7), 627-637.
73. Zhang, X., Wang, H., He, L., Lu, K., Sarmah, A., Li, J., ... & Huang, H. (2013). Using biochar for remediation of soils contaminated with heavy metals and organic pollutants. *Environmental Science and Pollution Research*, *20*, 8472-8483.
74. Bolan, N., Kunhikrishnan, A., Thangarajan, R., Kumpiene, J., Park, J., Makino, T., ... & Scheckel, K. (2014). Remediation of heavy metal (loid) s contaminated soils–to mobilize or to immobilize?. *Journal of hazardous materials*, *266*, 141-166.
75. Mukherjee, S., Sarkar, B., Aralappanavar, V. K., Mukhopadhyay, R., Basak, B. B., Srivastava, P., ... & Bolan, N. (2022). Biochar-microorganism interactions for organic pollutant remediation: Challenges and perspectives. *Environmental Pollution*, *308*, 119609.
76. Bolan, S., Hou, D., Wang, L., Hale, L., Egamberdieva, D., Tammeorg, P., ... & Bolan, N. (2023). The potential of biochar as a microbial carrier for agricultural and environmental applications. *Science of the Total Environment*, 163968.
77. Thies, J. E., & Rillig, M. C. (2009). Characteristics of biochar: biological properties. *Biochar for environmental management: Science and technology*, *1*, 85-105.
78. Xiang, L., Harindintwali, J. D., Wang, F., Redmile-Gordon, M., Chang, S. X., Fu, Y., ... & Xing, B. (2022). Integrating biochar, bacteria, and plants for sustainable remediation of soils contaminated with organic pollutants. *Environmental Science & Technology*, *56*(23), 16546-16566.
79. Lammirato, C., Miltner, A., & Kaestner, M. (2011). Effects of wood char and activated carbon on the hydrolysis of cellobiose by β-glucosidase from Aspergillus niger. *Soil Biology and Biochemistry*, *43*(9), 1936-1942.
80. Xu, N., Tan, G., Wang, H., & Gai, X. (2016). Effect of biochar additions to soil on nitrogen leaching, microbial biomass and bacterial community structure. *European journal of soil biology*, *74*, 1-8.
81. Abujabhah, I. S., Doyle, R. B., Bound, S. A., & Bowman, J. P. (2018). Assessment of bacterial community composition, methanotrophic and nitrogen-cycling bacteria in three soils with different biochar application rates. *Journal of Soils and Sediments*, *18*, 148-158.
82. Palansooriya, K. N., Wong, J. T. F., Hashimoto, Y., Huang, L., Rinklebe, J., Chang, S. X., ... & Ok, Y. S. (2019). Response of microbial communities to biochar-amended soils: a critical review. *Biochar*, *1*, 3-22.
83. Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., & Crowley, D. (2011). Biochar effects on soil biota–a review. *Soil biology and biochemistry*, *43*(9), 1812-1836.

84. Hammer, E. C., Balogh-Brunstad, Z., Jakobsen, I., Olsson, P. A., Stipp, S. L., & Rillig, M. C. (2014). A mycorrhizal fungus grows on biochar and captures phosphorus from its surfaces. *Soil Biology and Biochemistry*, *77*, 252-260.
85. Warnock, D. D., Lehmann, J., Kuyper, T. W., & Rillig, M. C. (2007). Mycorrhizal responses to biochar in soil–concepts and mechanisms. *Plant and soil*, *300*, 9-20.
86. Thies, J. E., Rillig, M. C., & Graber, E. R. (2015). Biochar effects on the abundance, activity and diversity of the soil biota. *Biochar for environmental management: science, technology and implementation*, *2*, 327-389.
87. Alengebawy, A., Abdelkhalek, S. T., Qureshi, S. R., & Wang, M. Q. (2021). Heavy metals and pesticides toxicity in agricultural soil and plants: Ecological risks and human health implications. *Toxics*, 9(3), 42.
88. Jagaba, A. H., Kutty, S. R. M., Isa, M. H., Ghaleb, A. A. S., Lawal, I. M., Usman, A. K., ... & Soja, U. B. (2022). Toxic effects of xenobiotic compounds on the microbial community of activated sludge. *ChemBioEng Reviews*, 9(5), 497-535.
89. Zhu, K., Jia, H., Zhao, S., Xia, T., Guo, X., Wang, T., & Zhu, L. (2019). Formation of environmentally persistent free radicals on microplastics under light irradiation. *Environmental Science & Technology*, 53(14), 8177-8186.
90. Wu, J. Y., Hua, Z. L., & Gu, L. (2021). Planktonic microbial responses to perfluorinated compound (PFC) pollution: Integrating PFC distributions with community coalescence and metabolism. *Science of The Total Environment*, 788, 147743.