BIOCHAR-MEDIATED CHANGES IN SOIL MICROBIAL COMMUNITIES AND THEIR IMPACT ON NUTRIENT CYCLING AND PLANT GROWTH

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Soil is a complex and dynamic ecosystem that plays a crucial role in sustaining plant growth and maintaining environmental quality [1]. The health and productivity of soils largely depend on the diversity and activity of microbial communities residing within them [2]. These microorganisms are involved in various biogeochemical processes, including decomposition of organic matter, nutrient cycling, and formation of soil aggregates [3]. In recent years, there has been growing interest in the use of biochar as a soil amendment to enhance soil fertility, sequester carbon, and promote sustainable agriculture [4]. Biochar is a carbon-rich product obtained from the pyrolysis of biomass under limited oxygen conditions [5]. When applied to soil, biochar can interact with native microbial communities, leading to changes in their composition, diversity, and functional activities [6][7].

The scope of this review encompasses studies conducted on a wide range of soil types, biochar feedstocks, and pyrolysis conditions [8]. Focus on the effects of biochar on soil bacterial, archaeal, and fungal communities, as well as specific functional groups involved in nutrient cycling processes [9]. The implications of biochar-mediated changes in soil microbiota for plant growth and nutrition are also discussed [10]. This review is intended to provide valuable insights for researchers, practitioners, and policymakers interested in harnessing the potential of biochar for sustainable soil management and crop production.

BIOCHAR: PRODUCTION, PROPERTIES, AND SOIL APPLICATION

Biochar production methods and feedstocks

Biochar is produced through the pyrolysis of biomass, which involves heating organic materials in the absence or limited presence of oxygen [11]. The pyrolysis process can be classified into three main categories based on the heating rate and residence time: slow pyrolysis, fast pyrolysis, and gasification [12]. Slow pyrolysis is the most common method for biochar production, typically conducted at temperatures between 300-700°C with a slow heating rate and longer residence times [13]. Fast pyrolysis and gasification involve higher heating rates and shorter residence times, primarily aimed at producing bio-oil and syngas, respectively, with biochar as a byproduct [14][15].

Physicochemical properties of biochar

The physicochemical properties of biochar are determined by the feedstock type and pyrolysis conditions, which in turn influence its interactions with soil and microorganisms [16].

Table 1. Physicochemical properties of biochar derived from different feedstocks and pyrolysis temperatures

Biochar Feedstock	Pyrolysis Temperature (°C)	pH	Carbon Content (%)	Surface Area (m2/g)	Pore Volume (cm3/g)
Wood	400	7.2	75.6	245	0.18
Rice husk	500	9.8	48.3	153	0.12
Sugarcane bagasse	600	10.5	82.1	327	0.29
Poultry litter	450	8.9	39.7	87	0.07
Sewage sludge	550	7.8	28.4	63	0.05

Biochar application rates and methods

The application rates and methods of biochar incorporation into soil are important factors that can influence its effects on soil properties, microbial communities, and plant growth [17]. Biochar application rates typically range from a few tons to tens of tons per hectare, depending on the soil type, crop, and desired outcomes [18]. Lower application rates (e.g., 1-10 t/ha) are generally recommended for highly fertile soils or when the primary goal is to enhance soil microbial activity and diversity [19]. Higher application rates (e.g., 10-50 t/ha) may be necessary for highly degraded or acidic soils, or when the aim is to improve soil physical properties and carbon sequestration [20].

BIOCHAR-MEDIATED CHANGES IN SOIL PHYSICOCHEMICAL PROPERTIES

Effects on soil structure and porosity

Biochar application can have significant effects on soil structure and porosity, which in turn influence soil microbial habitats and activities [21]. When incorporated into soil, biochar particles can act as binding agents, promoting the formation and stability of soil aggregates [22]. The porous structure of biochar can also contribute to increased soil porosity, particularly in the macropore and mesopore size ranges [23][24]. These changes in soil structure and porosity can improve soil aeration, water retention, and infiltration, creating favorable conditions for microbial growth and nutrient cycling [25].

Table 2. Effects of biochar application on soil porosity in different soil textures

Soil Texture	Biochar Feedstock	Application Rate (t/ha)	Effect on Soil Porosity
Sandy loam	Woodchip	10	Increased by 15%
Silt loam	Rice husk	20	Increased by 22%
Clay loam	Sugarcane bagasse	30	Increased by 18%

Influence on soil water retention and hydraulic properties

Biochar application can significantly influence soil water retention and hydraulic properties, with important consequences for microbial activity and nutrient cycling [26]. The porous structure of biochar can increase soil water holding capacity by providing additional surface area and pore space for water adsorption and storage [27]. This is particularly beneficial in sandy soils, where water retention is often limited [28].

Table 3. Effects of biochar application on soil water retention in different soil textures

Soil Texture	Biochar Feedstock	Application Rate (t/ha)	Effect on Water Retention
Sandy loam	Woodchip	10	Increased by 18%
Silt loam	Rice husk	20	Increased by 12%
Clay loam	Sugarcane bagasse	30	Increased by 8%

Alterations in soil pH and electrical conductivity

Biochar application can alter soil pH and electrical conductivity (EC), which are important factors influencing microbial community composition and activity [29][30]. The pH of biochar is typically higher than that of most soils, particularly when produced at high pyrolysis temperatures [31].

Table 4. Effects of biochar application on soil pH in different soil types

Soil Type	Initial pH	Biochar Feedstock	Application Rate (t/ha)	Final pH
Acidic	4.5	Woodchip	10	5.2
Neutral	6.8	Rice husk	20	7.3
Alkaline	8.1	Sugarcane bagasse	30	8.5

When incorporated into soil, biochar can increase soil pH through the release of alkaline substances, such as carbonates and oxides [32].

Impacts on soil organic matter and nutrient availability

Biochar application can significantly influence soil organic matter (SOM) dynamics and nutrient availability, with important implications for microbial communities and plant growth [33]. Biochar itself is a form of highly stable organic matter, resistant to microbial decomposition due to its aromatic structure and high C:N ratio [34][35].

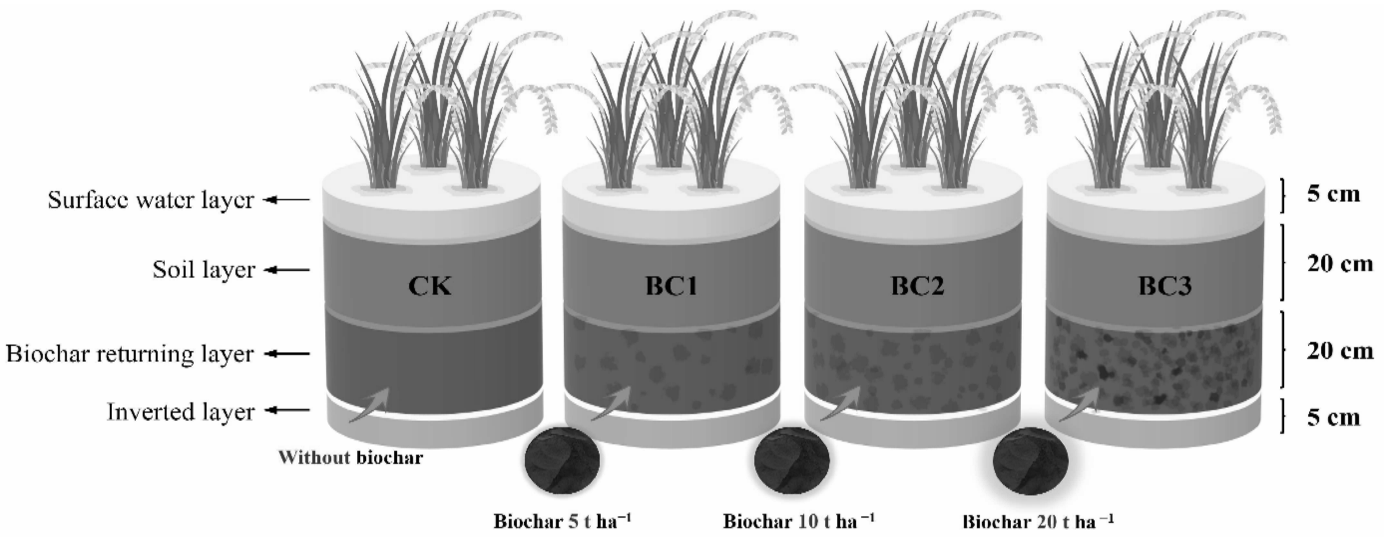

Fig.1 Soil Organic Carbon Changes After Biochar Application

When incorporated into soil, biochar can contribute to long-term carbon sequestration and improve soil organic carbon (SOC) stocks [36].

Table 6. Effects of biochar application on soil organic carbon (SOC) in different soil types

Soil Type	Initial SOC (%)	Biochar Feedstock	Application Rate (t/ha)	Final SOC (%)
Sandy	0.8	Woodchip	10	1.5
Loamy	1.5	Rice husk	20	2.8
Clayey	2.2	Sugarcane bagasse	30	4.1

BIOCHAR AS A HABITAT FOR SOIL MICROORGANISMS

Biochar pore structure and microbial colonization

The porous structure of biochar is a key factor influencing its ability to serve as a habitat for soil microorganisms [37]. Biochar porosity is determined by the feedstock type and pyrolysis conditions, with higher pyrolysis temperatures generally resulting in greater pore development [38]. The pores in biochar range in size from nanometers to micrometers, providing a diverse array of micro-habitats for microbial colonization [39].

Table 7. Pore size distribution and surface area of biochar derived from different feedstocks and pyrolysis temperatures

Soil Type	Initial SOC (%)	Biochar Feedstock	Application Rate (t/ha)	Final SOC (%)
Sandy	0.8	Woodchip	10	1.5
Loamy	1.5	Rice husk	20	2.8
Clayey	2.2	Sugarcane bagasse	30	4.1

Biochar surface properties and microbial attachment

In addition to its porous structure, the surface properties of biochar can significantly influence microbial attachment and colonization [40]. Biochar surfaces are characterized by a complex array of functional groups, such as carboxyl, hydroxyl, and phenolic groups, which can interact with microbial cells and affect their adhesion and growth [41].

Biochar as a refuge for microorganisms under environmental stresses

Biochar can serve as a refuge for soil microorganisms under various environmental stresses, such as drought, extreme temperatures, and soil contamination [42]. The porous structure and adsorptive properties of biochar can create protective micro-habitats for microorganisms, buffering them against adverse conditions and promoting their survival and activity [43].

Table 8. Effects of biochar on microbial communities under different environmental stresses

Environmental Stress	Biochar Feedstock	Application Rate (t/ha)	Effect on Microbial Communities
Drought	Woodchip	10	Increased microbial biomass and diversity
Heat stress	Rice husk	20	Maintained microbial activity and soil respiration
Heavy metal contamination	Sugarcane bagasse	30	Reduced metal toxicity and promoted metal-tolerant microbes
Organic pollutants	Poultry litter	15	Enhanced degradation and reduced toxicity
Salinity	Sewage sludge	25	Mitigated salt stress and increased microbial diversity

BIOCHAR EFFECTS ON SOIL MICROBIAL COMMUNITY COMPOSITION & DIVERSITY

Shifts in bacterial and archaeal communities

Biochar application can induce significant shifts in the composition and diversity of soil bacterial and archaeal communities [44]. These changes are driven by the complex interactions between biochar properties, soil characteristics, and environmental factors [45].

Table 9. Effects of biochar on soil bacterial and archaeal community composition in different soil types and cropping systems

Soil Type	Cropping System	Biochar Feedstock	Application Rate (t/ha)	Effect on Bacterial and Archaeal Communities
Sandy loam	Maize	Woodchip	10	Increased diversity and shifted towards Gram-negative bacteria
Silt loam	Wheat-soybean	Rice husk	20	Increased abundance of Actinobacteria and Firmicutes
Clay loam	Sugarcane	Sugarcane bagasse	30	Increased diversity and shifted towards Proteobacteria
Loamy sand	Vegetable	Poultry litter	15	Increased abundance of Chloroflexi and Planctomycetes
Sandy clay loam	Rice	Sewage sludge	25	Increased diversity and shifted towards Nitrospirae and Thaumarchaeota

Changes in fungal communities

Biochar application can also significantly influence the composition and diversity of soil fungal communities, with important implications for soil health and plant growth [46]. Fungi play key roles in soil nutrient cycling, organic matter decomposition, and plant symbioses, and their responses to biochar can have cascading effects on soil-plant interactions [47].

Table 10. Effects of biochar on soil fungal community composition in different soil types and cropping systems

Soil Type	Cropping System	Biochar Feedstock	Application Rate (t/ha)	Effect on Fungal Communities
Sandy loam	Maize	Woodchip	10	Increased diversity and shifted towards Ascomycota
Silt loam	Wheat-soybean	Rice husk	20	Increased abundance of Basidiomycota and AMF
Clay loam	Sugarcane	Sugarcane bagasse	30	Increased diversity and shifted towards Glomeromycota
Loamy sand	Vegetable	Poultry litter	15	Increased abundance of Chytridiomycota and Zygomycota
Sandy clay loam	Rice	Sewage sludge	25	Increased diversity and shifted towards Mucoromycotina

Impacts on microbial diversity and richness indices

Biochar application can have significant impacts on the diversity and richness of soil microbial communities, which are key indicators of soil health and functioning [48]. Microbial diversity refers to the variety and evenness of microbial taxa in a given soil, while microbial richness refers to the number of different taxa present [49]. These indices provide important information on the complexity and stability of soil microbial communities, as well as their potential for resilience and adaptation to environmental changes [50].

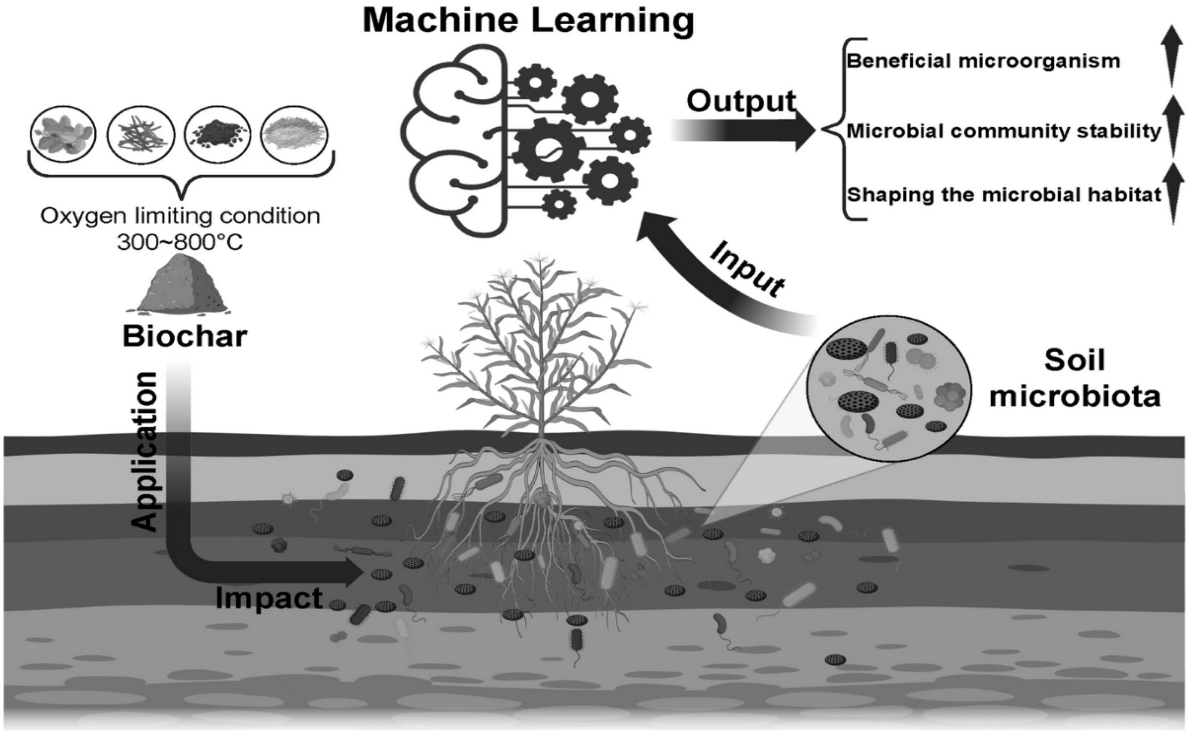

Fig. 2 Biochar Effects on Soil Microbial Community Composition

6. Biochar-Mediated Changes in Microbial Functions Related to Nutrient Cycling

Carbon cycle

Biochar application can significantly influence soil carbon cycling processes, such as organic matter decomposition, microbial biomass production, and greenhouse gas emissions [51]. The high carbon content and aromatic structure of biochar make it resistant to microbial degradation, allowing it to persist in soil for long periods and contribute to soil carbon sequestration [52].

Nitrogen cycle

Biochar can have significant impacts on soil nitrogen cycling processes, such as nitrogen mineralization, nitrification, and denitrification [53]. The high surface area and cation exchange capacity of biochar can adsorb ammonium and nitrate ions, reducing their leaching and increasing their retention in soil [54].

Phosphorus cycle

Biochar can affect soil phosphorus cycling processes, such as phosphorus solubilization, mineralization, and immobilization [55]. The high surface area and porosity of biochar can adsorb phosphorus ions, reducing their leaching and increasing their retention in soil [56]. Biochar can also modify soil pH and microbial community composition, affecting the activities of phosphorus-cycling microbes and the rates of phosphorus transformations [57].

Implications of Biochar-Induced Microbial Changes for Plant Growth and Nutrition

Biochar amendment can have significant implications for plant-microbe interactions in the rhizosphere, which is the narrow zone of soil surrounding plant roots [58]. Biochar amendment impacts plant-microbe interactions in the rhizosphere, influencing nutrient acquisition through plant growth-promoting microbes. These changes affect plant growth, yield, and nutrient uptake [59]. Additionally, biochar can serve as a carrier for beneficial microorganisms like plant growth-promoting bacteria and fungi, which can be inoculated into the biochar before soil application, further enhancing its positive effects on plant-soil systems [60].

Challenges, Knowledge Gaps, and Future Research Directions

One of the main challenges in understanding the effects of biochar on soil microbial communities is the high variability in biochar properties and the corresponding microbial responses [61]. Challenges in understanding biochar's effects on soil microbial communities include variability in biochar properties, lack of long-term studies, and interactions with other amendments [62]. Scaling up from small-scale experiments to field-level applications presents difficulties. Future research should focus on integrating biochar into sustainable agriculture practices, considering its complementary role with other soil and crop management strategies for optimal results [63].

CONCLUSION

Biochar application to soil has emerged as a promising strategy for enhancing soil microbial communities, nutrient cycling processes, and plant productivity, while also contributing to climate change mitigation through carbon sequestration. This review highlights the complex and multifaceted interactions between biochar, soil microorganisms, and nutrient cycling processes, and their implications for sustainable agriculture and environmental management. Future research should focus on addressing these challenges and knowledge gaps, by conducting long-term, large-scale, and integrative studies that can better capture the complexity and heterogeneity of biochar-soil-microbe interactions across different agroecosystems.

REFERENCES

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.

Bruun, E. W., Ambus, P., Egsgaard, H., & Hauggaard-Nielsen, H. (2012). Effects of slow and fast pyrolysis biochar on soil C and N turnover dynamics. Soil Biology and Biochemistry, 46, 73-79.

Cayuela, M. L., Van Zwieten, L., Singh, B. P., Jeffery, S., Roig, A., & Sánchez-Monedero, M. A. (2014). Biochar's role in mitigating soil nitrous oxide emissions: A review and meta-analysis. Agriculture, Ecosystems & Environment, 191, 5-16.

Chan, K. Y., Van Zwieten, L., Meszaros, I., Downie, A., & Joseph, S. (2008). Agronomic values of greenwaste biochar as a soil amendment. Soil Research, 45(8), 629-634.

Chen, J., Liu, X., Zheng, J., Zhang, B., Lu, H., Chi, Z., ... & Wang, J. (2013). Biochar soil amendment increased bacterial but decreased fungal gene abundance with shifts in community structure in a slightly acid rice paddy from Southwest China. Applied Soil Ecology, 71, 33-44.

Cheng, C. H., Lehmann, J., & Engelhard, M. H. (2008). Natural oxidation of black carbon in soils: changes in molecular form and surface charge along a climosequence. Geochimica et Cosmochimica Acta, 72(6), 1598-1610.

Chintala, R., Mollinedo, J., Schumacher, T. E., Malo, D. D., & Julson, J. L. (2014). Effect of biochar on chemical properties of acidic soil. Archives of Agronomy and Soil Science, 60(3), 393-404.

Clough, T. J., & Condron, L. M. (2010). Biochar and the nitrogen cycle: introduction. Journal of environmental quality, 39(4), 1218-1223.

Clough, T., Condron, L., Kammann, C., & Müller, C. (2013). A review of biochar and soil nitrogen dynamics. Agronomy, 3(2), 275-293.

Cornelissen, G., Martinsen, V., Shitumbanuma, V., Alling, V., Breedveld, G. D., Rutherford, D. W., ... & Mulder, J. (2013). Biochar effect on maize yield and soil characteristics in five conservation farming sites in Zambia. Agronomy, 3(2), 256-274.

Dai, Z., Zhang, X., Tang, C., Muhammad, N., Wu, J., Brookes, P. C., & Xu, J. (2017). Potential role of biochars in decreasing soil acidification-A critical review. Science of the Total Environment, 581, 601-611.

Dempster, D. N., Gleeson, D. B., Solaiman, Z. I., Jones, D. L., & Murphy, D. V. (2012). Decreased soil microbial biomass and nitrogen mineralisation with Eucalyptus biochar addition to a coarse textured soil. Plant and Soil, 354(1), 311-324.

Ding, Y., Liu, Y. X., Wu, W. X., Shi, D. Z., Yang, M., & Zhong, Z. K. (2010). Evaluation of biochar effects on nitrogen retention and leaching in multi-layered soil columns. Water, Air, & Soil Pollution, 213(1), 47-55.

Domene, X., Mattana, S., Hanley, K., Enders, A., & Lehmann, J. (2014). Medium-term effects of corn biochar addition on soil biota activities and functions in a temperate soil cropped to corn. Soil Biology and Biochemistry, 72, 152-162.

El-Naggar, A., Lee, S. S., Rinklebe, J., Farooq, M., Song, H., Sarmah, A. K., ... & Ok, Y. S. (2019). Biochar application to low fertility soils: a review of current status, and future prospects. Geoderma, 337, 536-554.

Fang, Y., Singh, B., Singh, B. P., & Krull, E. (2014). Biochar carbon stability in four contrasting soils. European Journal of Soil Science, 65(1), 60-71.

Farrell, M., Kuhn, T. K., Macdonald, L. M., Maddern, T. M., Murphy, D. V., Hall, P. A., ... & Baldock, J. A. (2013). Microbial utilisation of biochar-derived carbon. Science of the Total Environment, 465, 288-297.

Glaser, B., Lehmann, J., & Zech, W. (2002). Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal–a review. Biology and fertility of soils, 35(4), 219-230.

Gul, S., Whalen, J. K., Thomas, B. W., Sachdeva, V., & Deng, H. (2015). Physico-chemical properties and microbial responses in biochar-amended soils: mechanisms and future directions. Agriculture, Ecosystems & Environment, 206, 46-59.

Ippolito, J. A., Laird, D. A., & Busscher, W. J. (2012). Environmental benefits of biochar. Journal of environmental quality, 41(4), 967-972.

Kammann, C. I., Schmidt, H. P., Messerschmidt, N., Linsel, S., Steffens, D., Müller, C., ... & Stephen, J. (2015). Plant growth improvement mediated by nitrate capture in co-composted biochar. Scientific Reports, 5(1), 1-13.

Karhu, K., Mattila, T., Bergström, I., & Regina, K. (2011). Biochar addition to agricultural soil increased CH4 uptake and water holding capacity–results from a short-term pilot field study. Agriculture, ecosystems & environment, 140(1-2), 309-313.

Laird, D. A., Fleming, P., Davis, D. D., Horton, R., Wang, B., & Karlen, D. L. (2010). Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. Geoderma, 158(3-4), 443-449.

Lehmann, J., & Joseph, S. (2015). Biochar for environmental management: science, technology and implementation. Routledge.

Lehmann, J., Gaunt, J., & Rondon, M. (2006). Bio-char sequestration in terrestrial ecosystems–a review. Mitigation and adaptation strategies for global change, 11(2), 403-427.

Li, Y., Hu, S., Chen, J., Müller, K., Li, Y., Fu, W., ... & Wang, H. (2018). Effects of biochar application in forest ecosystems on soil properties and greenhouse gas emissions: a review. Journal of Soils and Sediments, 18(2), 546-563.

Li, Y., Hu, S., Chen, J., Müller, K., Li, Y., Fu, W., ... & Wang, H. (2018). Effects of biochar application in forest ecosystems on soil properties and greenhouse gas emissions: a review. Journal of Soils and Sediments, 18(2), 546-563.

Liang, B., Lehmann, J., Sohi, S. P., Thies, J. E., O'Neill, B., Trujillo, L., ... & Luizão, F. J. (2010). Black carbon affects the cycling of non-black carbon in soil. Organic Geochemistry, 41(2), 206-213.

Liu, X., Zhang, A., Ji, C., Joseph, S., Bian, R., Li, L., ... & Paz-Ferreiro, J. (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.

Novak, J. M., Lima, I., Xing, B., Gaskin, J. W., Steiner, C., Das, K. C., ... & Schomberg, H. (2009). Characterization of designer biochar produced at different temperatures and their effects on a loamy sand. Annals of Environmental Science, 3, 195-206.

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(1), 3-22.

Prendergast□Miller, M. T., Duvall, M., & Sohi, S. P. (2011). Localisation of nitrate in the rhizosphere of biochar□amended soils. Soil Biology and Biochemistry, 43(11), 2243-2246.

Rogovska, N., Laird, D., Cruse, R., Fleming, P., Parkin, T., & Meek, D. (2011). Impact of biochar on manure carbon stabilization and greenhouse gas emissions. Soil Science Society of America Journal, 75(3), 871-879.

Rondon, M. A., Lehmann, J., Ramírez, J., & Hurtado, M. (2007). Biological nitrogen fixation by common beans (Phaseolus vulgaris L.) increases with bio-char additions. Biology and fertility of soils, 43(6), 699-708.

Saarnio, S., Heimonen, K., & Kettunen, R. (2013). Biochar addition indirectly affects N2O emissions via soil moisture and plant N uptake. Soil Biology and Biochemistry, 58, 99-106.

Saifullah, Dahlawi, S., Naeem, A., Rengel, Z., & Naidu, R. (2018). Biochar application for the remediation of salt-affected soils: Challenges and opportunities. Science of the Total Environment, 625, 320-335.

Singh, B. P., Cowie, A. L., & Smernik, R. J. (2012). Biochar carbon stability in a clayey soil as a function of feedstock and pyrolysis temperature. Environmental science & technology, 46(21), 11770-11778.

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.

Spokas, K. A., Cantrell, K. B., Novak, J. M., Archer, D. W., Ippolito, J. A., Collins, H. P., ... & Nichols, K. A. (2012). Biochar: a synthesis of its agronomic impact beyond carbon sequestration. Journal of environmental quality, 41(4), 973-989.

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), 35-42.

Steinbeiss, S., Gleixner, G., & Antonietti, M. (2009). Effect of biochar amendment on soil carbon balance and soil microbial activity. Soil Biology and Biochemistry, 41(6), 1301-1310.

Steiner, C., Teixeira, W. G., Lehmann, J., Nehls, T., de Macêdo, J. L. V., Blum, W. E., & Zech, W. (2007). Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. Plant and soil, 291(1), 275-290.

Van Zwieten, L., Kimber, S., Morris, S., Chan, K. Y., Downie, A., Rust, J., ... & Cowie, A. (2010). Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. Plant and soil, 327(1), 235-246.

Wang, D., Fonte, S. J., Parikh, S. J., Six, J., & Scow, K. M. (2017). Biochar additions can enhance soil structure and the physical stabilization of C in aggregates. Geoderma, 303, 110-117.

Wang, J., Pan, X., Liu, Y., Zhang, X., & Xiong, Z. (2012). Effects of biochar amendment in two soils on greenhouse gas emissions and crop production. Plant and soil, 360(1), 287-298.

Weng, Z., Van Zwieten, L., Singh, B. P., Tavakkoli, E., Joseph, S., Macdonald, L. M., ... & Cowie, A. (2017). Biochar built soil carbon over a decade by stabilizing rhizodeposits. Nature Climate Change, 7(5), 371-376.

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), 1-9.

Xiao, X., Chen, B., Chen, Z., Zhu, L., & Schnoor, J. L. (2018). Insight into multiple and multilevel structures of biochars and their potential environmental applications: a critical review. Environmental science & technology, 52(9), 5027-5047.

Xu, G., Wei, L. L., Sun, J. N., Shao, H. B., & Chang, S. X. (2013). What is more important for enhancing nutrient bioavailability with biochar application into a sandy soil: Direct or indirect mechanism. Ecological Engineering, 52, 119-124.

Xu, G., Zhang, Y., Sun, J., & Shao, H. (2016). Negative interactive effects between biochar and phosphorus fertilization on phosphorus availability and plant yield in saline sodic soil. Science of the Total Environment, 568, 910-915.

Xu, R. K., Zhao, A. Z., Yuan, J. H., & Jiang, J. (2012). pH buffering capacity of acid soils from tropical and subtropical regions of China as influenced by incorporation of crop straw biochars. Journal of Soils and Sediments, 12(4), 494-502.

Xu, X., Zhao, Y., Sima, J., Zhao, L., Mašek, O., & Cao, X. (2017). Indispensable role of biochar-inherent mineral constituents in its environmental applications: A review. Bioresource Technology, 241, 887-899.

Yanai, Y., Toyota, K., & Okazaki, M. (2007). Effects of charcoal addition on N2O emissions from soil resulting from rewetting air□dried soil in short□term laboratory experiments. Soil Science & Plant Nutrition, 53(2), 181-188.

Yao, Y., Gao, B., Zhang, M., Inyang, M., & Zimmerman, A. R. (2012). Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. Chemosphere, 89(11), 1467-1471.

Ye, J., Joseph, S. D., Ji, M., Nielsen, S., Mitchell, D. R., Donne, S., ... & Munroe, P. (2017). Chemolithotrophic processes in the bacterial communities on the surface of mineral-enriched biochars. The ISME Journal, 11(5), 1087-1101.

Yu, H., Zou, W., Chen, J., Chen, H., Yu, Z., Huang, J., ... & Gao, B. (2019). Biochar amendment improves crop production in problem soils: A review. Journal of Environmental Management, 232, 8-21.

Yuan, J. H., Xu, R. K., & Zhang, H. (2011). The forms of alkalis in the biochar produced from crop residues at different temperatures. Bioresource technology, 102(3), 3488-3497.

Zhang, A., Liu, Y., Pan, G., Hussain, Q., Li, L., Zheng, J., & Zhang, X. (2012). Effect of biochar amendment on maize yield and greenhouse gas emissions from a soil organic carbon poor calcareous loamy soil from Central China Plain. Plant and soil, 351(1), 263-275.

Zhang, D., Yan, M., Niu, Y., Liu, X., van Zwieten, L., Chen, D., ... & Zheng, J. (2016). Is current biochar research addressing global soil constraints for sustainable agriculture. Agriculture, Ecosystems & Environment, 226, 25-32.

Zhang, H., Chen, C., Gray, E. M., Boyd, S. E., Yang, H., & Zhang, D. (2016). Roles of biochar in improving phosphorus availability in soils: A phosphate adsorbent and a source of available phosphorus. Geoderma, 276, 1-6.

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