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RESEARCH ARTICLE

BIOCHAR AND AGRICULTURAL SUSTAINABILITY: A REVIEW OF CROP, SOIL AND ENVIRONMENTAL INTERACTIONS

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ABSTRACT

Soil degradation resulting from modern agricultural practices is of great concern and requires a sustainable management approach. The use of biochar has gain popularity due to its potential for providing lasting improvements to soil quality, eco-friendliness and ease of preparation by farmers. This review delves into biochar's role towards addressing sustainability issues in agriculture with emphasis on mechanisms of its interactions with soil for improved crop yield and environmental safety. Biochar enhances soil water holding capacity (WHC) by proliferating soil water holding sites due to its surface area and numerous water retention pores thus nourishing crops with required moisture for its growth. It lowers soil bulk density by replacing peds and clogging voids between grains thus promoting root growth. Moreso, it increases soil aggregate stability by forming stable soil-biochar complexes thus fortifying soil aggregates against erosion and degradation. It increases soil nutrient retention through surface oxidation reactions in soil due to its functional group. It promotes microbial abundance and diversity due to its network of pore as well as its dark color which shields soil microbes from predators. It also increases crop resistance to diseases, reduce bio-availability of heavy metals and contaminants. By providing comprehensive analysis of mechanisms of biochar interaction with the soil system, it is envisaged that this may provide policy makers, farmers and land users the information on the inherent capabilities of biochar for achieving global food security through sustainable soil management, crop yield increases and getting the environment rid of pollutants.

KEYWORDS

Agricultural sustainability, Biochar, Soil properties, Crop productivity, Environmental sustainability.

1. INTRODUCTION

The anticipated surge in global population to more than 9.7 billion by 2050 is expected to drive up the demand for food worldwide by 35-56 % between 2010 and 2050 (UNDESA 2024). Upscaling food production as a means of achieving food security for the anticipated population surge had led to intensification of different agricultural system with consequential impacts on the soil, crop yield and the environment like soil acidification, degradation occasioned by organic matter loss and environmental pollution thus raises concern of sustainability. Organic soil amendment of various forms has been used before now to ameliorate the impacts of agricultural intensification on the soil with respect to crop yield and environmental sustainability. Such amendment could either be charred or uncharred. However, high temperature of the tropics may encourage fast decomposition of uncharred amendments thus making them release their nutrients faster when compared to charred ones.

Biochar, a charred form of organic amendment has gained popularity owing to its lasting influence on soil quality, ease of preparation by farmers, economically friendly nature in terms of production and re-usability, its recalcitrance which makes it effective in the soil for a longer period. It is produced by heating carbonaceous feedstock in an oxygen starved environment (Adwani and Singh, 2023). It is produced through stabilization and structural aromatization of organic wastes like manures, crop residues and municipal wastes in conditions of high temperature and less pollution leading to efficient resource utilization (Nguyen et al., 2019). Its use in soil helps to enhance soil physio-chemical and biological properties, consequently impacting crop growth positively. For instance, its incorporation improves the soil water holding capacity through proliferation soil water retention pores, it decreases the soil bulk density and porosity due to its porous structure and extensive surface area. Biochar promotes soil chemical properties by enhancing nutrient availability and minimizing losses due to the abundance of functional groups on its surface which helps to buffer the plants from the impact of pH extremes and enhances the soil reactivity. For instance, it reduces soil acidity by binding the abundant H^+ ions of acidic soils with its negatively charged functional groups thereby raising the soil pH. Moreso, biochar's incorporation in the soil system promotes microbial population in the soil due to its dark color which shields the organisms from their predators, thus promoting their mineralization activities.

Biochar has also been used as an efficient innovation for promoting environmental sustainability by ameliorating the consequences of excessive use of agrochemicals like pesticides, herbicides etc. from the environment. Its effectiveness has been linked to its adsorptive capacity which is directly proportional to its functional groups, cation exchange capacity and surface area (Yaashika et al., 2020). Agro-chemicals such as pesticides, herbicides often used in modern agriculture for the improvement of crop yield pose a major health risk to the environment, reduce soil enzymatic and microbial functions with negatively consequences on soil physio-chemical properties, crop growth and environment (Borowik et al., 2023; Safaei Khoran et al., 2016). Minimizing the impacts of these agrochemicals on the ecosystem with biochar at less cost offers a better alternative. Hence, this review aims to critically examine mechanisms of biochar interaction toward promoting agricultural sustainability from soil, crop and environmental viewpoints. It is envisaged that this may provide policy makers, farmers and land users the information on the mechanisms involved on the use of biochar for achieving global food security through sustainable soil management, crop

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yield increases and getting the environment rid of pollutants.

2. Biochar's Interaction with The Soil System

Biochar's interaction with the soil system is greatly influenced by its inherent properties i.e. elemental composition, density, porosity etc. which are traceable to the biomass source, treatment and pyrolysis conditions (figure 1). This is because biochar is produced from volatile and non-volatile compounds like aliphatic substances and aromatic substances respectively which are rich in carbon and low oxygen contents and rise in temperature during pyrolysis affects aliphatic compounds (Ortiz et al., 2020). Biomass, when transformed at low temperatures can better improve soil quality than those produced at high temperature, this is because pyrolysis at high temperature reduces hydrogen and oxygen to carbon ratios in the resulting biochar (Sato et al., 2019). During pyrolysis, there is rise in carbon contents and reduction in hydroxyl contents and Major changes occur between 200ºc and 400°c. Increasing the temperature results in gradual rise in carbon and oxygen to the limit values of 100% and 0% respectively. For instance, pyrolysis of wood at temperatures above 700ºc decreases its hydrogen contents below 2% from 5-7% (Weber and Quicker, 2018). Also, feedstock type from which biochar is made is of great importance with respect to biochar's inherent properties (physical and chemical). This is because biomass, substances of biological, organic and inorganic origin are categorized either as woody or non-woody with varying properties (Yaashika et al., 2020). Woody biomass has high density, less dampness, void and debris compared with non-woody biomass, thus requiring less energy to attain the required pyrolysis temperature and better yield.

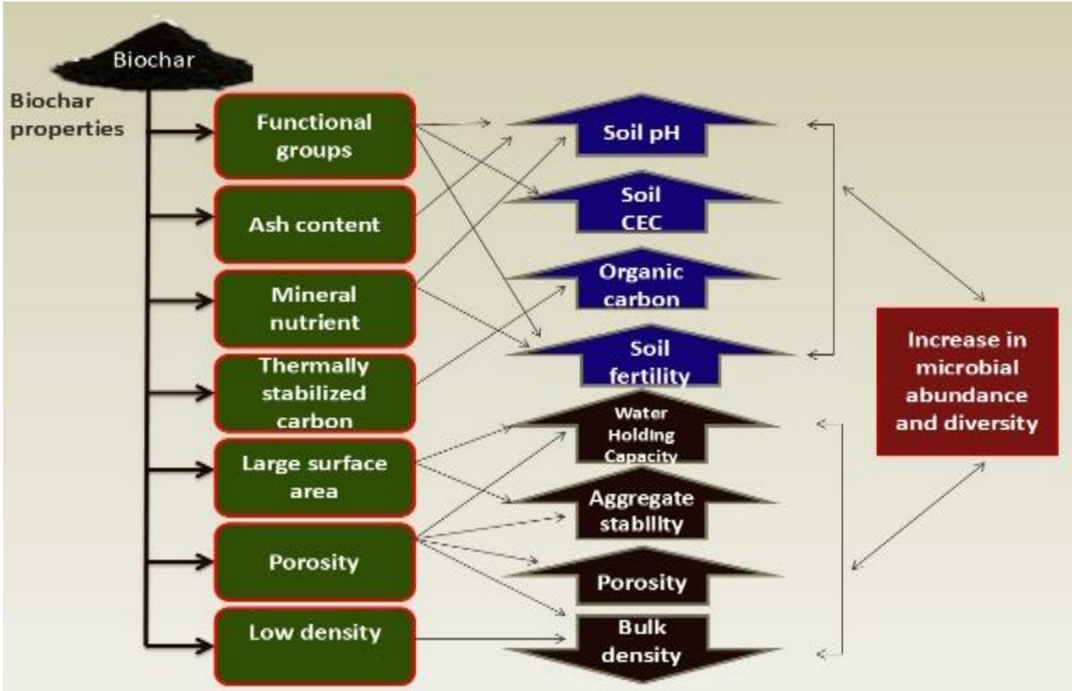

Figure 1: Biochar interaction with the soil system through its inherent properties.

2.1 Interaction of Biochar with the Physical Attributes of the Soil System

Biochar, when incorporated into soils exert direct influence on its physical attributes. These attributes which are usually described in the context of soil three phased system (solid, liquid and gaseous phases) largely projects the quality and health of the soil ecosystem. It influences pore size compositions, soil surface area, soil moisture retention capacity, bulk density and soil aeration for enhanced crop growth through different mechanisms. These influences and the mechanisms involved are discussed below;

2.1.1 Soil water retention capacity

Water retention capacity of soils has been reported by numerous studies to be impacted when biochar is incorporated into its system. However, the mechanism through which it impacts the soil moisture retention capacity could be linked to the multi-dimensional alteration of different soil physical properties upon incorporation (Figure 1). For instance, biochar's improvement of soil moisture retention was reported to have been linked to its porous nature which lowers the permeability resistance of the soil to fluid flow (Bhat et al., 2022). Its incorporation leads to the proliferation of soil water holding sites arising from additional water retention pores of biochar itself thus raising the soil moisture retention capacity (Yang et al., 2021). A group researcher attributed the rise in soil water retention upon biochar incorporation to its modification of soil structure rather than the internal porosity of biochar itself and that biochar age significantly influences its soil moisture retention rather than its application rates (Martin et al., 2023).

This suggests that the redistribution and rearrangement of biochar particles when incorporated into the soil may result to the alteration in the sizes and the number of drainage pores and a consequential increase in the number of soil water retention pores. However, this contradicts a study by a group researcher which found that adding more biochar to soil increases its moisture level and that there is a strong link between the amount of biochar applied and soil's ability to retain moisture (Chang et al., 2021). It was further reported that there is 1.2% increase in soil moisture retention by mass when incorporation rate increases by 1% up to 20%. This was in line with the study conducted which found that there is a strong link between soil moisture retention and percentage concentration of incorporated biochar below 10% on sandy loamy soil and that increase in soil moisture retention became constant at 12% biochar concentration (Yu et al., 2013).

2.1.2 Bulk density and total porosity

Soil bulk density has a direct link with the physical state of soil at a particular time because it reflects the degree of compaction or looseness of a dispersed soil system. It directly impacts pore distribution within the soil system because its status at a particular point exerts great influence on soil three phase composition. This is because reduced bulk density lowers soil compaction, increases porosity, moisture retention capacity and enhance nutrient release for crop use (Tang et al., 2022). Addition of biochar into soil influences its pore network via its own internal porous system and location in the dispersed soil system (Yi et al., 2020). It influences the soil bulk density and porosity through its location in the soil system by occupying and clogging voids between soil grains as well as replacing soil grains from previously occupied spaces which may occur through cultivation (Edeh et al., 2020). Research has shown that use of biochar can enhance soil porosity and decrease bulk density at a proportionate rate with its application (Liu et al., 2020). This was attributed to the fact that biochar retains the cell wall structure of its originating biomass feedstock. It also influences the porosity of the soil through its surface area and numerous interconnected pores which enhances the flow of gases, vapor or the mixture. Similarly, the range of biochar's particle and bulk densities i.e. 1.5-2.0 g cm^{-3} and 0.6 g cm^{-3} respectively which is considered low when compared to those of mineral soils i.e. 2.4–2.8 g cm^{-3} and 1.25 g cm^{-3} respectively has been attributed to its influence on reducing soil bulk density (Yu et al., 2019). A study demonstrated that, as the amount of biochar applied increased in greenhouse tomato cultivation, there was a corresponding decrease in soil bulk density and an increase in porosity (Zhang et al., 2020). This was attributed to the fact that biochar's bulk density was lower than that of the soil with which it was applied. Moreso, an assessment of the effects of biochar age and rate on soil properties by a group researcher revealed that soil bulk density reduces with increasing biochar application rate under different soil types (Zanutel et al., 2024).

2.1.3 Soil aggregation and structure

Soil aggregate stability reflects the resistivity or susceptibility of soil to deformation when exposed to destructive forces like rainfall, compaction and puddling. It is a reliable parameter for characterizing soil structure. Unstable soil aggregation enhances water and wind erosion, disintegration of particles and clogging of soil pores and surface crusting (Haque et al., 2021). Biochar incorporation in the soil promotes soil aggregation by shielding soil microbes like fungi from their predators, hence promoting the deposition of their mycelia which binds particles together. Also, biochar incorporation in soil raises the organic carbon level of the soil which binds soil peds together and reduces their disintegration (Yang and Lu 2021). Moreso, biochar surface characteristics and porous structure could assists in the adsorption and protection of soil mineral as well as organic matter through formation of organo-mineral complexes in the soil leading to enhanced aggregation of soil peds. Finally, the stability of saline and alkaline soils can be enhanced with the modification of biochar with Iron (Fe) such that it forms an organo-iron complex and increases its organic carbon concentration (Chen et al., 2024)

2.2 Interaction of Biochar with the Chemical Attributes of the Soil System

2.2.1 Soil pH

Biochar pH is largely dependent on its pyrolysis temperature, rates and residence time. This is because pyrolyzing biochar at higher temperature, low heating rate and elongated residence time results in biochar with alkaline pH values i.e. pH > 7 while biochar pyrolyzed at faster heating rate, reduced residence time and low temperature yield biochar with an acidic pH value (Uroic Stefanko and Leszczynska, 2020). This is because pyrolyzing biomass at high temperature results in the detachment and fracture of biochar's weak hydroxyl bonds leading to an increase in its pH. Biochar characterized with an alkaline pH assists in reducing soil acidification through its abundant functional groups (El-Naggar et al., 2019) thus enhancing nutrient availability for plant use. It does this through its interaction with the soil system through the binding of its functional groups with negative charges such as the phenolic, carboxyl and hydroxyl groups with the H^+ ions of the soil leading to a reduced H^+ ion influence and a consequential pH increase (Wu et al., 2020). Soils with acid pH reduce availability of essential nutrients for plants, while increasing mobility of heavy metals (Huang et al., 2023). Moreso, biochar could also be used to reduce pH of alkaline soils because biochar incorporation into the soil brings about oxidation reaction and production of acids (Zhang et al., 2019). A group researchers attributes the pH reduction to the transformation of $NaHCO_3$ and Na_2CO_3 in the soil to Ca $(HCO_3)_2$ and $CaCO_3$ consequently reducing the soil pH (Liu et al., 2020). Capitalizing on biochar pH could also assists in getting the soil rid of ionic pesticides. This is possible by adsorbing them on biochar surface because pesticides with negative charges are easily adsorbed on surface of biochar with an enriched positive charge and vice-versa.

Several research findings have shown that biochar modifies soil pH, leading to improved fertility and enhancement of crop growth. For instance, a group researcher reported that application of pinewood biochar helps to enhance buffering capacity of the soil thus providing suitable pH for improved root architecture of muscadine grape (Chang et al., 2021). Similarly, rice straw biochar was reported to have buffering effect and increase rice tolerance to osmotic stress when planted on salt affected soil (Hafeez et al., 2021). This may be due to the protonation of the hydrogen ions in acidic soils by the biochar's weak functional groups.

2.2.2 Soil cation exchange capacity

The extent which the soil can retain cations in forms that can be exchanged for plants use is regarded as its cation exchange capacity (CEC). This soil chemical attribute increases with the quantity of negative mineral charges on soil surface. Biochar incorporation into the soil brings about surface oxidation reactions when it comes in contact with soil water and oxygen due its functional groups thus contributing to soil reactivity (Cheng and Lehmann, 2009). Pyrolysis of biomass creates oxygen-containing functional groups like hydroxyl and carboxyl on surface of the resulting biochar. These functional groups are the key contributors to biochar's CEC and its reactivity in the soil system (Tomczyk et al., 2019). However, the extent of its contributions is moderated by the biomass feedstock source and pyrolysis temperature. Increasing pyrolysis temperature result in escape of organic acids, reduces the electrical charge density at biochar's surface and increase in its surface area (Lehmann et al., 2011; Hossain et al. 2020). This corroborates findings that increasing pyrolysis temperature for corn straw biochar from 450º C to 700º C led to a decrease in its CEC from 26.36 cmol kg^{-1} to 10.28 cmol kg^{-1} (Fang et al., 2016). Moreso, the feedstock source becomes important due to their varying ash yields upon pyrolysis because high ash yield signals abundant oxygen-containing functional groups on the resulting biochar. For instance, biochar produced from tamarind plant was reported to enhance the CEC of a highly weathered soil by 57 percent upon incorporation (Wang et al., 2022).

2.2.3 Soil organic carbon

Biochar is a less cost, easy to produce and ecofriendly strategy towards combating carbon availability and utilization in the agricultural ecosystem, consequently impacting the soil system, crop yield and promoting sustainable environment. This is because it is a thermally stabilized carbon enriched product of pyrolysis, with less susceptibility to biotic and abiotic degradation consequently lowering carbon loss from soil ecosystem (Zheng et al., 2018). The porosity and aromatized carbon of biochar resulting from biomass pyrolysis play crucial role in its carbon sequestration potential as reflected on its mineralization in any of these ways; (i) protection of soil organic matter through its encapsulation in biochar's pore structure as well as its external surface area. It can also adsorb and shield the soil organic carbon in its pore spaces from microbes and the enzymes they produce thus promoting their stability and resistance to degradation by soil micro-organisms (Rombola et al., 2022). (ii) biochar incorporation results in the creation of organo-mineral complexes where organic carbon binds with inorganic minerals thus reducing carbon loss and mineralization by soil microbes. (iii) inhibition of microbial and enzymatic activities through some harmful substances contained in biochar i.e furans and phenolic compounds, thus limiting the rate of soil carbon degradation. Several research findings validate that biochar play crucial role towards improving organic carbon contents of soil system when incorporated. For instance, a group researcher found out that biochar incorporation in soil brings about a stable increase in soil organic carbon upon incorporation and that its co-application with other soil amendment temporarily increase the soil SOC due to the ease at which they are mineralized after twelve and fourteen years of application (Gross et al., 2024). Also, a group researcher found that combined use of biochar with conservation tillage under eleven years wheat-maize rotation significantly raised the native and recalcitrant soil organic carbon of a Fluvisol and 39 – 51% of amended biochar was found at top 30 cm layer of the soil after eleven years, thus suggesting its slow pace of mineralization (Ding et al., 2023).

2.3 Biochar's interaction with soil biological properties

2.3.1 Microbial abundance and diversity

Abundance and composition of microbe population in the soil system is a pointer to its health and functionality for sustainable crop production (Yin et al., 2021). This is because of the crucial role microbes play in soil biochemical processes such as nutrient recycling and contaminant degradation. Incorporation of biochar to soil system changes the community structure of fungi and bacteria thus enhancing nutrient availability and soil functionality (Table 1). Research findings revealed that the surge in microbial abundance upon biochar incorporation is due to the shielding effects biochar offers to soil microbes from their predators when incorporated (Yin et al., 2021). Moreso, black nature of biochar, its numerous pore spaces and extensive surface area also offers a suitable atmosphere for microbial colonization within the soil system consequently enhancing aggregation of soil particles, nutrient retention through minimal leaching of nutrients, improved nutrient cycling for improved plant growth (Murtaza et al., 2021). For instance, a group researcher reported surge in pesticide degrading microbial population upon incorporation of biochar after an initial drop due to the inhibitory effects of chlorpyrifos and atrazine in a contaminated soil (Singh et al., 2024). This could be attributed to the adsorptive ability of biochar towards lowering the toxicity of chemicals to level favorable for the soil microbes. Nutrient availability, energy and shelter required for microbial growth upon biochar incorporation could also has been responsible for the increase (Tao et al., 2023). Similarly, researcher reported increase in the diversity of microbes in the rhizosphere of bayberry trees upon biochar incorporation owing to its modification of soil physiochemical properties as well as the regulation of secondary metabolites by the incorporated biochar (Ren et al., 2023). In addition, some researchers observed that increased pH of acidic soil upon biochar incorporation results in a drastic alteration in the soil microbe community (Gorovtsov et al., 2020). Thus, triggering a significant surge in Bacteroides and Gemmatimonadetes and less Acidobacteria.

Table 1: Biochar impacts on soil microbe abundance and diversity

Feedstock source	Rates of incorporation	Type of experiment	Targeted soil functions	Effects on soil microbial population and biodiversity	References
Fruit tree residues	0, 10 and 20 tons/ m^2	Field	Soil microbial diversity and community structure	Surge in alpha diversity, dominance of Proteobacteria, Cyanobacteria, and Actinobacteria phylla as well as Skermanella, Nostoc, Frankia, and Protect bacteria genera under 20 tons/ m^2 biochar incorporation compared to control.	Zhang and Shen, 2022
Mentha Avensis waste	4%	Pot	Pesticide degradation, Soil microbial diversity and enzyme activity.	Increase in plant growth-promoting bacterial genera such as Balneimonas, Kaistobacter, Rubrobacter, Ammoniphilus, and Bacillus upon biochar incorporation.	Singh et al., 2024
Pig dung	20 kg/ plant	Field	Community structure of soil microbes and decline in metabolites diseased bay berry.	Biochar application improves diversity of soil microbe in the rhizosphere at the levels of phyla, orders, and genera	Ren et al., 2023
Soft and hardwood biochar	-	Field	Long term effect of biochar on microbial community structure overwritten by land-use	Microbial community structure was more influenced by management practice than biochar after long term of application.	Handy et al., 2019
Combined source (cottonseed husk (30%) and rice husk (70%)	0, 30, 60, and 90 Mg ha^{-1}	Field	Native soil organic carbon pool and microbial activities	Microbial activities increased with increasing biochar application rate.	Ding et al., 2023

3. Biochar and Crop Growth

3.1 Crop Nutrient availability and uptake

Biochar promotes crop nutrient availability and uptake through restoration of soil ecosystem services. It provides abode for beneficial soil micro-organisms through its interconnected pore networks, thus promoting nutrient availability through increased mineralization as well as microbes-plant interactions, which helps in plant nutrient uptake (Bolan et al., 2023). Moreso, the enhanced microbial activities influence nutrient dynamics within the soil for the benefit of crop plants through nutrient cycling which are crucial for its continuous availability. Research findings have also shown that biochar is an effective tool for improving the nutrient use efficiency of crops such as phosphorus and nitrogen due to their adsorption capabilities and gradual release of nutrients, thus lowering their loss and improving uptake by crops (Panday et al., 2020). A group researchers reports that biochar aid the slow release of nitrogen during mineralization of fertilizers thus nourishing the plant throughout its growth stages (Wang et al., 2022). Its role in the availability of phosphorus, potassium, organic matter in the soil has also been linked to its adsorptive capacity. Similarly, some study reported significant increase in nitrogen and phosphorus uptake by 74%-80% and 76%-95% respectively by tomato plants upon biochar incorporation, consequently rising tomato yield by over 50% even with less application of nitrogen fertilizer (Guo et al., 2021). This increase may have resulted from additional nutrient release from biochar upon its incorporation.

Furthermore, biochar ameliorates the impact of biotic and abiotic stress conditions which may lower crop nutrient uptake and productivity. For instance, under saline condition, uptake of nutrient and water by plants can be improved with biochar incorporation. This is made possible owing to biochar improved cation exchange capacity which enables it adsorb sodium, making them less bio-available and raising the calcium and magnesium content in exchange for sodium thus modifying the soil pH and promoting crop growth.

3.2 Crop Development and Yield

Several research findings have shown that biochar improves crop morphological development and yield. The mechanisms through which it influences plants morphological development have not been well exploited. Meanwhile influencing factors as suggested by researchers are linked to its role towards nourishing plants with essential nutrients, improvement of soil carbon pool, enhancement of enzymatic functions like synthesis of sucrose, starch, glutamate and glutamine as well as enhancement of soil-microbe interactions in the rhizosphere, and amelioration of moisture stress in plants (Oelbermann et al., 2023). For instance, an experiment conducted by Ruan and wang, 2024 reveals that application of biochar enhances the diameter of root xylem vessels compared to control (no biochar) under two maize genotypes thus influencing crop lateral root growth. Its influence has been linked to the inducement of the root sap potassium concentration and decrease in sap calcium and sodium concentrations. In addition, studies indicated that biochar utilization rises the chlorophyl contents of plants which consequently impacts the crops morphological development. For instance, chlorophyl and carotenoid concentrations of tomato plants was reported to have increased proportionately with biochar rates (Abid et al., 2017). The increase has been linked to biochar role on boosting water and nutrient availability especially magnesium as well as enhancement of plant immunity to stress (biotic and abiotic).

Furthermore, Meta-analysis of biochar global influence on crop yield reveals that biochar utilization results in yield increase of at least 12%-21% under varying soil conditions (Xintan et al., 2024). For instance, in an experiment conducted at Wenzhou City, Eastern China, biochar incorporation at 22.5 t ha^{-1} increases rice yield by 6.3%-13.3% (Yang and Lu, 2022). The increase was attributed to biochar's enhancement of soil water retention capabilities raising its available water content by 15.2%-42.2% for rice use. Its application also increased soil aggregation and mechanical strength thus promoting crop root anchorage, growth and development. Kwame et al., 2021 reports similar findings in Ghana that one-time biochar application in combination with NPK fertilizer, Compost, or both significantly increased cassava yield when compared to sole NPK fertilizer and compost application. This increase was due to improved availability of essential nutrients as well as their uptake after biochar use.

4. BIOCHAR AND ENVIRONMENT

4.1 Remediation Potentials of Biochar: The Chemistry of Recent Advances

The popularity of biochar in environmental science may not be unconnected with its role in mitigating pollution as well as soil health improvement. Its physiochemical properties make it versatile for remediating contaminated soils and water systems. Recent studies provide robust evidence highlighting biochar's usefulness in immobilizing heavy metals, adsorbing organic pollutants, and enhancing soil resilience against contamination. This section explores the detailed chemistry of biochar-mediated remediation reactions and their mechanisms.

4.1.1 Immobilization of Soil Heavy Metals

One significant area where biochar shows promise is immobilization of soil heavy metals. Heavy metals like cadmium (Cd), lead (Pb), and copper (Cu) are deleterious environmental pollutants because of their persistence, toxicity, and bioaccumulation potential (Yahaya et al., 2022). Biochar helps immobilize these contaminants through a series of chemical reactions like complexation, adsorption reactions e.t.c. that reduce their bioavailability (Figure 2).

An assessment of the use of wheat straw biochar for remediating cadmium-contaminated soil by a group researcher found that biochar significantly reduced the bioavailability of Cd by 94% and improves wheat yield (Rahim et al., 2024). This reduction was primarily due to cation exchange and complexation reactions facilitated by the extensive surface area and functional groups of biochar.

In a **cation exchange reaction**, carboxylic acid groups (–COOH) on the biochar surface interact with Cd^{2+} ions. The reaction can be represented as:

$$\text{Biochar–RCOOH} + Cd^{2+} \rightarrow \text{Biochar–RCOO–}Cd^{2+} + H^{+} \quad (1)$$

This reaction involves the exchange of protons (H^+) with Cd^{2+}, effectively binding the heavy metal to the biochar surface and reducing its mobility.

Additionally, **complexation reactions** occur when hydroxyl groups (–OH) on biochar surface binds Cd^{2+} ion. The reaction can be described as:

$$\text{Biochar–R-OH} + Cd^{2+} \rightarrow \text{Biochar–R-O–}Cd^{2+} + H^{+} \quad (2)$$

These complexation reactions formed stable metal complexes, effectively sequestering Cd in a non-bioavailable form. The combination of cation exchange and complexation significantly reduces the environmental risks posed by heavy metals.

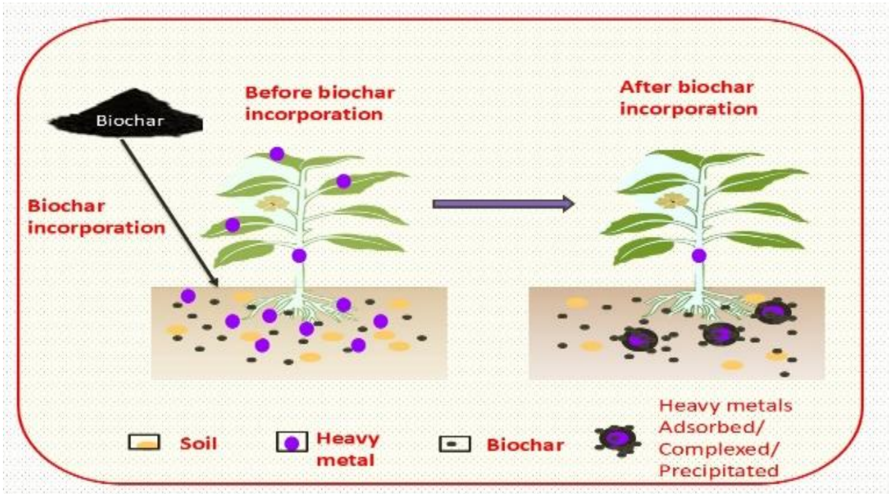

Figure 2: Effects of biochar on bioavailability of heavy metals when incorporated into the soil

4.1.2 Adsorption of Heavy Metals in Water

Biochar is also effective in adsorbing heavy metals from industrial wastewater. Research by a group researcher investigated the use of coconut shell biochar for removing lead (Pb) and copper (Cu) from wastewater (Minh et al., 2023). The study reported an adsorption efficiency of 83% for Pb and 76% for Cu within 24 hours. The increased adsorption capacity was linked to biochar's porous structure and functional groups on its surface.

The primary mechanism for Pb and Cu removal involves **surface complexation** and **precipitation reactions**. In a surface complexation reaction, the biochar surface provides binding sites for metal ions. The reaction for Cu adsorption can be expressed as:

$$\text{Biochar–R-COO}^{-} + Cu^{2+} \rightarrow \text{Biochar–R-COO-Cu} \quad (3)$$

For Pb removal, precipitation reactions occur where Pb^{2+} ions react with hydroxide ions (OH^-) on the biochar surface to form insoluble lead hydroxide. This reaction can be described as:

$$Pb^{2+} + 2OH^{-} \rightarrow Pb\,(OH)_{2(s)} \quad (4)$$

These reactions immobilize the heavy metals, preventing them from leaching into water bodies and posing environmental risks. However, the extent of biochar's effectiveness in heavy metal adsorption can be moderated by its source, pyrolysis condition and pH of the environment.

4.1.3 Remediation of Pollutants

Biochar has demonstrated considerable potential in mitigating organic pollutants like polycyclic aromatic hydrocarbons (PAHs). These pollutants are persistent in the environment and pose significant health risks. Biochar derived from agricultural residues can effectively adsorb PAHs and change soil microbial communities, as shown by (Zhou et al., 2023).

The primary mechanisms for PAH remediation involve **π-π electron donor-acceptor (EDA) interactions** and **hydrophobic partitioning**. Graphitic structures on biochar interact with aromatic rings in PAHs through π-π stacking interactions. The reaction can be represented as:

$$\text{Biochar Surface–}\pi\text{(Graphitic)} + \text{PAH} \rightarrow \text{Biochar Surface–PAH} \quad (5)$$

This interaction provides strong adsorption sites for PAHs, effectively reducing their mobility and bioavailability in the soil.

Hydrophobic partitioning also plays a crucial role in PAH adsorption. Since PAHs are hydrophobic, they tend to partition into the hydrophobic regions of biochar pores. This mechanism traps PAHs within the biochar structure, preventing them from leaching into groundwater.

4.1.4 Reducing Pesticide Residues in Agricultural Soils

Biochar has also been revealed to reduce pesticide residues in agricultural soils. A group researcher assessed the use of biochar to reduce pesticide in soils (Losacco et al., 2024). The study found that biochar reduced pesticide leaching by 45%, thereby preventing groundwater contamination.

The primary mechanisms for pesticide adsorption involve **hydrophobic interactions** and **van der Waal forces**. Hydrophobic regions on the biochar surface interact with nonpolar pesticide molecules, forming stable pesticide-biochar complexes. The reaction can be described as:

$$\text{Biochar–Surface} + \text{Pesticide} \rightarrow \text{Biochar–Pesticide Complex} \quad (6)$$

Additionally, weak intermolecular forces known as **van der Waals forces** enhance the adsorption of pesticide molecules onto the biochar surface. These interactions effectively reduce the mobility of pesticides, preventing them from contaminating groundwater.

4.1.5 Enhancing Soil Health and Phytoremediation

Biochar's ability to improve soil fertility and sequester carbon contributes ultimately to its remediation potential. By enhancing soil health, biochar supports the growth of plants that can assist in the phytoremediation of contaminated sites. A research conducted by a group researcher found that biochar not only immobilize contaminants but also improves soil structure and availability of nutrients (Lohar et al., 2024).

The mechanisms for enhancing soil health include **nutrient release** and **carbon sequestration.** Biochar gradually releases essential nutrients such as potassium (K) and calcium (Ca) into the soil. This reaction can be represented as:

$$\text{Biochar} + H_2O \rightarrow \text{Biochar-OH} + \text{Nutrients} \quad (7)$$

The stable carbon structures in biochar also resist degradation, sequestering carbon in the soil for long periods. This carbon sequestration improves soil structure, enhances microbial activity, and supports plant growth, thereby aiding in phytoremediation.

4.2 Reduction of Greenhouse Gas Emissions

Biochar shows a crucial role in mitigating greenhouse gas (GHG) emissions, particularly nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4) (Sultan et al., 2024). These three gases are among the most significant contributors to global warming, with their cumulative impact driving much of the observed climate change. Biochar offers numerous pathways for reducing emissions of these gases, making it a promising strategy for climate change mitigation and sustainable agriculture.

The unique physiochemical properties of biochar like its large surface area, porosity, polyfunctional hydroxyl, carboxyl, and carbonyl groups, enable it to interact effectively with soil nutrients, microbial communities, and gases. These interactions play crucial role in lowering GHG emissions through various soil processes accompanying its incorporation. The potential mechanisms through which biochar achieves these reductions may, depending on the environmental conditions and specific GHG, but its overall impact is consistent across different ecosystems.

4.2.1 Reduction of Nitrous Oxide (N_2O) Emissions

Nitrous oxide (N_2O) has a high global warming potential, about 298 times more harmful to the environment than CO_2 over 100-year timescale (Dacic, 2024). It is primarily produced in agricultural soils through microbial nitrification and denitrification processes. These processes are triggered by the availability of nitrogen compounds such as ammonium (NH_4^+) and nitrate (NO_3^-), soil moisture, and oxygen levels.

Biochar reduces N_2O emissions by modifying soil conditions to inhibit the microbial processes. When biochar is incorporated into soil, it improves aeration by increasing soil porosity and reducing waterlogging. This change in soil structure reduces the anaerobic conditions that favor denitrification, thereby lowering N_2O emissions. Additionally, biochar has high cation exchange capacity (CEC), which enables it to adsorb and retain ammonium ions (NH_4^+), reducing the availability of nitrogen for microbial conversion to N_2O (Equation 8). The functional group on biochar surface also facilitate the adsorption of nitrates (NO_3^-), further limiting the substrate available for denitrification.

$$\text{Biochar-COOH} + NH_4^+ \rightarrow \text{Biochar-COONH}_4 + H^+ \quad (8)$$

Research has demonstrated significant reductions in N_2O emissions following biochar use. For example, meta-analysis by a study found that use of biochar reduces N_2O emissions by an average of 16.2% (Zhang et al., 2024). The reduction varies based on the feedstock source from which the biochar was produced, soil characteristics, and environmental condition. In agricultural settings, this reduction translates into both environmental benefits and improved nitrogen use efficiency, because more nitrogen remains available for plant use instead of being lost to the atmosphere.

4.2.2 Carbon Dioxide (CO_2) Sequestration

Carbon dioxide (CO_2) occupies a large proportion of greenhouse gas emitted through the combustion of fossil fuels, deforestation, and soil respiration (Yoro and Daramola, 2020). Biochar contributes to CO_2 mitigation by sequestering carbon in a stable form that resists microbial decomposition. Unlike traditional organic matter, which decomposes rapidly and releases CO_2 back into the atmosphere, biochar is highly recalcitrant, meaning it remains stable in the soil for hundreds to thousands of years (Maurya and Hande, 2024).

The pyrolysis process used to produce biochar converts biomass into a carbon-rich material with a stable aromatic structure. The aromatic structural stability prevents the carbon from being easily broken down by soil microbes. As a result, the carbon in biochar remains locked in the soil, effectively removing CO_2 from the atmosphere. This process of carbon sequestration can help offset CO_2 emissions from other sources, contributing to overall carbon neutrality.

A group researchers estimated that large-scale biochar application could sequester up to 1.8 gigatons of CO_2 annually (Shahbaz et al., 2024). This potential represents a significant opportunity for mitigating climate change, especially when combined with sustainable agricultural practices and biomass management. In addition to sequestering carbon, biochar also improves soil fertility, leading to increased plant growth and further CO_2 uptake through photosynthesis.

4.2.3 Mitigation of Methane (CH_4) Emissions

Methane (CH_4) is another potent greenhouse gas, with a global warming potential approximately 25 times that of CO_2 over a 100-year period (Costa et al., 2021). CH_4 is primarily emitted from anaerobic environments, such as flooded rice fields, wetlands, and livestock manure (Zheng et al., 2024). In these conditions, methanogenic bacteria produce CH_4 as a byproduct of organic matter decomposition.

Biochar helps reduce CH_4 emissions by improving soil aeration and enhancing the activity of methanotrophic bacteria, which consume methane. When biochar is added to anaerobic soils, it increases soil porosity, allowing better oxygen diffusion. This increased oxygen availability suppresses methanogenesis (the process by which CH_4 is produced) and promotes methanotrophy (the process by which CH_4 is consumed).

Research have demonstrated significant reduction in CH_4 emissions from agricultural soils upon biochar incorporation. For instance, a group researchers reported that applying biochar to paddy fields reduced CH_4 emissions by 42.9% (Somboon et al., 2024). The reduction is linked to the dual effect of improved aeration and the stimulation of methanotrophic bacterial activity. Additionally, biochar's ability to adsorb organic substrates reduces the availability of carbon sources for methanogenic bacteria, further curbing CH_4 production.

4.2.4 Combined Impact on Greenhouse Gas Emissions

The combined impact of biochar on reducing N_2O, CO_2, and CH_4 emissions makes it a powerful tool for mitigating climate change. The multiple mechanisms through which biochar interacts with soil nutrients, microbial communities, and carbon pools create synergies that enhance its overall effectiveness. By incorporating biochar into agricultural soils, land managers can achieve significant reductions in GHG emissions while also improving soil health, crop yields, and long-term sustainability.

Moreover, biochar's role in reducing GHG emissions is not limited to direct soil applications. It can also be integrated into waste management systems, such as composting and manure management, to further reduce emissions. For example, adding biochar to compost piles helps trap nitrogen, reducing ammonia (NH_3) volatilization and N_2O emissions during decomposition (Raza et al., 2021).

In summary, biochar offers a multifaceted approach to GHG mitigation by addressing the primary sources of N_2O, CO_2, and CH_4 emissions. Its ability to sequester carbon, alter microbial processes, and improve soil conditions highlights its potential as a sustainable and scalable solution for reducing the impact of agriculture and other land-use activities on climate change.

5. Conclusion

Biochar has materialized as a versatile tool for addressing sustainability issues from modern agriculture, especially in areas of soil health, crop yield and environmental safety. Its unique potentials for enhancing soil physical, chemical, and biological properties makes it a valuable for addressing concerns of soil degradation, yield sustainability, and environmental impacts of agricultural intensification. Biochar improves soil water retention, reduces bulk density, enhance aggregation, and increase nutrient availability thus reflecting its capacity to transform agricultural systems sustainably.

Beyond its benefits to soil and crop productivity, biochar is a critical tool in mitigating environmental pollution. By immobilizing heavy metals, adsorbing organic pollutants, and reducing pesticide leaching, biochar significantly contributes to the remediation of contaminated soils and water systems. These capabilities are a direct result of its complex structural and chemical properties, including its high surface area, porosity, and abundance of functional groups, which enable it to interact effectively with pollutants and nutrients.

Moreover, biochar plays crucial role in reducing greenhouse gas emissions, especially nitrous oxide, carbon dioxide, and methane, which are major contributors to climate change. Its potential for sequestering carbon in a stable form, alter microbial processes, and improve soil aeration highlights its potential as a climate mitigation strategy. The incorporation of biochar into waste management systems and its application in diverse soil and climatic conditions further emphasize its versatility and scalability.

The evidence presented in this review shows the transformative potential of biochar across multiple dimensions of agricultural and environmental sustainability. However, realizing its full potential requires careful consideration of factors such as feedstock type, pyrolysis conditions, application rates, and the specific needs of the target soil and crop systems. Future research should focus on optimizing these parameters to maximize biochar's benefits while minimizing potential trade-offs.

In conclusion, biochar represents a promising innovation for achieving global food security and environmental sustainability. By enhancing soil fertility, boosting crop yields, and reducing the ecological footprint of agriculture, biochar provides a pathway toward more resilient and sustainable agricultural practices. Its adoption by policymakers, farmers, and land managers could be vital in meeting the growing global demand for food while protecting the planet's natural resources for future generations.

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