Benefits of Biochar Addition in a Sustainable Agriculture Practice: Soil Nutrients Dynamics, Enzyme Activities and Plant Growth

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Abstract

Biochar is a carbon-rich material resulting from the pyrolysis of plant and animal biomass. Biochar has a long history as a soil amendment for centuries since the Mayan civilization. Attaining sustainability in agriculture is not easy; however, the addition of biochar may reduce the adverse effects of numerous malpractices in conventional agriculture. Biochar benefits soil physicochemical properties such as soil bulk density, aggregate stability, porosity, water holding capacity and soil organic carbon content. However, it is essential to focus on the negative aspects of biochar in terms of atmospheric emissions during the production and occupational health and safety at the time of use. Still, there are many benefits and detriments of the application of biochar, i.e., the priming effect; thus, this review highlights the importance of further research on the application of biochar as a soil amendment. It has been understood that the lack of long-term field studies in various soils using commercially produced biochar may restrict the knowledge of biochar's true potential and effect on soil nutrient dynamics, microbial structure, and crop yield.

Keywords: Land degradation, Biochar, Nutrient retention, Soil quality, Microbial community

1. Introduction

Soil is the outermost thin layer of earth that links to everything around, performing many crucial roles in sustaining life on earth. The quality of soil can be described considering a set of aspects such as the ability to provide nutrients and other physicochemical conditions essential for plant growth, stimulate and sustain crop production, provide habitat to soil organisms, resist degradation, and maintain or improve human and animal health. However, in the last few decades, a considerable decline in soil quality has occurred worldwide. It is estimated that about 75 billion tons of arable land are degraded each year (Anderson, 2019). Nearly 40% of the world's agricultural lands have become unproductive due to soil erosion, atmospheric pollution, extensive crop cultivation, over-grazing, land clearing, salinization, and desertification (Bado and Bationo, 2018). Interestingly, conventional agricultural practices are considered more harmful due to the heavy use of agrochemicals, monoculture, continuous soil disturbances etc. Nevertheless, the importance of maintaining and improving soil quality for sustainable agriculture has been recognized (Sofo et al., 2021).

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It is indeed challenging to maintain soil quality for sustainable agriculture; hence, rehabilitation of degraded soils is essential. The introduction of biochar as an amendment is considered one of the best options to rehabilitate soil properties sustainably (Semida et al., 2019). The ancient Mayan civilization provides one of the best examples of improving soil quality by using biochar. Among soils in central Amazonia (Ferralsols, Acrisols, Lixisols and Arenosols), Terra Preta is the most fertile soil in small islands in an average of approximately 20 ha. These soils consist of about three times higher soil organic matter (SOM) content, higher nutrient levels, and a better nutrient retention capacity than surrounding infertile soils (Barrow, 2012; Glaser, 2007). Later on, the discovery of Amazonian black magic soil attracted many researchers interested in studying biochar and its application in soil quality improvement, carbon sequestration, and nutrient management (Adekiya et al., 2020).

Biochar is a carbonaceous material produced by pyrolysis of plant and animal-based organic materials under a limited oxygen environment. The carbon stability and aromaticity of biochar are vary depending on the feedstock material, temperature, and pyrolysis technique used (Weber and Quicker, 2018). Biochar has shown a unique capacity to improve soil fertility and nutrient use efficiency in a sustainable way (Hue, 2020). The incorporation of biochar into the soil influences the physical, chemical, and biological properties of soil (Figure 1). This can be attributed to its unique properties, which include high organic carbon content, high porosity, large surface area, presence of micropores etc. Improvements in soil hydraulic properties, including soil structure, aggregation, bulk density, and water holding capacity, enhance the biochar used at optimum levels (Chang et al., 2021). Biochar further improves soil chemical properties by increasing soil pH, cation exchange capacity, exchangeable ions, and organic carbon content and reduces nitrogen leaching, which helps reduce fertilizer use and lime requirements to maintain proper soil health (Ginebra et al., 2022). Biochar-induced changes in soil's physical and chemical properties ultimately influence the biological properties, providing microbes with a more favourable environment (Adekiya et al., 2020). Further, biochar has depicted the potential of adsorbing organic and inorganic molecules onto its surface. This reduces the mobility of agrochemicals in the surrounding environments (Mayakaduwa et al., 2016; Vithanage et al., 2016). Due to its sustainability and affordability, biochar can be used in soil remediation as well.

Compared to other amendments, biochar addition to the soil is virtually irreversible, and it is evident to persist in the soil system even more than 2000 years (Lehmann et al., 2015). Biochar application influences almost all the biotic and abiotic processes of soil, including nutrient dynamics, soil microbial abundance and community structure, and plant growth, which could further cause a whopping alteration of the entire soil system with utilization over an extensive period. Therefore, it is vital to have an inclusive understanding of how biochar interacts with soil in the long term prior to wide-scale application. The focus of this review is to summarize the most recent understanding of biochar effects on soil nutrient cycling, microbial communities, soil enzyme activities, and plant growth considering its use in sustainable agriculture.

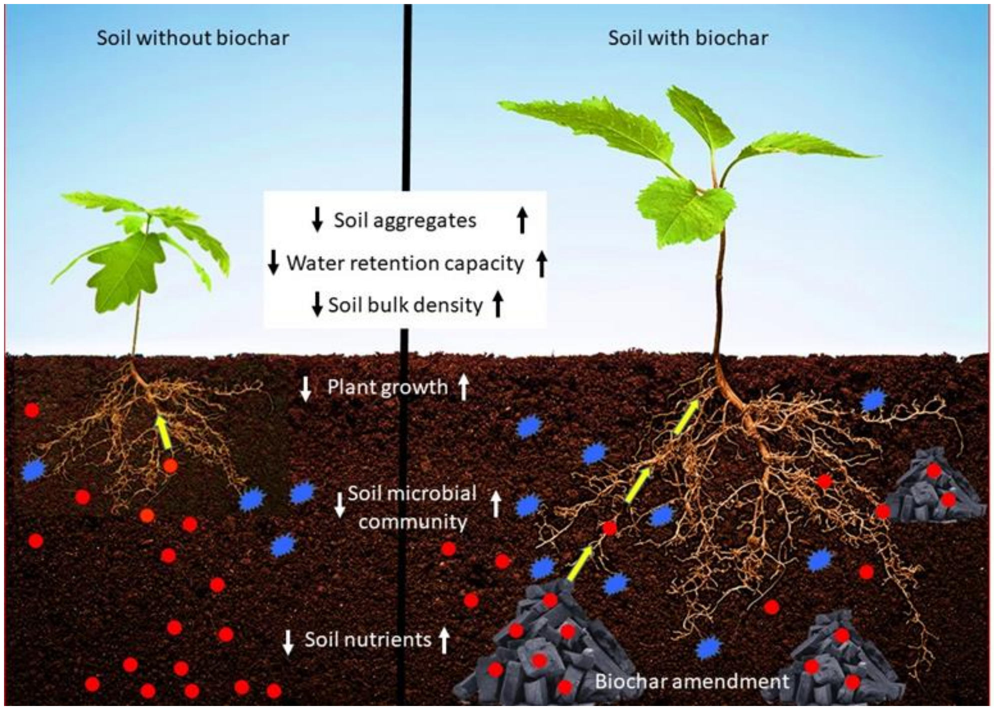

Figure 1. Schematic diagram displaying the changes in soil properties, nutrients, microbes, and plant growth with the addition of biochar.

2. Biochar Induces Soil Physico-Chemical Property Alterations

2.1. Biochar on soil chemical properties

The introduction of biochar into soil influences the changes in soil pH, electrical conductivity (EC), cation exchange capacity (CEC), soil organic carbon (SOC), and nutrient level in the soil (Diatta et al., 2020). Among chemical properties, soil pH is positively influenced by the presence of biochar. Interestingly, the pyrolysis temperature and feedstock material also determine the pH of biochar. Usually, the pH of biochar rise with increasing pyrolysis temperature mainly as a result of the separation of alkali salts from organic materials and loss of acidic functional groups at high pyrolysis temperature (Al-Wabel et al., 2013; Vithanage et al., 2014). Furthermore, although peanut, corn straw, canola straw, and soybean straw biochar are produced at the same pyrolysis temperatures of 300 °C, the pH has varied due to the ash alkalinity or due to the presence of excess cations (Wan et al., 2014). Table 1 summarizes the changes in pH and other major chemical properties of biochar with the feedstock type and pyrolysis temperature used. The application rate of biochar is important since soil pH positively correlates with biochar addition rates in acid soils (Dai et al., 2017). In contrast to these findings, Agegnehu et al. (2015) observed that willow wood-derived biochar (550 °C) did not change the pH of Ferralsol. Alkaline pH, copious reactive surface functional groups, high CEC, mineral content, and labile C (5–10% of total fixed C) of biochar improve soil fertility (Hue, 2020). The biochar-amended weathered soil has depicted an increase in the CEC by significantly increasing the exchangeable K^+, Ca_2^+, and Mg_2^+ contents in the soil (Jien and Wang, 2013; Ndor et al., 2015; Peng et al., 2011). The scale of the changes was roughly relative to the biochar application rates, nutrient content, and pore structure. Furthermore, the capability of biochar in

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diminishing soil carbon mineralization will be promising to be used in over-fertilized soils with excessive application of compost (Tsai and Chang, 2019).

Table 1: The effects of feedstock type and pyrolysis temperature on properties of biochar.

Feedstock type	Pyrolysis temperature (°C)	pH	Ash content (%)	Fixed carbon (%)	C (%)	C/H	C/O	C/N	Reference
Conocarpus sp. waste	200	7.4	4.5	-	64.2	16.2	2.4	-	Al-Wabel et al. (2013)
	400	9.7	5.3	-	76.8	27.2	5.4	-	
	600	12.2	8.6	-	82.9	65.0	12.7	-	
	800	12.4	8.6	-	85.0	137.1	17.5	-	
Poultry waste	350	8.7	-	-	51.1	-	-	12.0	Purakayastha et al. (2015)
Dairy manure	700	9.9	-	-	56.7	-	-	38	
Turkey litter	700	9.9	-	-	44.8	-	-	23	
Corn stover	300	7.3	-	-	59.5	-	-	51	Mandal et al. (2017)
	600	9.95	-	-	69.8	-	-	70	
Paddy straw	500	10.5	52.4	39.1	86.3	27.7	11.74	-	Lee et al. (2013)
Palm kernel shell	500	6.9	6.9	80.9	87.9	30.2	10.8	-	
Corn cobs Corn strew Rice strew Walnut shells	250	6.5–9.4	-	-	60.0-75.8	-	-	-	Zhang et al. (2017)
	400	8.8–10.7	-	-	76.0-85.7	-	-	-	
	600	10.0–12.4	-	-	89.9-90.1	-	-	-	

2.2 Biochar on soil physical properties

Biochar possesses a high specific surface area that could potentially interact with other substances in the soil solution. Therefore, physical properties, including depth, texture, structure, pore size distribution, bulk density, and hydraulic properties, can be considerably changed with biochar application to the soil matrix (Figure 1).

Toková et al. (2020) have depicted a 12% reduction in soil bulk density and a 12% increase of soil porosity in the presence of a mixture of paper fibre sludge and grain husks derived biochar at 20 t ha^{-1} even though the application rate is far too high. Interestingly, changes in field capacity, soil bulk density, and water holding capacity at the lowest biochar application rate of 0.1% were not significant, whereas the changes were highly significant with the rate of 2.5% (Peake et al., 2014). Moreover, 0.1% of biochar decreased soil bulk density by 3.3%, while 2.5% reduced by 10.2% compared to the control soil.

Soil saturated hydraulic conductivity (SHC) is considered as a function of soil texture, soil particle packing, clay content, organic matter content, soil aggregation, bioturbation, shrink–swelling, and overall soil structure (Spokas et al., 2015). The application of biochar is also capable of improving the SHC of soil (Asai et al., 2009). However, SHC is influenced by the particle size distribution of biochar, application rate, and the original soil textures (Spokas et al., 2015). Hussain et al. (2021) have reported that particle sizes of biochar alter the SHC by changing the pore size distribution or porosity of the soil. In contrast, applying 1 or 3% (w/w) of biochar cannot change SHC in clay soil even after 1 year of application (Wang et al., 2021).

3. Biochar Enrich Nutrient Dynamics in Soil

Regular cycling of nutrients in the soil system is affected by the application of biochar. Therefore, comprehensive knowledge of soil nutrient transformations is critically required (Figure 1).

3.1 Soil carbon dynamics

In natural vegetation, soil carbon equilibrium is determined by several natural phenomena, such as root residues and exudates, above-ground plant parts additions, soil organisms, etc. Nevertheless, in the cropping system, the natural contribution of organic carbon is limited. Furthermore, the intensive tillage which exists in agricultural lands influences losing of SOC. Moreover, biochar is highly resistant to microbial decomposition due to its aromatic graphite structure (Ameloot et al., 2013). Hence, a minimum loss of organic matter is through soil microbial decomposition, and reduction of CO_2 evolution to the atmosphere occurs.

The addition of biochar in the soil can be induced either a positive or negative priming effect on native SOC and may increase or decrease influence the C storage potential of biochar (Keith et al., 2015). The priming effect is defined as a change in the mineralization rates of SOC due to the addition of fresh organic matter (Weng et al., 2015). Soil microbial community and C availability simultaneously control SOC decomposition, and therefore, the addition of biochar induces a priming effect on soil C mineralization (Lu and Zhang, 2015). However, controversial data have been reported regarding the priming effects on soil C mineralization with biochar. Ding et al. (2018) have reported that within the first two years of biochar addition, positive priming has occurred, whereas shifting to negative priming with time occurred afterwards. Furthermore, an increase in the amount of negative priming was observed with residence time, biochar C/N ratio, and soil clay content, while a decrease was noted with soil C/N ratio. Biochar itself did not affect total soil CO2 emission; however, when combined with the N amendment significantly reduced the CO2 emission from native SOC. A six-year-long study has demonstrated a negative priming effect with the addition of biochar to corn cultivation with twice of increase in total C stocks (Blanco-Canqui et al., 2020). These findings indicate that biochar inhibited the decomposition of native SOC and the stimulating effect of inorganic N on native SOC degradation.

3.2 Soil nitrogen (N) dynamics

Nitrogen (N) is a vital element in soil solution, as it is a significant component of chlorophyll in plant cells, amino acids, enzymes, energy-transfer compounds, etc. Plants take up approximately 70% of NH4+-N and NO3-N ions in the total cations and anions concentration (Wang et al., 2015). The majority of plant N requirements are fulfilled with N-based chemical fertilizers. However, N pollution results from excessive use of them. In the agricultural soils, N is lost as gaseous emissions (N_2, N_2O, NO, NH_3), ammonium (NH_4^+) and nitrate (NO_3^-) leaching (Zheng et al., 2013). Therefore, it is vital to reduce N losses from agricultural lands to achieve maximum crop production and maintain a sustainable ecosystem. Studies indicated biochar incorporation into soil has a greater impact on soil N dynamics (Table 2).

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Table 2: The short- and long-term biochar-specific effects on N retention and mineralization.

Biochar type	Pyrolysis temperature (°C)	Application period	Effect on N retention/ mineralization	Reference
Maize straw biochar	400	1-2 months	Significant decrease of N_2O emission by 77% - 86% with biochar application rate at 30Mg ha^{-1} under N-fertilizer incorporation	Jia et al. (2012)
Rice straw biochar	500	1.5 months	Biochar incorporation reduces the N_2O emission	Xu et al. (2014)
Pinewood chip biochar	550	12 months	Soil NH_4^+-N concentration was significantly decreased while NO_3^--N concentration was increased	Bai et al. (2015)
Chicken manure biochar and Organic city waste biochar	500	4 months	Biochar caused to transform NH_4^+-N to NO_3-N and reduced the N loss via reducing N loss by leaching	Widowati et al. (2011)
Corn straw biochar	500	5 months	N mineralization was increased with biochar application	Xu et al. (2016)
Maize stover biochar	600	4 years	82% of less N loss resulted from fertilizer application with biochar	(Güereña et al., 2013)
Green waste biochar	600	Ca. 2.5 months	Significantly high accumulation of NO_3-N in the soil and lower NH_4^+-N with 11% w/w biochar application	Van Zwieten et al. (2010)
Giant reed (*Arundo donax* L.) biochar		9 weeks	Leaching of NH_4^+-N from NO_3-N fertilized soil was significantly reduced, while NO_3-N leaching from both NO_3-N and NH_4^+-N fertilized soils was significantly reduced	Zheng et al. (2013)

Sanford and Larson (2020) have observed that corncob-derived biochar (700 °C), decreases N leaching by 25% compared to the soil itself. Moreover, O-containing surface functional groups and cationic minerals enhance the retention of N in the soil. It has been proven that rice growth and N retention in flooded paddy fields are beneficially affected by introducing biochar as a soil amendment (Dong et al., 2015). Furthermore, Shi et al. (2020) depicted that biochar loaded with urea enhances the N retention through organo-mineral surface interaction and adsorption. However, the potential of biochar to modulate N dynamics in soil remains contentious, according to previous studies. A recent review has demonstrated that the biochar maximizes N use efficiency by reducing the loss of N by volatilization and leaching, stimulating N inputs by microbes, and by N retention (Ahmad et al., 2021). Short-term controlled laboratory pot experiments have shown stimulating behaviour of biochar for available N resulting from reduced N leaching, whereas contradictory results were observed in long-term field investigations indicating minimal or negative effects (Ahmad et al., 2021). Another review specified that the short- and long-term effects of biochar on N retention and mineralization are biochar-specific (Clough et al., 2013). Further, it was mentioned that most N_2O emission-related studies were short-term reporting emission reductions, and due to the lack of long-term studies elucidating N_2O dynamics remains a challenge.

3.3 Soil phosphorous (P) dynamics

The P dynamic in biochar amended soil is strongly associated with the leaching of P salts during the pyrolysis, CEC, interference with P adsorption to Al and Fe oxides, and biochar adsorption of plant and microbial chelates (DeLuca et al., 2015). Surface characteristics and chemical composition of biochar determine the fate of soil P (Chintala et al., 2014). Biochar with high ash and P concentrations are potential soluble P sources with high-agronomic efficiency (Wang et al., 2012). A recent meta-analysis found an enhancement of P availability and plant uptake in P-poor acidic soils with the application of biochar at a dosage up to 10 t ha^{-1} (Tesfaye et al., 2021). In general, increased P availability with biochar addition into the soil is determined by increased soil pH and immediate release of P from biochar (Xu et al., 2013). The interaction between P species and the surface of biochar is based on the "ion bridge" mechanism; hence the cations and soil solution could control the migration of P (Qian et al., 2013). Further, biochar can be used for recovering excess P from dairy manure effluent via exchange with surface hydroxyl groups (Sarkhot et al., 2013). Nevertheless, the production of animal manure biochar is a successful solution for the high release of P from manure (Liang et al., 2014).

4. Soil Biological and Enzymatic Activities

4.1 Impact of biochar on soil microbial diversity and abundance

Microbial diversity and abundance are two vital factors that determine a sustainable soil ecosystem. Sorption of dissolved organic carbon has been increased with the porous structure of biochar. Furthermore, porosity enhances the surface area and water holding capacity while providing a habitat for soil microorganisms (Ladygina and Rineau, 2013). Therefore, soil-biochar amendments potentially increase the soil microbial activity and influence the priming effect on organic matter decomposition (Herath et al., 2014). A meta-analysis conducted by Li et al. (2020) has concluded that biochar properties govern soil microbial biomass, whereas soil properties determine soil microbial diversity. A clear effect on the microbial growth, diversity, and community compositions in soil was observed after the addition of biochar, which provides growth promotion due to the change in soil properties (Dai et al., 2021). This was governed by the porosity, labile C, alkaline pH, and CEC of biochar, and it varies with biochar types, production temperature, and feedstock type (Dai et al., 2021).

Yin et al. (2021) have observed that N-enriched biochar amendments result in significant shifts in bacterial and fungal taxa of paddy soil via changes in soil physicochemical properties. Biochar produced from Pinus radiate considerably promotes phosphate-solubilizing bacteria by increasing the abundance of bacterial families and potentially decreasing bacterial and plant pathogens (Anderson et al., 2011). A contrasting observation after applying Eucalyptus marginata biochar was reported, where the activity of the microbial community was reduced by decreasing soil organic matter decomposition and N mineralization (Dempster et al., 2012). However, introducing fast pyrolyzed woody biochar at large rates could improve soil fertility and lead to gram-negative bacteria dominating the community (Gomez et al., 2014).

In the presence of biochar, a negative influence has been observed on the existence of plant pathogenic bacteria, whereas a positive influence was observed on phosphate-solubilizing bacteria. Additionally, an alteration of C-fluxes has been observed with an increased abundance of recalcitrant C compounds degrading bacteria (Anderson et al., 2011). Biochar controls root or foliar fungal pathogens by modifying root exudates, soil properties, and nutrient availability. The addition of biochar into soil induces a systemic defence in the roots, which reduces foliar pathogenic fungi. This was indicated by the activation of stress-hormone responses and changes in reactive oxygen species that coordinate hormonal

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signalling in the plant (Poveda et al., 2021). Further, biochar supports suppressing nematode and pest attacks. Furthermore, chronological changes in bacterial family abundance in biochar amended soils have promoted *Streptosporangineae*, *Bradyrhizobiaceae*, *Thermomonosporaceae*, and *Hyphomicrobiaceae*, whereas *Streptomycetaceae* and *Micromonosporaceae* have been negatively promoted compared to control soil (Anderson et al., 2011). However, Chen et al. (2013) have reported significant increases of 28% and 64% in bacterial 16S rRNA gene copy numbers and a significant decrease of 35% and 46% of fungal 18S rRNA in the presence of wheat straw biochar amendment at 20 and 40 t ha^{-1} respectively. These results implied that the bacterial abundance was significantly boosted with increasing biochar application rates while fungal abundance declined.

Nutrient cycling in a soil ecosystem is one of the major functions in the presence of microbes. Ducey et al. (2013) have demonstrated that the addition of switchgrass-derived biochar to an acidic subsoil increases microbial N-cycling gene abundances. Hence, biochar as a soil amendment impacts both soils' physicochemical and biological properties. Moreover, the introduction of high-temperature pyrolyzed biochar in soil improves microbial N_2O reduction and positively influences the abundance of N_2-fixing microorganisms (Harter et al., 2014; Nelissen et al., 2014).

4.2 Biochar and soil mycorrhizal fungi

Fungi in the soil ecosystem play a significant role in nutrient cycling, water holding, disease suppression, and improving soil structure that ultimately influences better growth of plants (Went and Stark, 1968). Hammer et al. (2014) have observed that the hyphae of Arbuscular mycorrhizal fungi (AMF) develop by attaching firmly to the inner and outer surfaces of biochar. Generally, biochar is considered a nutrient lacking soil amendment; however, due to colonization with mycorrhizal fungi, biochar is loaded with plant nutrients. The pore size of biochar is an essential factor that determines the growth of fungi. The hyphae of most recorded fungi range from 3–6 μm in diameter and they can only colonize in pores larger than the diameter of hyphae (Ladygina and Rineau, 2013). Four mechanisms are suggested to explain the mycorrhizal fungi and biochar interaction (Warnock et al., 2007). Biochar,

1) changes soil nutrient availability,
2) alters the activity of other microorganisms that have effects on mycorrhizae,
3) alters the signalling dynamics between plants and mycorrhizal fungi or detoxifies allelochemicals,
4) serves as a refuge for colonizing fungi and bacteria.

The addition of biochar and fertilizers increase mycorrhizal colonization in clover plants' bioassay. It has been reported that deep-banded biochar provides suitable conditions for mycorrhizal fungi to colonize the rhizosphere (Solaiman et al., 2010). Furthermore, the drought stress of plants is possible to be reduced by improved water supply resulting from the activity of AMF hyphae. Potting mixture amended with biochar and inoculation of AMF achieves the best plants' performance, such as greater floral clusters, intensely coloured flowers, and greener leaves in *Pelargonium* sp., a major ornamental plant that grows under nursery conditions (Conversa et al., 2015). However, mycorrhizal fungi biomass or colonization in corn roots were not affected by the addition of hard wood-derived, fast-pyrolyzed biochar into Aridisol (Elzobair et al., 2015).

Biochar addition into the soil provides a habitat for AMF (Figure 2). This can increase the overall biomass productivity, crop performance, and nutrient and water retention and reduce chemical fertilizers addition by augmenting nutrient uptake (Gujre et al., 2021). The type of biochar and soil conditions greatly determine the response of AMF in biochar-added soil. The application of corn stalks-derived-biochar with AMF has been examined for heavy metals bioavailability in sewage sludge applied soils (Qiao et al., 2015). The results implied that AMF inoculation slightly affected heavy metal bioavailability in either controlled or biochar amended soil. Furthermore, a significant interaction between biochar and AMF inoculation has not been observed.

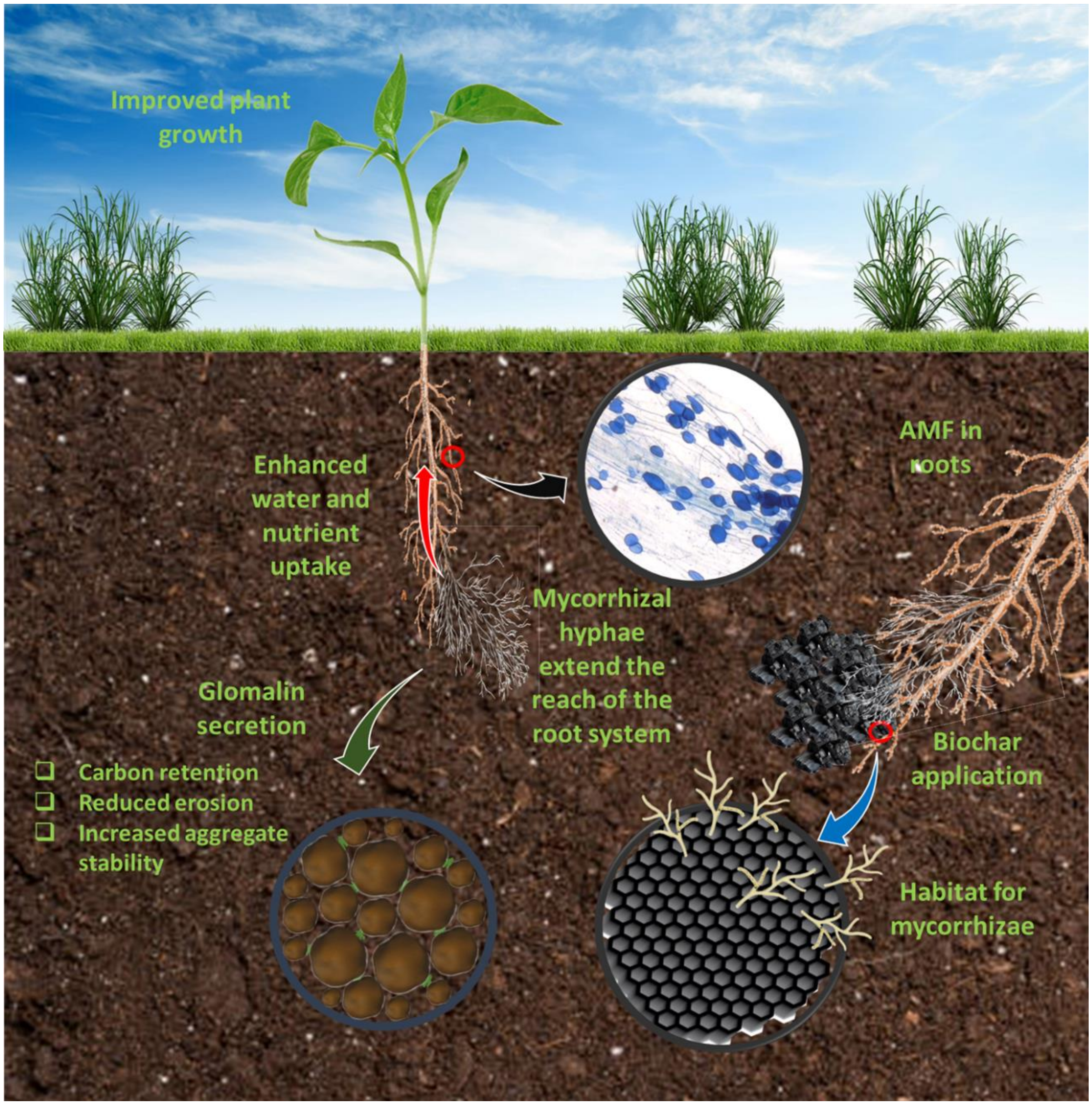

Figure 2. Interactions among plant roots, mycorrhizae, and biochar in soil.

4.3 Biochar and soil enzymes

The soil enzyme activities, which are also related to soil's biological and biochemical properties, have been considered indicators of soil quality and health (Xiong et al., 2013). Nevertheless, the addition of biochar as a soil amendment has reported contrasting data on soil enzyme activities (Awad et al., 2013; Oladele, 2019). A recent meta-analysis reported that the soil type, biochar properties, and the type of enzyme studied govern the effect of biochar on soil enzyme activities (Pokharel et al., 2020). As per most studies, biochar increased microbial biomass C, urease, alkaline phosphatase, and dehydrogenase activities; however, it showed no significant negative effects (Demisie et al., 2014; Gunarathne et al., 2020; Zhou et al., 2017).

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Among various soil enzymes, dehydrogenase has been recognized as a critical biochemical indicator of soil. It was observed that 0.5% Oakwood biochar and 0.5% Bamboo biochar would give higher dehydrogenase activity compared to the 1% and 2% application rates (Demisie et al., 2014). Furthermore, straw biochar does not affect the dehydrogenase activity, whereas the addition of raw straw increases dehydrogenase activity with escalating application rates (Wu et al., 2013). High sorptive affinity in biochar has been demonstrated due to porous structure and high surface area. Therefore, Swaine et al. (2013) examined soil enzyme assay products to determine the potential of biochar for the sorption of organic chemicals as artificial substrates. The results indicated a significant decline in the concentration of assay substrates (INT) of dehydrogenase and product (INTF) in biochar added soils compared to the pristine soil (Swaine et al., 2013).

More exciting findings have been reported by Du et al. (2014) regarding the field application of biochar on the four enzymatic activities in the winter wheat–growing season. Substantial fluctuations have been demonstrated in enzyme activities throughout the observation period and the depth of soil profile. Deeper the soil horizon, minimum soil enzyme activities have been observed. The highest amendment rates (9.0 t $ha^{-1}y^{-1}$) lead to the peak activities of invertase, urease, and phosphatase in 0-5 cm soil depth after three years of application. In addition, they observed that the low application rate of biochar (4.5 t $ha^{-1}y^{-1}$), and crop residue addition were highly variable and limited to enzymatic activities.

5. Biochar and Plant Growth

Soil quality is one of the major factors determining plant growth. Therefore, soil quality maintenance is crucial for sustainable crop production. Moreover, soil physical, chemical, and biological parameters play a major role in soil quality. Thus, long-term management plans are needed to formulate and implement to make crop production environmentally and economically sustainable.

Plant growth has been enhanced by mobilizing and immobilizing plant nutrients in biochar which acts as a soil conditioner (Lehmann et al., 2006). Biochar applied to tropical and subtropical soils has depicted a significant increase in plant growth and yield (Jeffery et al., 2017). Additionally, in conventional arable soils, biochar has been used as a soil fertility enhancer (Alburquerque et al., 2014). However, potentially negative effects on plant growth and development in the presence of some biochar types have been reported (Intani et al., 2019; Hafeez et al., 2019). The adverse effects of biochar are mainly attributed to toxic compounds in biochars, such as potentially toxic elements, free radicals, and polycyclic aromatic hydrocarbons (Bandara et al., 2020). Hence, to encourage agricultural applications, in-depth knowledge on beneficial aspects of utilizing biochar to enhance crop yield is essential.

Farhangi-Abriz et al. (2021) have observed improved wheat and maize grain yields by 14% and 14-35%, respectively, in biochar applied soils. Further, Laghari et al. (2015) investigated the effect of biochar produced at different temperatures on sorghum plant growth in desert soil. The sorghum yield has increased by 19% with biochar pyrolyzed at 400 °C and by 32% with biochar produced at a pyrolysis temperature of 700 °C. On the other hand, Jia et al. (2021) have reported that biochar obtained from the pyrolysis process is more suitable for crop growth than hydrothermal converted biochar. Table 3 further summarizes the influence of different types of biochar application on the growth and yield of crop plants.

Table 3: Effects of biochar application on plant growth and yield.

Plant type	Biochar type	Application rate	Effect/s on plant growth	Reference
Cherry Tomato	Wastewater sludge biochar	10 t ha^{-1}	Yield increased by 64%	Hossain et al. (2010)
Maize	Commercial wood charcoal	20 Mg ha^{-1}	Yield was not increased significantly in 1st year and 28%, 30%, and 140% respectively in 2nd, 3rd, and 4th years	Major et al. (2010)
Wheat	Sorghum biochar	200 bushels ha^{-1}	Yield increased by 31%	Sigua et al. (2015)
Amaranth and Choy Sum	Maize straw biochar	20, 30, and 40 t ha^{-1}	Yield increased by 28% - 48%	Jia et al. (2012)
Rice	Wheat straw biochar	3% w/w	Increased yield	Muhammad et al. (2017)
Cabbage and Lettuce	Rice husk biochar	25, 50, and 150 g kg^{-1}	Biomass increment by 903%	Carter et al. (2013)
Rice and Leaf Beet	Wood chip biochar	2% and 5% w/w	No significant effect on crop growth and yield	Lai et al. (2013)
Maize	Rice straw biochar	1% w/w	No effect on yield	Naeem et al. (2017)

Soil acidification is one of the most common phenomena in the world that negatively affects crop growth. Remediation of acidified soils using biochar can increase crop yield by changing the availability of nutrients and improving other soil chemical properties (Xu et al., 2014). The laboratory experiments conducted by Deenik et al. (2009) depicted the negative effects of biochar with high volatile matter content on plant growth. Furthermore, soil respiration had increased, and considerable quantities of inorganic N have been immobilized due to high volatile matter in biochar. Moreover, a significant increase in plant growth has been observed with the mixture of mineral fertilizer and biochar compared to pristine mineral fertilizer (Deenik et al., 2009).

6. Future Perspectives and Conclusions

The addition of biochar increases soil physicochemical and biological properties depending on the feedstock material, production temperature, and application rate. In the tropical belt, most of the soils are highly weathered and considered infertile. When managing tropical soil, biochar plays a significant role in improving soil quality. Soil microbes and enzymes are considered primary indicators of soil quality. Biochar alters soil microbial community composition and diversity. Nevertheless, the effect of biochar on soil enzymatic activities is yet to be further studied in the long term. Therefore, future research is needed to identify the interaction mechanisms of biochar versus enzymes. The improved crop productivity resulting from biochar application is implied by most of the agronomic research. However, further research should be carried out to investigate the impact of biochar on crop growth.

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