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Effect of Biochar on Soil Properties – A Review

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Abstract— Biochar is produced by carbonizing organic matter under high temperatures in a little to no oxygen environment. There are seven key factors to evaluate biochar including pH, volatile organic compound content, water holding capacity, ash content, density, pore volume, and surface volume. The choice of raw materials affects the end biochar product, changing its chemical component level, hardness, density, and porosity. Biochar has a notable influence on soil properties. This review summarizes biochar's effect on soil physical properties, hydraulic properties, microbial biomass, and soil remediation. Biochar decreases the bulk density by interacting with soil particles enhancing porosity. Thus, soil forms a good structure and serves excellent medium for the transport and uptake of water and nutrients. Available water content (AWC), saturation water content (SWC), water holding capacity (WHC), and permanent wilting point (WP) significantly increase with the biochar application. Additionally, biochar-amended soils have greater hydraulic conductivity values. Furthermore, biochar application alters the abundance of soil microorganisms by modifying the soil. In certain stressed environments, biochar promotes the colonization of mycorrhizal fungi, encouraging root growth. Biochar can effectively immobilize the heavy metal and organic pollutants in the soil through various sorption mechanisms. Despite its advantageous nature, biochar can change nutrient availability and soil nutrient ratios, which could adversely affect plant growth. Altogether, these recent studies suggest that biochar has a huge capacity for boosting soil and reducing environmental pollution.

Index Terms—Biochar, microorganisms, physical properties, remediation

1 INTRODUCTION

Biochar is a fine-grained product derived from the pyrolysis of biomass and biodegradable waste and it is characterized by its high organic carbon content and resistance to degradation [1,2]. With a history of production and use spanning millennia, biochar, a solid byproduct obtained through biomass pyrolysis, is most recognized in its form as charcoal, particularly when derived from woody biomass feedstock [3].

Although biochar is a charcoal-like material produced by combusting feedstock in a limited oxygen environment, as a potential soil conditioner and carbon sequestration tool for mitigating climate change [4], when plant matter is heated without much oxygen (pyrolysis), it breaks down into various products. These include gases like hydrogen and methane, liquid oils and tars, and a solid, carbon-rich residue called char. Biochar is a specific type of char intended for use in soil. It's similar to charcoal but can be made under different conditions, with or without oxygen. Both biochar and regular char are made up of stable carbon and won't easily turn back into CO_2, even in environments like soil where decomposition happens [5].

The raw materials used to make biochar (like wood, crop leftovers, or manure) affect the final product in several ways, such as concentrations of elemental constituents, density, porosity, and hardness [6]. Moreover, Biochar is primarily composed of carbon and ash, with its elemental makeup and properties exhibiting significant variation depending on the feedstock employed and the pyrolysis conditions implemented [1]. In assessing the suitability of biochar for various applications, its composition serves as a critical determinant [3]. To get biochar with the right properties for a particular use, one needs to choose the right feedstock as well as the pyrolysis production technique [6].

Scientists can analyze biochar in its pure form (ex-situ) to understand its properties and how they change over time in different environments. Elemental ratios (O: C, O: H, C: H) are a simple way to assess both the initial processing (pyrolysis) and how much the biochar has been altered by oxygen in the soil. Analyzing biochar's impact on soil chemistry (biogeochemical characterization) is key to unlocking its full potential [5].

The elemental composition of biochar, specifically the content of carbon (C), nitrogen (N), potassium (K), calcium (Ca), and other elements, is demonstrably influenced by both the feedstock employed and the pyrolysis conditions. For instance, biochar derived from feedstocks rich in potassium, such as animal manure, will exhibit higher K content compared to biochar produced solely from wood, which typically boasts a greater proportion of carbon [7].

Biochar's structure plays a key role in its impact on soil. Biochar inherits the porous architecture of the plant material it's made from, which can be beneficial for water retention and nutrient absorption in soil. Additionally, the form and size of the raw material and the final biochar product can influence its properties [5].

The Biochar production process begins with drying the biomass, followed by heating it to release volatile components. These volatile components can either become permanent gases like carbon dioxide or methane, or they can condense into liquids like methanol. Further reactions can occur within the gas phase, influencing the final product yield. Ultimately, pyrolysis yields three distinct products: permanent gases, liquid condensates (including water and tar), and a solid biochar residue [3].

Moreover, there are two main types of pyrolysis: slow pyrolysis and fast pyrolysis. The key differentiating factors between these methods are residence time and heating rate. Slow pyrolysis, characterized by lower temperatures and slower heating, favors the production of syngas [8]. In detail, slow pyrolysis also referred to as conventional carbonization, biochar is produced through the thermal treatment of biomass. This process is characterized by the application of relatively low heat over an extended residence time, which can span several days [9]. In contrast, fast pyrolysis, achieved with high temperatures and rapid heating, yields a greater output of oils and liquids [8]. This is because of the shorter residence time and higher temperatures employed [10]. Therefore, Slow pyrolysis yields lower bio-oil and gas compared to fast pyrolysis [11,12].

Scientists have identified seven key characteristics to evaluate biochar: pH, volatile compound content, ash content, water holding capacity, density, pore volume, and surface area [5]. In the field of biochar research, a growing body of evidence suggests a significant influence of production factors on both the characteristics of the final product and its subsequent environmental and agricultural applications [6]. The raw material used (feedstock) and the burning temperature (pyrolysis temperature) significantly impact these properties [6,5]. Higher burning temperatures create biochar with more carbon content and higher ash content, but this comes at the cost of a lower overall yield. In other words, while more carbon gets concentrated in the biochar at higher temperatures, you end up with less total biochar. Interestingly, the amount of ash in the raw material stays relatively constant, so the proportion of ash in the final biochar goes up as the overall yield goes down [5].

2 IMPORTANCE OF BIOCHAR

Recent research has highlighted biochar production and application as a promising technique for utilizing by-products from industrial and agricultural processes in a low-carbon manner. This approach has gained significant attention due to its potential benefits for soil health and crop productivity [13]. Factors beyond just biochar stability need to be considered, including changes in crop productivity, residue decomposition/humification rates, soil organic matter cycling, and potential emissions of methane (CH4) and nitrous oxide (N2O). Additionally, a complete assessment should encompass the GHG emissions associated with biochar production, transportation, and application to soil [6]. The versatility of biochar is evident in its diverse applications. It can be employed as a soil amendment, incorporated into animal feed and silage for potential health benefits, or utilized in water treatment processes [14]. Multifaceted applications of biochar, including its potential as a tar filter during thermochemical conversion processes like pyrolysis and gasification, its utilization as a pelletized fuel source, and its role as a substrate for hydrogen production [15, 16, 17]. Biochar's incorporation into the soil is hypothesized to improve carbon sequestration, enhance soil fertility, stimulate microbial activity, improve soil pH, promote nutrient recycling, increase water-holding capacity, and potentially remediate soil contamination [18,19].

Research suggests biochar can improve crop yields, but it often depends on how it's used. Studies have shown that biochar can help crops utilize fertilizer more efficiently, leading to sustained yields even in poor soils. Combining biochar with fertilizer has been particularly effective in pot and field trials (5). Biochar application has been linked to reduced agrochemical dependence, increased crop yields, and long-term improvements in soil health. This translates to a positive environmental impact through two main pathways: biochar directly sequesters carbon in the soil, and it also indirectly reduces greenhouse gas emissions by enhancing fertilizer use efficiency [20]. The potential of biochar as a soil conditioner to mitigate the ongoing depletion of soil organic carbon caused by agricultural practices [21].

Interestingly, biochar can also increase nitrogen fixation in some plants, potentially boosting yields and nutrient uptake. An important concern is that biochar may tie up existing soil nitrogen, making it unavailable to plants. This could happen through various mechanisms, such as microbial breakdown of biochar using soil nitrogen, direct adsorption of nitrogen by biochar, or trapping nitrogen in tiny pores [5].

Biochar itself is particularly good at holding water because of its large pores, which are remnants of the plant material it was originally made from. Since biochar is very stable in soil, it offers a long-term solution for improving a soil's ability to retain water [5].

While biochar can trap some nutrients in a usable form for plants, it also acts like a magnet for organic materials. This means it could potentially absorb harmful leftovers from the wastewater treatment process [5]. With a long history of application, charcoal demonstrates efficacy in contaminant removal from aqueous environments [22]. For effective stabilization of metals to occur within a biochar matrix, a range of interaction mechanisms are necessary. These mechanisms include electrostatic interactions, ionic exchange, sorption via proton exchange, and specific ligand binding [23]. In a study by [24], biochar produced through the pyrolysis of anaerobic digester dairy fiber demonstrated efficacy in removing phosphorus (P) from dairy lagoon effluent. This method achieved a significant reduction in waste stream P content, reaching up to 70%. These findings suggest that biochar-based effluent filters have the potential to not only reduce P in dairy waste streams but also recover it in plant-available forms [6]. In addition to its primary function, biochar demonstrates applicability in various environmental management practices. Notably, biochar can be utilized for immobilizing contaminants present in soil, aiding in sewage treatment processes [25, 26, 27, 28, 29, 30].

Further, biochar has been demonstrated as an effective sorbent for immobilizing various pollutants. Studies have shown that biochar can be used to remove pharmaceutical residues, such as sulfamethoxazole, and bacteriostatic antibiotics from sewage [31, 32]. Additionally, biochar has been successfully employed to sequester heavy metals from aqueous solutions, municipal sewage, and industrial wastewater [33, 34, 35, 36]. Researchers investigated the use of biochar to immobilize specific pesticides, including carbaryl, atrazine, simazine, and acetochlor. This indicates that biochar may be a viable approach for reducing the mobility and environmental impact of these harmful chemicals in soil [37, 38, 39].

Additionally, biochar can potentially reduce greenhouse gas emissions in two ways. First, it avoids emissions of nitrous oxide (N_2O) during fertilizer production and use [5]. Second, biochar may help avoid future emissions by increasing agricultural productivity. If crops grow better with biochar, less land may need to be converted to farmland, protecting forests and savannas that store carbon [5]. This study investigated the potential of biochar to reduce nutrient leaching in soil. The research suggests that biochar application significantly decreases N_2O emissions by up to 83%. This reduction in gaseous nitrogen losses aligns with the reported benefits of biochar as a soil conditioner and organic fertilizer [18, 19]. Furthermore, it serves as a supplementary material to enhance composting and methane fermentation [25, 26, 27, 28, 29,30]. Moreover, biochar production through pyrolysis offers an alternative to traditional waste management methods, potentially leading to reduced methane emissions from landfills [40]. This study [41] investigates the potential of biochar as a bio-sequestration tool under atmospheric conditions. Biochar's organic carbon content, which can reach up to 90% depending on the source material, contributes to its increased capacity for carbon sequestration. These findings suggest biochar is a promising strategy for both soil remediation and carbon capture [42].

Biochar could be especially useful in restoring and improving poor quality or degraded soils, leading to a future with better environmental health [43]—Biochar is a sustainable tool for environmental remediation. Biochar production utilizes waste materials like animal manure, agricultural biomass, and sewage sludge, transforming them into a valuable resource. This process not only reduces the need for landfill disposal but also eliminates harmful pathogens present in these wastes [40].

3 EFFECTS OF BIOCHAR ADDITION ON SOIL PHYSICAL PROPERTIES

3.1 Soil bulk density

A key indicator of the physical characteristics of soil is its bulk density. It is directly related to the arrangement or packing of soil particles [43]. It is a proportion of the bulk volume (volume of pore spaces

+ volume of soil particles) to the mass of oven-dried soil. Both soil characteristics and plant growth are significantly influenced by the bulk density of the soil. The study by (45) found that with increasing biochar levels, bulk density decreased and porosity increased. [46] reported that biochar application can reduce bulk density by 7% compared to the control treatment. Soil bulk density decrease was impacted by biochar addition rate, biochar particle size, biochar type, and soil type [43]. Planosol, Chernozem, and Cambis with woodchip biochar amendments had bulk densities of 13.3%, 10.3%, and 9.9%, respectively [47]. The decrease in bulk density following biochar application might be caused by at least two different mechanisms [48]. In comparison to soil, biochar has a lower bulk density than soil [49]. Hence, the application of biochar certainly has a mixing or diluting activity that lowers the soil bulk density. In addition, biochar may eventually lower bulk density by interacting with soil particles and enhancing aggregation and porosity [48]. Recent research that was released in 2018 -2023 is included in Table 1.

Table 1. The effects of biochar on the soil bulk density

Soil type	*Study type*	*Study duration*	*Biochar type*	*The application rate of Biochar (t ha^{-1})*	*Bulk Density (g/cm3)*	*References*
Dolomitic Leptosols	Field	1 year	Leafy trees	0	1.48	[50]
				40	1.35	
				60	1.26	
				80	1.17	
			Sunflower husk	0	1.48	
				40	1.32	
				60	1.30	
				80	1.19	
sandy loam	Field	-	Mulberry stalk	0	1.33	[51]
				5	1.31	
				7.5	1.30	
				10	1.30	
Acidic Soil	Field	-	Coconut shell	0	1.39	[52]
				5	1.33	
				7.5	1.30	
				10	1.28	
Sandy loam Alfisol	Field	2 years	Hardwood	0	1.59	[45]
				10	1.38	
				20	1.20	
				30	0.91	
Silty Loam Haplic	Field	4 years		0	1.41	[53]
				10	1.39	

Luvisol				20	1.36	
Ultisol	Pot	-	Cassava straw	0	1.38	[54]
				20	1.15	
				40	0.96	
				60	0.87	
Ultiso	Field	90 days		0	1.45	[55]
				5	1.38	
				10	1.37	
				15	1.35	
Alfisol	Field	One month after sowing	Hardwood	0	1.56	[56]
				25	1.29	
				50	1.17	
Albeluvisol	Field	4 years	Miscanthus	0	1.39	[46]
				8	1.29	
				25	1.21	

3.2 Porosity

In addition to influencing water transformation, preservation, and consumption, soil pores supply oxygen for plants and animals. The soil pore structure is significantly impacted by the biochar's pore distribution, connectivity, and particle size [43]. Applying biochar to the soil can result in a 2–41% increase in porosity [48]. In lab incubation and field experiments, there was a significant improvement in total porosity with biochar of 9.9% and 6.4%, respectively [57].Application of biochar directly caused a decrease in soil bulk density and an increase in soil porosity. [45] reported that the formation of macropores and the rearrangement of soil particles caused the change in porosity with biochar-treated soils. Applying biochar leads to an adjustment in the soil pore size distribution to a smaller pore size, which has a beneficial impact on crop growth [58]. According to some scientists, incorporating biochar will reduce soil porosity because the dust from the biochar will block soil pores [59]. The following table (Table 2) demonstrates the impact of various biochar application types and rates on the soil porosity of various soils.

Table 2. The effects of biochar on the porosity

Soil type	Study type	Study duration	Biochar type	The application rate of Biochar (t ha^{-1})	Total Porosity %	References
Sandy loam Alfisol	Field	2 years	Hardwood	0	40.0	[56]
				10	47.9	
				20	54.7	

				30	66.0	
Ultisol	Pot	-	Cassava straw	0	41.07	[54]
				20	57.25	
				40	64.08	
				60	66.24	
Silty Loam Haplic Luvisol	Field	4 years	-	0	44.19	[53]
				10	45.73	
				20	44.12	
Ultisol	Field	90 days	-	0	45.28	[55]
				5	47.92	
				10	48.30	
				15	49.06	
Silty loam soil	Field	-	Control	25	11.33	[60]
			rice straw	25	9.062	
			corn straw	25	8.735	
			bamboo	25	5.873	
Alfisol	Field	one month after sowing	Hardwood	0	41.1	[56]
				25	51.3	
				50	55.8	
Albeluvisol	Field	4 years	Miscanthus	0	49.93	[46]
				8	49.67	
				25	53.27	

3.3 Soil aggregation

Complicated biological, chemical, and hydrophysical processes in the soil matrix lead to the formation of soil aggregates [61]. A well-aggregated soil has a good structure and serves as an excellent medium for the transport of nutrients and water into the soil and uptake by plants [59]. Microorganisms are protected from desiccation and predators through the application of biochar [59]. Polysaccharides secreted by the microbes promote soil aggregation. The effects of the various biochar dosages on the distribution of the soil aggregates in the various aggregate fractions showed various variations. [62] has indicated that compared to the control treatment, biochar had no significant influence on the large macroaggregate fraction; however, when the biochar dose was raised, the small macroaggregate fraction initially increased and subsequently declined. The impact of biochar on soil's physical structure depends on the properties of the biochar. [63] has revealed that biochar generated using hydrothermal carbonization had a higher potential to increase soil aggregate stability than biochar produced through slow pyrolysis. The mean weight diameter (MWD) and geometric mean diameter (GMD) can be used to measure soil aggregation. A high MWD and GMD value as a measure of the treated aggregate's structural stability indicates that the bigger, more stable aggregates predominate over the smaller, less stable portions [64]. According to [47] after three years, all biochar-amended Planosol treatments had higher soil aggregate stability compared to the control, with 92%, 37%, 28%, and 50% relative increases in the straw, 525 °C vineyard-pruning, 400 °C vineyard-pruning, and woodchip biochar treatments, respectively. Aggregate stability was considerably increased by 5.3% and 9.7% respectively high biochar application rates [57].

4 EFFECTS OF BIOCHAR ADDITION ON SOIL HYDRAULIC PROPERTIES

4.1 Plant available water and water holding capacity

The AWC, which indicates the amount of water plants can use, is the most significant indicator when considering the productive roles of agricultural soil and water retention in the soil [50]. The amount of water released by a soil between its field water-holding capacity (WHC) and its permanent wilting point is defined as its available water content (AWC) [64] .The ability of soils to retain water that is available to plants is a significant measure of soil quality. According to [64] several forms of biochar have varying effects on saturation water content (SWC), WHC, WP, and AWC. SWC, WHC, WP, and AW levels significantly increased in the biochar-amended soils [64]. When compared to the control, the application of biochar enhanced the soil moisture content. This could be attributed to biochar soils having more micropores to physically hold water and enhanced aggregation that resulted in the formation of larger pore spaces as a result of increased earthworm burrowing [56]. [50] reported that field capacity was raised by the addition of biochar the applied biochar dose had a considerable impact on the field capacity [50]. Water held both inside biochar pores and between biochar particles as a result of capillary forces and/or attraction of water to the exterior surfaces of biochar is one explanation for the increased water retention in biochar-amended soils [64].

The modification of biochar affects soil water-holding capacity in two different ways [65]. The internal pores of biochar itself may hold water and the hydrophilic functional groups on the surface of biochar may help to raise soil water holding capacity. According to [56] long-term column research, biochar-amended Clarion soil held up to 15% more water than control, and 13% and 10% more water at -100 kPa and -500 kPa soil matric potential, respectively. [65] reported that the water holding capacity of 20% biochar-amended soil reached 52%, while pure sandy soil only had water holding capacity of 28%.Throughout the agriculturally relevant range up to 20% biochar concentrations, soil water holding capacity by 1.2% by mass for each 1% addition of biochar [65]. According to [51] potential of biochar to increase the soil's total porosity, extensive pore structure, and specific surface area, the water-holding capacity of the soil was improved. [46] observed that with more biochar applied, the amount of water available to plants increased. In comparison to the control, straw biochar increased plant available water in the Planosol by 38%, compared to 24% and 21% increases in the vineyard-pruning biochars, generated at 525 °C and 400 °C, respectively [66]. Regardless of the applied dose, soils, where biochar was applied, showed increased field capacity and available water capacity [50].

4.2 Hydraulic conductivity

Saturated hydraulic conductivity depends on soil pore number, soil structure, texture, etc. [67]. Adding biochar to the soil dramatically reduced the soil bulk density, which caused noticeably greater hydraulic conductivity values [68]. Increasing the amount of applied biochar causes different changes in the order of total porosity, hydraulic conductivity, and a decrease in bulk density [55]. The addition of biochar significantly affects the pore size distribution and hydraulic conductivity, but the degree of change varies on the particle size and shape as well as the original mineral pore size distribution [69]. [49] was reported that average hydraulic conductivity enhanced in rice husk biochar from 0.99 cm/h in the control to 2.41 cm/h. Biochars produced from wood and manure considerably raised the hydraulic conductivity by 35.7% and 6.6%, respectively [57]. Mean hydraulic conductivity is increased significantly by 39.7% when biochar was applied at high pyrolysis temperatures, and not at low pyrolysis temperatures [57]. [69] observed in the biochar-amended soils, the saturated hydraulic conductivity values significantly decline. The smaller biochar particles have also caused to the initial decrease in K_{sat} in all amended soil due to the clogging of the large water-conducting pores and the formation of bottlenecks [69].

5 EFFECTS OF BIOCHAR ON SOIL MICROORGANISMS

Applying biochar to soil has been demonstrated to improve soil quality. It can also alter the availability of nutrients in the soil by enhancing host plant performance, increasing the rate at which AMF colonizes the roots of the host plant, and improving soil characteristics [70, 71]. Also as described in [72, 73] the biological qualities of soil can be significantly impacted by the use of biochar. Although there has been comparatively little experimental focus on the interactions of biochar with soil microbes, such as arbuscular mycorrhizal fungi (AMF), evidence for these interactions is currently developing from various experimental systems [74, 75, 76]. Impacts of biochar on soil microbial communities mostly supported the idea that soil amendments containing biochar typically enhanced soil microbial activity and biomass, as well as ratios of Gram-positive to Gram-negative bacteria and fungal to bacterial biomass [77]. Additionally, biochar dramatically changed the dynamics of ammonia-oxidizing soil microorganisms, boosted their abundance, and changed the makeup of their communities, favoring the diversity of ammonia-oxidizing bacteria over ammonia-oxidizing archaea [78]. It has also been suggested that biochar, by creating suitable refugia, may shield beneficial soil microorganisms, especially bacteria, from predators [79].

The increase in extraradical hyphae in soil, however, cannot be described as direct interactions between AM fungal hyphae and biochar surfaces or as an indirect reaction resulting from interactions between biochar and roots that induced AM fungal growth inside roots and hyphae proliferation in the soil [80]. Applying biochar has the potential to significantly alter the microbial populations in soil. In theory, certain plant-pathogenic microbes may be stimulated by biochar [81, 77]. In water-stressed environments, biochar would promote the mycorrhizal colonization of roots, promote plant development, and increase the amount of AM fungal hyphae that form in the soil. Elevated hyphal development in the soil may lead to greater mycorrhizal colonization [82]. As an example [83] report that Biochar may facilitate mycorrhizal colonization, which might impact wheat's ability to absorb P and N and withstand drought stress. As well as Biochar also stimulates the colonization of roots by AM fungi, leading to an increase in mycorrhizal hyphae and increased soil exploration for water [84]. As a result, Plants cultivated in soil treated with biochar experienced less water stress and invested more carbon in shoot development compared to those grown under water-stressed conditions [85, 86].

However, the increase in extraradical hyphae in the soil cannot be described as direct interactions between AM fungal hyphae and biochar surfaces or as an indirect reaction resulting from interactions between biochar and roots that induced AM fungal growth inside roots and hyphae proliferation in the soil [80, 86].

Compared to uncharred organic matter, biochar is more resistant to microbial degradation due to its macromolecular structure, which is dominated by aromatic C [87].

The porous nature of biochars derived from plant materials can be attributed mostly to the presence of water-conductive trace elements. Biochar holes may be filled by AM fungal hyphae According to certain theories, biochar especially biochar made from plant materials might thus act as a habitat for AM fungi. It becomes sense to speculate that nonfilamentous microorganisms like bacteria or perhaps protozoa find protection in biochar [88, 89, 90, 91]. For fungi, the situation is less clear. Even while soil animals bigger than the holes in biochar may not harm the hyphae within, the hyphae still need to enter the pores from the outside. The hyphae outside of the pores are still vulnerable to damage. Therefore, if the hyphae are cut between the root and the biochar particle, as appears likely, it is unclear if the protection that the particles give helps preserve nutrient transport to the root [92]. However, hyphae or spores might serve as inoculum sources. Moreover, they are in a protected habitat when they are detected inside the pores of a biochar particle. Therefore, adding to soils can significantly raise the soil's capacity to hold inoculum in upcoming years. The usage of various porous materials containing mycorrhizal fungal propagules that have been suggested as sources of inoculum in the past may be comparable to these phenomena [92, 93].

Microbial populations and soil biogeochemistry are impacted by biochar produced from biomass. The functions of soil microorganisms, particularly arbuscular mycorrhizal fungi (AMF), ectomycorrhizal fungi (ECM), and ericoid mycorrhizal fungi (ERM), in terrestrial ecosystems are well known [94]. The effects of biochars on AMF infectivity and effectiveness are highly debatable in the research that is currently available [95, 96, 97]. According to [98] biochar made from forestry products and rice husk can increase the microbial activity in native soil. The relationship between biochar and arbuscular mycorrhizal fungi (AMF), which are significant root symbionts of most terrestrial plants, including most crops, has not been fully investigated [99]. Investigating the relationships between biochar and mycorrhizal hyphae for plants is crucial because biochar may directly supply the roots with more readily available nitrogen, allowing the hyphae to take up organic substrates from the plant without contributing nitrogen in return [97, 100].

As described in [86, 101] the mechanisms of biochar/mycorrhizal fungi interactions involve biochar acting as a habitat for bacteria and fungi found in soil; in fact, it has been demonstrated lately that, in artificial environments, AM fungi can penetrate and reach microsites within biochar pores. However, there was minimal indication that the hyphae of naturally existing AM fungus expanded surrounding biochar particles when biochar was studied in agricultural field soil [102]. The types of mycorrhizal fungi present in the community might be impacted by variations in the pore diameter of biochar. For instance, AM fungi generate spores that vary in size by more than an order of magnitude, which is mostly related to the family. Therefore, the distribution of soil pore diameters, which is a function of the species of biochar feedstock, may determine the species composition of AM fungal spores contained within biochar particles [92, 103].

Biochar may cause changes in the overall amount and/or activity of mycorrhizal fungi in soils and plant roots, which may be explained in at least four different ways [94, 97, 99].

(i) By altering the physicochemical characteristics of the soil (such as pH, water-holding capacity, and cation exchange capacity), biochar may alter the concentrations and accessibility of nutrients (C, N, P, and K), which have an impact on the growth of fungi as well as the host plant.

(ii) The rhizosphere microbiome, which includes phosphate-mobilizing and mycorrhizal helpful bacteria, may be altered by biochar, thereby promoting plant development.
(iii) Plant-AMF signaling pathways, such as the transport and concentration of signal molecules, or allelochemical absorption, may be affected by biochar, which might result in modifications to AM fungal root colonization.
(iv) For hyphae consumers, biochar could act as a microrefugia and a place to hide.

Applying biochar combined with inoculated mineral fertilizer resulted in a considerable increase in mycorrhizal colonization in wheat roots [98]. The advantages of biochars and the biochar-mineral complex (BMC) have been linked to enhanced nutrient absorption from sandy soil with poor nutrient availability and mycorrhizal colonization [104]. Applying biochar encourages the colonization of arbuscular mycorrhizal (AM) fungi, which can assist in providing P to a variety of crops and rhizobia, which can fix atmospheric N2 supply to leguminous plants [98, 105, 106, 107]. Plant P absorption can be enhanced by AM fungi by extending their extraradical hyphae into the charcoal and sporulating inside biochar particles buried in soil [108, 109]. The impact of biochar on soil qualities on mycorrhizal fungi varies according to the kind of fungus involved. In mycorrhizal fungal communities, for instance, the relative abundance of the component species is influenced by pH, N availability, and P availability [92, 110, 111].

In temperate forest habitats, the benefits of biochar on soil microbial activity have also been identified [112, 113]. The benefits of biochar for plant nutrition and microbial activity in the humid tropics were also noted by [114]. According to [115] biochar has been suggested to affect microbial activity by creating a favorable microhabitat (pore space) because of its low alkalinity and by acting as a substrate that is unfriendly to saprophytes [98]. Furthermore, biochar will have an impact on a few agricultural system components, including mycorrhizal symbiosis [92].

Biochar has the potential to mitigate the severity of diseases through a variety of mechanisms, such as modifying the population density of certain bacteria, releasing chemicals that enhance plant vigor and induce systemic acquired resistance, or promoting AM fungal colonization. Plants have been demonstrated to benefit from AM fungal colonization, which may be achieved through competition-induced reduction of disease incidence or severity. Should biochar mitigate disease via promoting mycorrhizal fungi, then the impact of biochar and AM fungi would be the same. Nonetheless, biochar and AM fungus may work in concert or additively if their respective processes for reducing disease are different [92, 116, 117, 118, 119, 120, 121, 122]. Additionally, the capacity of AMF to help their host resist plant pathogen invasion can be enhanced by biochar [97]. Biochar can shield rhizobia in pores smaller than 50 mm from predators and enhance nitrogen fixation, suggesting that it might serve as a useful microhabitat in soils with low clay concentration [98, 123, 124].

However [125] found that applying biochar did not always improve the soil. For instance, adding biochar to the soil may result in an unfavorable nutrient ratio or a decrease in the availability of nutrients [126]. According to [127] this negative effect may be more noticeable if the biochar has a very high C/N ratio, some of which is decomposable, or if the biochar is applied at a rapid rate, which immobilizes N.

Certain studies have shown adverse effects on mycorrhizal fungal abundance, in contrast to the beneficial effects of charcoal additions. In these situations, it seems that nutritional impacts were mostly responsible for the detrimental effects of the biochar inputs on AMF [94]. As an example, compared to rates from plants grown on river sand or clay-brick granules, the biochar medium reduced the quantity of P taken up by host plants, indicating that P was less accessible [127]. When biochar was applied, mycorrhizal fungus reacted more favorably than when other forms of organic material were added [94, 128, 129].

When the biochar has a high C/N ratio and some of it decomposes, resulting in N immobilization, this detrimental effect may be more noticeable. Biochar could potentially have a detrimental effect on plant development in some circumstances [127].

Biochar changes the activity of microorganisms that affect mycorrhizae, such as Mycorrhization Helper Bacteria [130]. In addition to providing nutrients and/or decreased carbon compounds, biochar can operate as a home for soil bacteria that are colonizing it, such as MHB and PSBs [131,132].

Applying biochar to soil may either boost or diminish the hosts' susceptibility to a symbiotic relationship. Biochar's large surface area, porosity, and adsorptive qualities may encourage AMF activity by creating favorable environments. The observed colonization of AMF roots and production of glomalin was the consequence of the cumulative direct and indirect impacts of biochar. AM fungus may be able to get nutrients from biochar [133]. Even while treated soils have higher pH values and a high concentration of macroelements like potassium and phosphorus, which are good for plant nutrition, applying biochar to the soil may somewhat reduce the hosts' susceptibility to a symbiotic connection [97,134].

6 EFFECTS OF BIOCHAR ON SOIL REMEDIATION

According to recent studies, incorporating biochar into the soil can reduce the soil contamination. Organic pollutants and heavy metals are effectively trapped by the large surface area of biochar, which lowers their mobility and toxicity [135,136]. Biochar uses processes like adsorption and other physicochemical reactions in soil remediation [137,136]. It surpasses traditional soil remediation methods for immobilizing different contaminants such as antibiotics, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and others [138].

Biochar efficiently removes major pollutants from soil using a range of techniques. Such a technique is ion exchange. In ion exchange, biochar switches the charged particles such as H+ with other cationic contaminants or heavy metal ions via functional groups on the surface of biochar. Physical adsorption, another technique occurs when pollutants are trapped on the surface or within the micropores of biochar due to their surface area and porosity. On the other hand, in electrostatic contact, heavy metal ions are drawn to the charged surface of biochar. Precipitation is the making of insoluble compounds when mineral components in biochar react with heavy metal ions. In complexation, heavy metals bond to oxygen-containing functional groups on the biochar's surface, making stable complexes [139].

6.1 Effect of heavy metal contamination

The slow-acting nature of heavy metals in soil can cause environmental issues. They can move to water and through crops to join the food chain [140,141]. Several studies offered reliable information about the potential efficacy of biochar in eliminating heavy metals from soils and aqueous solutions [30]. Biochar lowers crop uptake of heavy metals and enhances soil quality. It can also reduce the leaching of metals through its effect on redox reactions of metals [136]. The plant, microorganisms, and earthworms are potential biotic factors that influence the remediation of soils by biochar [138]. It is a promising treatment for lowering the ecotoxicity of heavy-metal-contaminated soils because it can effectively absorb heavy metal cations from water and immobilize heavy metal components in soil. By interacting with the heavy metals in the soil, the applied biochar adsorbs the metal ions on the pore surfaces. Then stabilizes heavy metals by converting the harmful components like precipitates of phosphate, carbonate, and hydroxide, which are less bioavailable and less soluble, sometimes even changing them [135]. The alkaline nature of biochar helps in this stabilization process [136].

Biochar performs poorly in the removal of Arsenic (As). However, when modifying biochar by adding Fe increases the sorption of As. Biochar has shown remarkable efficacy in the sorption removal of lead (Pb) with an average of 90% sorption rates in water and 60% in soil [142]. Some potential mechanisms for heavy metal stabilization in soils treated with biochar include (1) metal exchange with Ca^{2+} and Mg^{2+}, which may contribute to co-precipitation and inner sphere complexation with complexed humic matter and mineral oxides of biochar; (2) surface complexation with free carboxyl and hydroxyl functional groups; (3) others, including inner sphere complexation with the free hydroxyl of mineral oxides and other surface precipitation [143]. Derakhshan *et.al*, 2017 examined the impact of incorporating biochar derived from rice straw on the mobility and bioavailability of Cu(II), Pb(II), and Cd(II) in Ultisol. As the quantity of biochar amendment increased, the acid-extractable Cu(II) and Pb(II) fell by 19.7e100% and 18.8e77.0%, respectively. Reducible Pb(II) for treatments with 3% and 5% biochar was 2.0 and 3.0 times higher than that of samples without biochar when 5 mmol/kg of these heavy metals were added. Table 3 shows the experiments showing the effect of biochar on heavy metal contamination.

Table 3. Effect of biochar on heavy metal contamination

Biochar type	Pyrolysis temperature (°C)	Heavy metals	Effect	Reference
Rice husk (RHB), Maple leaves (MLB)	550	Cd, Cu, Pb, and Zn	• Increased soil pH to the appropriate range for plant growth • Great reduction of the leaching of Cd, Cu, Pb, and Zn • Decreased plant uptake and accumulation of Cd, Cu, Pb, and Zn by 79-66, 13-19, 87-86, and 37-36% in soils treated with RHB and MLB, respectively • Stabilized metals primarily	[145]

			through organic and carbonate bonding	
Magnetic nanoscale zero-valent iron-assisted biochar using wetland plant reed	-	Pb, Cd, Cr, Cu, Ni, and Zn	• Formed a nanoscale Fe° core and Fe_3O_4 shell on its surface, pores, and channels • Effectively removed heavy metals such as Pb2+, Cd2+, Cr6+, Cu2+, Ni2+, and Zn2+ from solutions	[146]
Meat and bonemeal (contain 10% by volume willow (Salix spp.))	-	Zn	• Fast adsorption of Zn (in less than five hours) above pH 6.1, with a maximum adsorption capacity of 0.65 mmol Zn g^{-1} • Formation of tetrahedral zinc in a monodentate inner-sphere surface complex with phosphate groups • Promoted the precipitation of a ZnPO4 phase at a lower pH and with an acidification pretreatment	[147]
Bamboo and rice straw	≥ 500	Cd, Cu, Pb and Zn	• Reduced the bioavailability of heavy metals on *Sedum plumbizincicola* • Decreased Cd concentrations in shoots by 49% • Decreased Cu and Pb concentrations by 46 and 71%, respectively from rice straw biochar	[148]
Oakwood	400	Pb, Sb	• Reduced exchangeable Pb by up to 99% • Lowered Pb bioavailability in maize by up to 71%. The Decreased Sb absorption in maize by up to 53.44% • Association of unavailable Pb with phosphorus	[149]
Wine lees (made from sorghum, rice,	600	Cr, Ni, Cu,	• Reduced the exchangeable heavy metals, raising soil pH, and encouraging the transition	[150]

glutinous rice, wheat, and corn, with a mass ratio of 23:37:19:17:4)		Pb, Zn, and Cd	of heavy metals into residual fractions • Lessens the accumulation of heavy metals in paddy plants, and hinders their ability to move above ground • Dropping of the levels of soil-exchangeable in paddy (Cr, Ni, Cu, Pb, Zn, and Cd by 18.8, 29.6, 26.3, 23.0, 23.01, and 48.14%, respectively, at the biochar 0.5% in weight) • Decreased Zn, Cd, and Pb levels by 10.96, 8.89, and 83.3%, respectively	
Bamboo and rice straw	≥500	Cd, Cu, Pb and Zn	• Improved the soil pH, electrical conductivity, and cation exchange capacity at a 5% application rate • Significant drop in $CaCl_2$-extractable heavy metal content	[151]
Wood, bamboo, Chinese walnut shell, and rice straw	500	Cu, Pb	• Decreased the Cu uptake in roots by 15%, 35%, and 26%, respectively (at 5% application rate) • Decreased the solubility of soil heavy metals (Pb- 10.59 $mgkg^{-1}$, Cu- 58.91 $mgkg^{-1}$) by Rice straw biochar	[141]
Bamboo	750	Cd, Pb	• Increased the soil pH. • Reduction of Cd content in maize shoots by 50.9% • Reduction of accumulation Cd in shoots by 47.3 % • Shoot Pb did not decrease	[152]
Bamboo and rice straw	750	Cd, Cu, Pb and Zn	• At a 5% application rate, dropping the amount of CaCl2 and DTPA-extractable Cd, Cu, Pb, and Zn • Reduced acid extractable Cd, Cu, Pb, and Zn levels	[153]

			• Rice straw biochar was shown to be more effective than bamboo biochar • Increased effect on the higher application rates • Deduction of DTPA extractable metal concentrations in the following order: Cd, Cu, Pb, and Zn • Reduced the acid-extractable pools of Cd, Cu, Pb, and Zn by 11%, 17%, 34%, and 6%, respectively	
Wheat straw	350-550	Cd, Pb	• Increased the pH and total organic carbon of the soil • Decreased the amount of extractable Cd and Pb (mainly in roots). • Decreased whole rice plant Cd content • Immobile Pb and Cd	[154]
Rice straw	500	As, Cu, Zn, and Cd	• Lightly stimulated the As and Cu accumulation • Decreased the availability of Zn and Cd • The combined application of compost and biochar is more effective	[155]

6.2 Effect of organic pollutants contamination

Studies have also shown that different organic pollutants in soils can be held in biochar and even encourage their breakdown [135]. For paddy and non-paddy soils with pH between 5-6.5, wood and sewage sludge biochar (pyrolysis temperature: 500-800 °C) are effective in removing PAHs with an expected sorption rate of >60% [142]. Organic pollutants can be stabilized by biochar through various physical and chemical sorption mechanisms. This comprises the following interactions: electrostatic attraction, pore-filling, hydrophobic effect, surface adsorption and precipitation, hydrogen bonding, partition, and additional interactions such as Vander Waals forces [135].

Beesley *et.al*, 2010 showed that biochar application (at < 1% application rate) would not be a suitable strategy for treating soil contaminated with 2,4-dichlorophenol and phenanthrene. It greatly accelerated the buildup of the metabolites of both organic contaminants in the soil and greatly inhibited their breakdown and mineralization. Over 60 days of field experiment by [157], biochar reduced the concentrations of PAHs, and heavier PAHs with more relevance to toxicology were decreased by greater than 50%.

Different biochar products have varying primary sorption mechanisms and sorption capabilities for stabilizing organic pollutants in soil. The interactions between biochar and organic compounds are primarily influenced by the surface features of biochar, including its specific surface area, pore size, pore volume, polarity, aromaticity, and hydrophobicity [135]. The half-life of MCPA rises with wheat straw biochar amendment at a 1% application rate. It went from 5.2 days in unamended soil to 21.5 days in amended soil. When it comes to absorbing diuron, biochar produced by burning leftover wheat and rice is 400–2500 times more efficient than regular soil [158]. Corn stover biochar reduces the dibenzo-p-dioxin/dibenzofurans and 17 2,3,7,8-substituted dioxins and furans by 52.3%, and 37.5% respectively. IN chip-based biochar these values were recorded as 40% and 27.7% [159].

In another experiment, two triazine herbicides, atrazine and simazine, were absorbed using green waste biochar. It took less time for the biochar with a smaller particle size to reach sorption equilibrium. As the pH of the solution increased, the sorption ability of biochar for atrazine and simazine decreased. As the solid/solution ratio decreased, the sorption ability of biochar rose. Here atrazine and simazine had increases in their sorbed quantities from 451 to 1158 mg/kg and 243 to 1066 mg/kg, respectively. Competitive sorption between the two pesticides—atrazine and simazine—occurred on the biochar when they coexisted, resulting in a drop in sorption capacity for atrazine (from 435 to 286) and simazine (from 514 to 212) [39]. Feng et.al, 2018 used red gum (*Eucalyptus* spp.) and wood chips biochar to test the sorption and desorption behaviors of diuron pesticide in soil. Wood chip biochar is microporous while red gum biochar is non-microporous. When the amount of biochar in the soil grew, sorption-desorption hysteresis significantly increased; this was especially true when using wood chip biochar due to its microporous nature.

As per [161] base-modified biochar is made from bamboo, wood, and rice straw (at temperatures of 300°C, 350°C, 400°C, 500°C, and 700°C). Only biochar pyrolyzed at low temperatures (< 500°C) yielded the supernatant from which base soluble carbon was recovered; the quantity reduced as the pyrolysis temperature increased. The sorption of phenanthrene on biochar from which soluble carbon could be recovered was shown to be enhanced by base modification. On the other hand, biochar from which no soluble carbon could be recovered showed minimal response to base treatment. It was proposed that base modification increased the surface area and hydrophobicity of extractable biochar, hence improving the sorption of phenanthrene by eliminating the soluble carbon.

Xiong et.al, 2017 investigated the effect of two wood biochar (Biochar 1 and biochar 2) on the effects of biochar on the 14C-naphthalene. Here the relationship between 14C-naphthalene mineralization and calcium chloride ($CaCl_2$), hydroxypropyl- β-cyclodextrin (HPCD), or methanol extraction in soil modified with 0%, 0.1%, 0.5%, and 1% biochar 1 and biochar 2 after 1, 18, 36 and 72 d contact times were tested. HPCD extraction measured the bio-accessible percentage of PAHs in soil while $CaCl_2$ extraction predicted the maximum rate of mineralization. Mineralization and extraction were reduced with increased concentration of biochar, but biochar 2 showed high sorption capacity. The results show that biochar can lower the bioaccessibility of PAHs and the associated risk of exposure to biota.

Coke plant soil contaminated with PAHs was modified with rice biochar inoculated with *Mycobacterium* *gilvum* was investigated by [163]. The combination of microbes and biochar has a high capacity to break down pyrene, fluoranthene, and phenanthrene. It was proposed that the higher mass transfer of PAHs from the soil to the carbonaceous biochar "sink" and the subsequent breakdown by *M. gilvum* were the reasons for the improved remediation. A surfactant was used to lessen PAH mass transfer to charcoal and sorption to investigate the mechanism. In biochar-immobilized *M. gilvum* treatments, the surfactant decreased PAH degradation ($P<0.05$), indicating a higher level of PAH degradation between the two treatments.

Zand & Grathwohl, 2016 used the column leaching test to examine the effects of granular activated carbon and two types of biochar—crushed and pulverized—on the immobilization and leaching behavior of certain PAHs from contaminated soil into water. Adding biochar to soil had a significant impact on the leaching and release of naphthalene, fluorene, and pyrene; however, the presence of pulverized biochar did not significantly change the leaching behavior of higher molecular weight PAHs, such as benzo(b) fluoranthene and indeno(1,2,3-c, d)pyrene. Pulverized biochar performed as well in decreasing PAH leaching from polluted soil when compared to crushed biochar.

7 CONCLUSIONS

The study provides an overview of utilizing biochar to enhance soil health, enrich soil, and remediate soil contamination. Biochar's properties, including its large surface area and pore structure, improve soil physical attributes and hydraulic properties. However, its effectiveness depends on factors like feedstock selection, pyrolysis conditions, and soil characteristics. In soil remediation, biochar shows promise in sorbing and stabilizing heavy metals and organic pollutants, reducing their bioavailability and environmental risks. It can also enhance soil microbial activity, biomass, and diversity, benefiting plant performance. However, its impact on soil microbial communities varies based on biochar type, application rate, and soil conditions. While biochar offers benefits like improved nutrient cycling and disease suppression, it may also affect soil nutrient availability and plant growth. Further research is needed to optimize biochar application methods, assess long-term effectiveness, and understand its interactions with soil properties and organic pollutants for enhanced soil remediation strategies.

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