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Biochar as a Fertilizer Replacement for Sustainable Agriculture

Parwiz Niazi[1], Zaland Hekmatullah[2], Mohammad Usman Mohammad[3], Abdul Wahid Monib[4], Mohammad Hassan Hassand[5], Hamidullah Ozturk[6], Azizaqa Azizi[7], Mujibullah Mansoor[8], Mohammad Shafi Akhundzada[9] and Obaidullah Alimyar[10]
[1]Department of Biology, Faculty of Education, Kandahar University, Kandahar, AFGHANISTAN and Department of Plant Protection, Faculty of Agriculture, EGE University, İzmir, TURKEY.
[2, 3, 9]Department of Horticulture, Faculty of Agriculture, Helmand University, Helmand, AFGHANISTAN.
[4]Department of Biology, Faculty of Education, Kandahar University, Kandahar, AFGHANISTAN and School of Environmental Sciences, Jawaharlal Nehru University, New Delhi, INDIA.
[5]Department of Biology, Faculty of Education, Kandahar University, Kandahar, AFGHANISTAN.
[6]Department of Agronomy, Faculty of Agriculture, Faryab University, Faryab, AFGHANISTAN and Department of Soil Science and Plant Nutrition, Faculty of Agricultural, EGE University, İzmir, TURKEY.
[7, 10]Department of Biology, Faculty of Education, Parwan University, Parwan, AFGHANISTAN.
[8]Department of Horticulture, Faculty of Agriculture, EGE University, Izmir, TURKEY.

Corresponding Author: Parwiz Niazi

https://orcid.org/0009-0006-9628-8337

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ABSTRACT

Biochar is a promising solution for pesticide pollution and soil degradation in agriculture. It improves fertilizer efficiency by increasing nutrient availability, and acts as a slow-release fertilizer. Biochar enhances soil fertility by retaining nutrients, and increasing organic matter, water retention, and microbial activity. It also shows potential in pesticide degradation through chemical, and microbial processes. However, the sorption of pesticides on biochar can hinder degradation. Factors like feedstock, pyrolysis temperature, and application rate influence biochar's nutrient retention capabilities. Understanding these factors is crucial for optimizing biochar's effectiveness in agricultural systems.

Keywords- Biochar, organic fertilizer, biodegradation, bioremediation.

I. INTRODUCTION

The application of fertilizer, specifically nitrogen (N), phosphorus (P), and potassium (K), along with pesticide use in agricultural soil, has significantly intensified as a strategy to enhance crop yields. Over the years, there has been a substantial increase in fertilizer usage. Initially, the amount of fertilizer used per hectare was 12.4 kilograms, but it has now risen to 175 kilograms per hectare. This surge indicates an annual growth rate of 5.96 percent [1]. To establish more sustainable agricultural systems and strengthen rural economies, fundamental reforms in agriculture management are necessary. Intensive application of fertilizers and pesticides can result in leaching losses, which deteriorate soil fertility and lead to pollution. Moreover, nutrient leaching from agricultural soils can decrease soil fertility, increase farming costs, accelerate soil acidification, and reduce crop yields [2]. Pesticides have the potential to travel long distances, cross borders, and bio-accumulate in the food chain, posing a significant threat to human health and the environment

[3]. On one hand, meeting the high food demand in certain countries requires urgent improvement of soil fertility and nutrient availability to increase crop yields. On the other hand, pesticide degradation is a crucial objective for both soil management and environmental protection. Bioremediation is a less hazardous, more cost-effective, and socially acceptable alternative to traditional remediation [4]. However, some pesticides, such as organochlorine compounds, pesticides, such as organochlorine compounds, pose a challenge in terms of their biodegradation within a short period of time. Additionally, microorganisms are sensitive to environmental changes like heat, desiccation, and ultraviolet radiation [5]. The competition between different microbial species and other organisms in the soil also presents a challenge, as it can significantly reduce the efficiency of pesticide biodegradation under such conditions. Overall, effective and low-cost solutions are required to improve soil conditions, enhance microbial activity, and facilitate pesticide breakdown in order to increase crop yields, rehabilitate pesticide-polluted soil, and achieve sustainable agriculture [70]. Manures and composts can contain pathogens, heavy metals, and medications, leading to long-term contamination in agriculture. Furthermore, they can generate ammonia and methane, exacerbating global warming and causing significant nutrient contamination in groundwater and streams. Biochar offers a viable option for managing soil fertility as it is a renewable resource with economic and environmental benefits. Additionally, biochar containing ammonium, nitrate, and phosphate can serve as a slow-release fertilizer, thereby enhancing soil fertility [6, 7].

Biochar is a carbon-rich solid produced by heating biomass in the absence of oxygen. It possesses a porous carbonaceous structure, functional groups, and an aromatic surface. The basic methods for producing biochar include slow pyrolysis, hydrothermal carbonization, flash carbonization, and gasification [8]. Biochar derived from biomass pyrolysis can alter the physicochemical properties of the soil [9], reduce gaseous nitrogen emissions [10], influence soil nutrient availability [11], minimize nutrient leaching [12], and enhance crop production [13]. Furthermore, biochar derived from pig manure has the capacity to degrade up to 90.6 percent of carbaryl [14]. It also improves soil microbial properties, such as microbial abundance, activity, and mycorrhizal associations [15]. These studies indicate that biochar has significant potential in preserving soil fertility, facilitating abiotic breakdown of pesticides, and accelerating pesticide biodegradation. This paper examines the potential benefits of biochar in improving fertilizer use efficiency by increasing nutrient availability and soil fertility through enhanced nutrient retention (i.e., reduced nutrient leaching and gaseous nutrient emissions) and release. Furthermore, the mechanisms behind biochar's impact on soil fertility improvement are explored. The paper also discusses the physical and chemical properties of biochar, presents the factors and mechanisms influencing various biochar functions, and identifies future prospects and knowledge gaps (See table 1).

II. PROPERTIES OF BIOCHAR& SURFACE AREA

The adsorption properties of biochar are influenced by its physical and chemical properties. For instance, increasing the presence of acidic functional groups in biochar can enhance NH4+ adsorption [16]. Biochar exhibits a large specific surface area, abundant oxygen-containing functional groups, and remarkable stability [17]. The physicochemical characteristics of biochar are mainly determined by the feedstock and pyrolysis temperature [18]. Various feedstocks, including wood chips, organic wastes, plant residues, and poultry manure, can be used to produce biochar [19]. Typical pyrolysis temperatures range from 200 to 800°C [20].

The specific surface area of biochar plays a crucial role in the adsorption of substances such as heavy metals and organic compounds [21]. Increasing the pyrolysis temperature can enhance the specific surface area of biochar and promote the formation of micro-pores. For example, the surface area of sugarcane bagasse biochar increased from 0.56 to 14.1 m2 g-1 when the pyrolysis temperature was raised from 250 to 600°C [22]. Similarly, the surface area of soybean Stover biochar produced at 700°C was 420 m2 g-1, significantly higher than that of biochar produced at 300°C (6 m2 g-1) [23]. One possible explanation is that higher pyrolysis temperatures lead to increased release of volatiles within the biochar. Additionally, the feedstock used can also affect the surface area of biochar. Biochar derived from bagasse and cocopeat exhibited surface areas of 202 and 13.7 m2 g-1, respectively. Furthermore, compared to the biomass, the volatiles in biochar produced from bagasse and cocopeat decreased by 87.1% and 70.1%, respectively [24]. The release of volatile matter, particularly celluloses, and hemicelluloses, during pyrolysis can enhance the formation of a vascular bundle structure in biochar, thereby improving its specific surface area and pore structure [25]. Overall, the influence of feedstocks and pyrolysis temperatures on the surface area of biochar can primarily be attributed to the release of volatile matter.

III. CATION EXCHANGE CAPACITY (CEC), PH VALUES, AND BIOCHAR STABILITY

The cation exchange capacity (CEC) of biochar measures its ability to adsorb cations, which are essential nutrients for plants, such as NH4+ and Ca2+

[26]. A high CEC in biochar can reduce nutrient loss through soil leaching. For cordgrass biochar, as the pyrolysis temperature increased from 200 to 550°C, the CEC increased from 8.1 to 44.5 cmolc kg-1, and then decreased to 32.4 cmolc kg-1 [27]. Similarly, for sugarcane bagasse biochar, the CEC increased from 6.40 cmolc kg-1 (pyrolyzed at 250°C) to 9.66 cmolc kg-1 (pyrolyzed at 500°C), before decreasing to 4.19 cmolc kg-1 (pyrolyzed at 600°C) [22]. Based on these comparisons, biochar produced at high pyrolysis temperatures (>500°C) tends to have a lower CEC. The decrease in CEC at high pyrolysis temperatures has been attributed to the aromatization of biochar and the disappearance of functional groups.

The use of biochar can increase soil pH due to its own pH and its ability to improve cation retention in the soil (e.g., Ca2+, Mg2+, and K+). Biochar produced at higher temperatures generally has a higher pH due to the release of alkali salts from the organic matrix of the feedstock [23]. For example, when the pyrolysis temperature was increased from 300 to 600°C, the pH value of corn straw biochar increased from 9.37 to 11.32 [28]. The pH of swine manure biochar produced at 400 and 800 degrees Celsius was 7.60 and 11.54, respectively [29]. Therefore, biochar with a high CEC and pH has the potential to retain NH4- and K-fertilizers and enhance their utilization efficiency. While biochar is increasingly recognized as a valuable tool for long-term soil amendment, including carbon sequestration, nutrient retention, and remediation of pesticide-contaminated soil, its long-term environmental stability is still not fully understood. As mentioned earlier, biochar stability is mainly influenced by the pyrolysis temperature and feedstock. Some studies suggest that certain types of biochar can degrade relatively quickly in certain soils, potentially depending on the production conditions, indicating the possibility of optimizing pyrolysis to produce more stable biochar [30]. In general, higher pyrolysis temperatures can enhance biochar stability. For instance, increasing the pyrolysis temperature from 350 to 550°C significantly improved the stability of sugarcane bagasse biochar [31]. The amount of recalcitrant carbon substrates also affects biochar stability.

IV. BIOCHAR AS A NUTRIENT SOURCE (ROLE OF BIOCHAR AS A FERTILIZER)

Organic matter and inorganic salts, including Humic and fulvic-like substances, as well as available N, P, and K, can serve as fertilizers and be assimilated by plants and microorganisms. For instance, Lantana camara biochar at 300°C contained available P (0.64 mg kg-1), available K (711 mg kg-1), available Na (1145 mg kg-1), available Ca (5880 mg kg-1), and available Mg (1010 mg kg-1) [32]. Similarly, fresh biochar has the potential to increase nutrient availability by releasing significant amounts of N (23–635 mg kg-1) and P (46–1664 mg kg-1) [33]. These findings indicate that biochar can serve as a valuable source of available nutrients. While total N, P, and K in biochar may not always directly reflect the actual nutrient availability to plants, available forms of N, P, and K (such as ammonia (NH4+), nitrate (NO3-), phosphate (PO43-), and K+) may be related to total N, P, and K content. Recent studies have used short-term column leaching experiments or kinetic models to assess nutrient availability in biochar. In practice, total N, P, and K in biochar can be used as an indirect indicator for selecting appropriate biochar [69].

V. FACTORS INFLUENCING BIOCHAR NUTRIENT CONTENT& AVAILABILITY

The choice of feedstock source and pyrolytic temperature significantly influence the nutrient content of biochar. For instance, in three woody and four herbaceous biochars, nitrogen (N) losses started at around 400 °C, with half of the N being lost as volatiles around 750 °C [34]. However, biochars produced at lower temperatures had significantly higher available phosphorus (P) compared to those produced at higher temperatures. This could be attributed to lower temperature biochars containing fewer crystallized P-associated minerals. Additionally, the total potassium (K) content increased from 3.7% at 300 °C to 5.02% at 600 °C, while the available K (water-soluble) content increased with increasing pyrolysis temperature [35]. Furthermore, the nutrient composition of biochars varies depending on the feedstock used. For example, swine manure biochar produced at 400 °C had high levels of N (3.2%) and P (6.1%) [36], while Arundo donax biochar produced at 400 °C had low levels of N (0.69%) and P (0.13%). Additionally, the ash content of poultry litter biochar produced at 350 °C was significantly higher than that of pine wood chip biochar [16]. The pH of the soil also plays a significant role in biochar nutrient availability. The release of phosphate (PO43-) and ammonium (NH4+) from biochar was pH-dependent, whereas the release of potassium (K+) and nitrate (NO3-) was not. Similarly, the initial release of calcium (Ca) and magnesium (Mg) from corn straw biochar was pH-dependent, increasing as pH decreased from 8.9 to 4.5 [37].

It is crucial to consider the impact of application time on biochar nutrient release. Additionally, the high carbon (C) mineralization and nitrogen (N) immobilization of volatile matter in biochar by microorganisms may reduce nutrient release. In practice, these influencing factors may coexist when applying biochar to soil. Lowering the pyrolysis temperature and pH may increase the availability of N and P, while higher pyrolysis temperature may enhance K availability [79].

VI. POTENTIAL OF BIOCHAR FOR INCREASING SOIL FERTILITY

Improving crop yield by enhancing fertilizer use efficiency is a promising approach. A study investigated the effects of green waste biochar on radish plants and found that biochar application alone did not increase radish yield in the absence of nitrogen (N) fertilizer. However, when N fertilizer was present, the application of biochar led to a significant increase in radish yield, indicating that biochar effectively improved plant nitrogen utilization. For instance, with a biochar application rate of 100 t ha-1, the yield increase in the presence of N fertilizer was 266% compared to the control without N fertilizer. Moreover, when N fertilizer (100 kg N ha-1) was applied, the yield increase with biochar application ranged from 42% at 10 t ha-1 to 96% at 50 t ha-1, compared to the control [38]. Additionally, biochar has demonstrated the ability to enhance maize grain yield by 28% and increase the availability of calcium (Ca), magnesium (Mg), potassium (K), and phosphorus (P) by 17%-600% in biochar-amended fields [13]. Therefore, biochar is considered to have great potential for improving plant fertilizer use efficiency by increasing nutrient availability in the soil [71].

VII. NUTRIENT RETENTION IN BIOCHAR-TREATED SOIL

Biochar's heterogeneous composition means that its surface can have hydrophilic, hydrophobic, acidic, and basic properties, all of which affect the biochar's ability to adsorb soil solution components and hence fertilizer retention. Biochar, on the one hand, can improve nutrient retention through the adsorption process. For example, the total amount of NO3, NH4+, and PO43 in the leachates was reduced by 34.0%, 34.7%, 20.6%, and 34.3%, 14.4%, 39.1% respectively, using peanut hull and pepperwood biochar's generated at 600 degrees Celsius [39]. Furthermore, one study found that spartina spartina biochar prepared at 350°C may absorb 0.5 mmol g1 of K+. As a result, biochar can be used to address nutrient deficiencies in soil [40]. N2O emissions were reduced by 80% with the use of biochar, according to one study [41]. Indeed, improved soil physicochemical features, such as increased porosity and water storage capacity, and decreased bulk density, may contribute to improved nutrient retention after biochar amendment. Overall, biochar offers a lot of promise for increasing fertilizer efficiency by reducing nutrient leaching and gaseous nitrogen losses.

VIII. BIOCHAR, MICROORGANISMS & FERTILITY

Biochar has been observed to bring about alterations in soil biological characteristics and enhance soil physicochemical properties. These modifications can contribute to the improvement of soil structure by increasing the formation of organic/mineral complexes (aggregates) and pore spaces. Additionally, biochar can enhance nutrient cycles by promoting nutrient retention and immobilization, as well as reducing nutrient leaching, ultimately fostering plant growth [42]. Moreover, certain microbes, such as rhizosphere bacteria and fungi, may directly facilitate plant growth [43]. Consequently, changes induced by biochar in the composition and activity of microbial communities can have implications for nutrient cycles, plant growth, and the cycling of soil organic matter. This section provides an overview of the impact of biochar properties on the microbial community, encompassing aspects such as organic and inorganic composition and surface properties.

IX. INFLUENCE OF BIOCHAR ON MICROORGANISM'S COMMUNITY& BIOCHAR'S EFFECT ON MICROBIAL ABUNDANCE

There is a growing interest in using biochar to regulate soil biota, although the modest changes in soil biota resulting from biochar application are also a cause for concern. Several mechanisms can explain how biochar affects soil microorganisms: (1) changes in food availability; (2) changes in other microbial populations; (3) changes in plant-microbe signaling; and (4) habitat creation and protection against hyphal grazers. The soil food web plays a crucial role in shaping microbial characteristics, and the quantity, quality, and distribution of organic matter significantly influence the trophic structure of the soil food web. Despite soil organic matter production being modest compared to other carbon cycle processes, its relative stability for microbial breakdown enables the accumulation of soil organic matter. In one study, the addition of 30 t/ha biochar resulted in an increase in microbial abundance from 366.1 gC/g (control) to 730.5 gC/g. Similarly, with different preincubation times (2–61 days), microbial abundance increased by 5–56% as maize Stover biochar rates increased (from 0 to 14%) [44]. The increased microbial abundance could be attributed to various factors, such as increased availability of nutrients or labile organic materials on the biochar surface, improved habitat suitability and refuge, and enhanced water retention and aeration [45]. Microbial abundance can also be influenced by nutrient and carbon availability, with the specific impact varying depending on the forms of biochar and the bacterial groups involved. Different plant requirements may result in symbiotic partnerships with specific biota formed through varying nutrient supplies. Similar arguments can be made for the effect of increased carbon supply in the rhizosphere through exudation or root turnover, serving as an energy source for heterotrophic microbes [46]. Consequently, the effect on microbial abundance varied depending on whether biochar additions were made in the rhizosphere or bulk soil. In nutrient-limited environments, microbial abundance may increase due to enhanced nutrient availability after biochar application [47].

Recent studies suggest that the impact of nutrient and carbon availability on microbial biomass can be influenced by factors such as existing nutrient and carbon availability in the soil, the amount of nutrients and carbon added, and microbial characteristics. Microbial abundance may increase as microorganisms attach to biochar surfaces, rendering them less susceptible to leaching in the soil. Major processes of adsorption to biochar include hydrophobic attraction, electrostatic forces, and the formation of precipitates [48]. Additionally, biochar with a well-developed pore structure can provide habitats for microorganisms, offering protection against predators or competitors [49, 50].

Biochar can also adsorb toxins and chemical signals that inhibit microbial growth. Furthermore, high-temperature biochar has shown greater adsorption capacity for chemicals harmful to microbes [51]. Moisture levels can significantly impact microbial abundance, as microorganisms can be stressed in soils experiencing periodic drying, leading to dormancy or even death. Due to its large surface area, biochar has high water-holding capacity, which can promote microbial growth. However, further inferences cannot be drawn solely based on the original components and properties of biochar. Some theories suggest that bacterial cells or growth-regulating chemicals may play a role in sorption.

X. ENHANCING THE REMEDIATION OF PESTICIDE-CONTAMINATED SOIL WITH BIOCHAR (POTENTIAL OF BIOCHAR ENHANCING THE DEGRADATION OF PESTICIDE IN SOIL)

Biochar has been found to facilitate the breakdown of pesticides by soil microorganisms. On one hand, the addition of biochar can influence pesticide biodegradation by enhancing natural microbial activity in the soil and reducing pesticide bioavailability. Numerous studies have demonstrated that biochar improves the living conditions for microorganisms by modifying soil pH, increasing soil organic matter, enhancing soil water content, providing habitat, and reducing competition from other microbes, all of which promote microbial characteristics such as microbial community composition, abundance, and activities [52].

However, the addition of biochar can also enhance pesticide sorption in the soil, leading to lower pesticide concentrations in the soil solution and reduced pesticide bioavailability to microorganisms [53]. Chemical degradation and biodegradation are the two primary mechanisms responsible for pesticide elimination in soil when biochar is present. Since modern pesticides are designed to readily dissolve, chemical hydrolysis is a significant pathway for their abiotic degradation in the soil. Some research has suggested that the presence of biochar in soil can catalyze pesticide hydrolysis, which may be attributed to the combined effects of higher pH, dissolved metal ions released from biochar, and active groups on mineral surfaces [54]. Overall, the addition of biochar can be a viable and effective approach to enhance pesticide bioremediation in damaged soils. It can promote microbial activity and create favorable conditions for pesticide degradation, while also reducing pesticide bioavailability through sorption processes.

XI. CHEMICAL DEGRADATION OF PESTICIDE IN BIOCHAR-AMENDED SOILS

Indeed, biochar has been found to exhibit catalytic properties that can accelerate pesticide hydrolysis in soil. The extent of this catalytic effect, however, depends on various factors including the biochar's feedstock, pyrolysis temperature, and application rate. For example, studies have shown that biochars produced from pig manure and maize straw at 350 °C can hydrolyze carbaryl at rates of 55.0% and 52.8%, respectively [55]. Moreover, pig manure biochar produced at 350 and 700 °C can hydrolyze carbaryl at rates of 59.1% and 90.6%, and atrazine at rates of 21.2% and 63.4%, respectively [56]. However, in the case of rice straw biochar, the hydrolysis rate of carbaryl decreased from 53.7% to 50.0% when the pyrolysis temperature was increased from 350 to 700 °C [55].

The catalytic effects of biochar on pesticide hydrolysis can be attributed to several factors, including changes in pH, presence of dissolved metal ions, active functional groups, and pesticide sorption [72]. The pH of the system plays a significant role in the chemical hydrolysis of pesticides. For instance, the base-catalyzed hydrolysis of carbaryl can be facilitated by an increase in pH, whereas atrazine, as a persistent herbicide, can undergo hydrolysis in strongly acidic or alkaline conditions [57]. Additionally, nucleophiles accumulated on the surface of biochar can contribute to pesticide degradation. Hydroxy groups on the biochar surface can act as nucleophiles, and metal atoms attached to the biochar surface can form complexes with pesticides, facilitating hydrolysis through nucleophilic attack by water molecules [58]. Moreover, pesticide sorption in biochar-amended soil can increase, reducing the concentration of free pesticides in the soil solution and potentially slowing down the hydrolysis process and decreasing the breakdown rate. It is important to consider all these factors when assessing pesticide hydrolysis rates. Overall, while biochar can have catalytic effects that enhance pesticide hydrolysis, increased pesticide sorption may counteract these effects [59].

XII. BIODEGRADATION OF PESTICIDES IN SOIL TREATED WITH BIOCHAR

Biochar can influence pesticide biodegradation through its effects on microorganism activity and pesticide bioavailability, as well as its catalytic role in pesticide hydrolysis. In terms of biodegradation, the application of pig dung biochar produced at 350 °C at a 0.5% rate resulted in an increase in carbaryl breakdown efficiency from 55.0% to 75.0% after 40 days of incubation in unsterile soil, indicating enhanced pesticide biodegradation compared to sterile soil [55]. The impact of biochar on pesticide biodegradation varies depending on factors such as feedstock, pyrolysis temperature, and application rate. For instance, using a 0.5% application rate, carbaryl biodegradation enhancement ranged from 19.5% to 27.3% for biochars derived from rice straw, pig manure, and maize straw pyrolyzed at 350 °C, and from 3.1% to 27.3% for maize straw biochars produced at 350 and 700 °C, respectively [55].

The influence of biochar on microbial characteristics and pesticide bioavailability is largely determined by its properties. Biochar with high levels of amorphous carbon, and liquid organic matter can enhance microbial activity, as these compounds serve as easily digestible food sources for microorganisms. The activity of native microorganisms can be significantly affected, usually decreased, by changes in soil pH resulting from biochar treatment [60]. Furthermore, increased pesticide sorption after the addition of biochar can reduce pesticide concentration in the soil solution, lowering pesticide bioavailability and biodegradation. One study found that biochar inhibited microbial atrazine mineralization by interfering with sorption and desorption processes, thereby reducing atrazine bioavailability. Therefore, pesticide sorption in biochar-amended soil can have an impact on biodegradation [61].

Pesticide sorption in soil treated with biochar can minimize pesticide mobility, volatilization, leaching, and plant uptake. However, as mentioned earlier, the addition of biochar to the soil can enhance pesticide sorption, leading to lower pesticide concentrations in the soil solution and reduced pesticide bioavailability to microorganisms, which in turn can hinder chemical and biodegradation of the pesticide. While both biochar and soil can adsorb pesticides, biochar has been found to be more effective in pesticide adsorption than soil [62]. The pesticide sorption capacity of biochar is influenced by its properties, such as organic carbon concentration, aromatic nature, specific surface area, and ash content [63]. For instance, hydrophobic effects, pore-filling, and π-π electron donor-acceptor interactions were found to influence the adsorption of carbaryl and atrazine [56]. Additionally, since some pesticides are weak bases and exist as neutral molecules, they can form weak hydrogen bonds with carboxyl groups or the clay surface through their heterocyclic nitrogen atoms.

XIII. BIOCHAR’S NEGATIVE IMPACT ON SOIL BIODIVERSITY

The effects of biochar on the soil microbial community can vary depending on the type of biochar and soil. It is important to note that biochar can contain organic pyrolytic products, such as phenolics and polyphenolics that may be harmful to soil microorganisms. In some cases, applying biochar has been associated with a decrease in mycorrhizae and total microbial biomass [64]. Increased retention of toxic substances like heavy metals and pesticides, as well as the release of pollutants from biochar such as bio-oil and polycyclic aromatic hydrocarbons, can lead to a decrease in microbial abundance and activity. Therefore, it cannot be concluded that a specific biochar that benefits one soil biota will also be beneficial to others [65, 66]. Factors like volatile matter, biochar properties, and the presence of salts such as chloride or sodium are likely responsible for the negative effects of biochar on soil biota. For instance, one study observed withered petioles and discolored leaves in clover plants after the application of biochar that had not undergone washing procedures to remove organic and inorganic matter [67]. Moreover, certain biochar’s may directly pose a threat to soil biota, and these effects could contribute to the reported lower crop yields found in the literature. It is important to consider these potential short-term effects and evaluate the suitability of biochar as a soil amendment accordingly.

XIV. FUTURE PERSPECTIVE

You are correct that the soil properties of biochar-amended field soils with long aging times can differ significantly from short-term laboratory experiments. While short-term studies have shown that fresh biochar can release nutrients and promote short-term crop growth, the long-term effects of biochar on soil nutrient availability are hypothesized to be related to increased surface oxidation and cation exchange capacity (CEC) over time. This can lead to greater nutrient retention in aged biochar compared to fresh biochar [68]. However, long-term studies investigating nutrient dynamics in biochar-amended soil are still lacking, and further research is needed to better understand and predict nutrient dynamics in both laboratory and field settings. Developing and improving kinetics models can aid in this understanding. Regarding pesticide sorption, biochar has been found to have a high pesticide sorption capacity and can accumulate pesticide residues in soil. However, the release of pesticides from biochar, which could potentially act as a new source of pollution, has not been extensively studied in short-term experiments. It is important to assess the long-term environmental fate of sequestered pesticides when using biochar for pesticide-polluted soil remediation. Currently, most studies on this topic are based on laboratory, greenhouse, or small-plot short-term experiments [78]. However, field conditions are complex, and biochar properties can change over time due to aging, oxidation, or microbial degradation, affecting both pesticide adsorption and hydrolysis capacity. Therefore, future studies should include large-scale and long-term field trials to better understand the real-world implications of biochar use in pesticide-contaminated soils.

XV. CONCLUSION

In order to increase sustainable agricultural productivity, and conserve natural resources, integrated nutrient and pest management is required. Fertilizers and pesticides are important plant nutritional and protective agents for increasing crop production in agriculture development. However, fertilizer use efficiency in crop systems is typically very low. Furthermore, indiscriminate pesticide use can lead to severe environmental contamination. Biochar amendment in agricultural soil may be a suitable method for improving plant nutrient uptake and pesticide degradation. Biochar can be used to improve fertilizer utilization efficiency, and soil fertility due to its large surface area, high number of functional groups, and good stability. Biochar can not only improve nutrient adsorption (e.g., NO_3^-, NH_4^+, and PO_4^{3-}) thereby reducing nutrient leaching, but it can also reduce gaseous N losses. Furthermore, the nutrients that have been adsorbed by biochar can be released into the soil later (slow-release fertilizer). Furthermore, biochar has the potential to accelerate pesticide degradation in soil, and reduce pesticide uptake by plants. On the one hand, the addition of biochar to soil may improve pesticide removal rates by catalyzing the chemical hydrolysis process. Microbial activities, on the other hand, may be increased after the application of biochar to polluted soil. Notably, pesticide sorption on biochar can reduce the free pesticide concentration in soil solution, thereby impeding the hydrolytic process (chemical degradation), and lowering pesticide bioavailability (biodegradation). As a result, pesticide sorption in biochar-amended soil may be detrimental to degradation. The function of biochar in practical applications is determined by the feedstock, pyrolysis temperature, and application rate. Overall, biochar amendment can improve overall soil health, and crop yield by increasing fertilizer use efficiency, soil fertility, and pesticide degradation, resulting in a benefit for sustainable agriculture.

Further research should concentrate on the following identified knowledge gaps:

1- Long-term effects of biochar on soil properties and large-scale field trials should be considered.
2- Biochar characteristics vary with different biomass materials, and pyrolysis conditions, necessitating the production of biochar specifically designed for soil management based on soil properties and environmental conditions.
3- In order to maximize the efficiency of pesticide remediation, the dynamic mechanisms of pesticides between microorganisms, and biochar should be understood.
4- More research is needed to thoroughly investigate the influencing factors for pesticide degradation by microorganisms and biochar and.
5- The synthesis and application of functionalized biochar as a potential material for soil amendment and remediation should be evaluated.

Table 1: Illustrating the use of biochar as a fertilizer alternative in sustainable agriculture:

Aspect	Description	
	Biochar is a type of charcoal produced from organic biomass through pyrolysis.	
Benefits	1. Enhances soil fertility and structure.	[72].
	2. Improves water retention capacity.	
	3. Increases nutrient availability and uptake.	
	4. Promotes beneficial microbial activity.	
	5. Reduces greenhouse gas emissions.	
	6. Mitigates soil erosion.	
	7. Acts as a long-term carbon sink.	
Production Methods	1. Pyrolysis: Heating biomass in the absence of oxygen.	[73].
	2. Gasification: Partial combustion of biomass in limited oxygen	

	conditions. 3. Torre-faction: Heating biomass at a lower temperature than pyrolysis.	
Application Techniques	1. Mixing biochar with soil during planting or as a top dressing. 2. Incorporating biochar into compost or vermicomposting. 3. Applying biochar-based fertilizers or soil amendments. 4. Soil amendment in combination with organic matter. 5. Biochar as a carrier for slow-release nutrients.	[74].
Factors to Consider	1. Biochar type, and quality (pH, porosity, nutrient content). 2. Application rate and method. 3. Soil type, and characteristics. 4. Crop type and specific nutrient requirements. 5. Environmental considerations (e.g., water quality, carbon sequestration).	[75].
Challenges, and Considerations	1. Biochar production can require significant energy inputs. 2. Quality control, and standardization of biochar products. 3. Site-specific considerations for optimal application. 4. Long-term effects, and sustainability. 5. Economic viability, and scalability.	[76, 77].

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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