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Review

Advances in the Effects of Biochar on Microbial Ecological Function in Soil and Crop Quality

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Abstract: Biochar, a late-model environmental functional material, has been widely applied in environmental remediation, agricultural production, and energy utilization due to its excellent characteristics such as porosity and high specific surface area. In recent years, many studies on the effects of biochar on agricultural soil and crop quality have been performed. The application of biochar can influence soil microbial status directly or indirectly by changing the physicochemical properties of soil. Apart from increasing soil pH, biochar can also increase soil organic matter and nutrient elements, which ultimately affect crop yield and quality. This review summarizes and overviews the recent research advances on the influence of biochar application on soil microbial community diversity, microbial ecological functions, soil enzymes and their functional genes, and on crop quality and yield from the perspective of soil microorganisms. This review provides guidance and references for further research into biochar applications.

Keywords: biochar; soil microbes; microbial community diversity; microbial ecological functions; soil enzymes; functional genes

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1. Introduction

Biochar is a kind of carbon sequestration substance pyrolyzed by organic biomass materials such as crop residues, garden waste, domestic waste, and animal feces under complete or partial anoxic circumstance [1]. Biochar has been widely used in soil improvement, wastewater treatment, energy regeneration, carbon sequestration, and emission reduction due to its characteristics of high carbon content, strong adsorption, and porous structure (Figure 1).

The application of biochar is mainly in soil improvement in agriculture. The influence of biochar on soil physical properties is shown in Figure 2. Biochar forms a loose and porous structure due to the volatilization of a large number of compounds during the preparation process, and its specific surface area is also enormously enlarged. Applying biochar can promote soil porosity and water holding capacity, reduce soil bulk density, and loosen the soil, which is more conductive to vegetation growth. Biochar is generally alkaline, which is correlated with its pyrolytic temperature and raw material [2]. Livestock-manure-based biochar has a higher pH, with herbs in the middle, and woody species at a lower level. Biochar pyrolyzed at a high temperature has a higher pH and is more effective in improving acidic soils [3]. Biochar regulates pH by adsorbing H^+ and exchangeable Al^{3+} in the soil [4]. The raw materials contain plentiful nutrients that are concentrated in the resulting biochar except for a small portion lost during the pyrolytic process. Therefore, the biochar itself contains a large amount of nutrients, such as N, P, K, Ca and Mg. As a result of its porous structure, ample specific area, and surface functional groups, biochar has relatively strengthened adsorption. It can absorb and enrich elemental ions and organic molecules of the soil, and then polymerize into organic matter with surface catalysis to add the content of organic compounds and nutrients [5]. The abundant aromatic structures, oxygen-containing functional groups, and alkaline functional groups of the biochar augment the pH-dependent charge of the soil, and reduce the leaching of alkaline cations contended against H^+ by enhancing the combination of negatively charged functional sites of the organisms and complexes of biochar, and organisms for heightening soil cation exchange capacity and reducing nutrient loss [6].

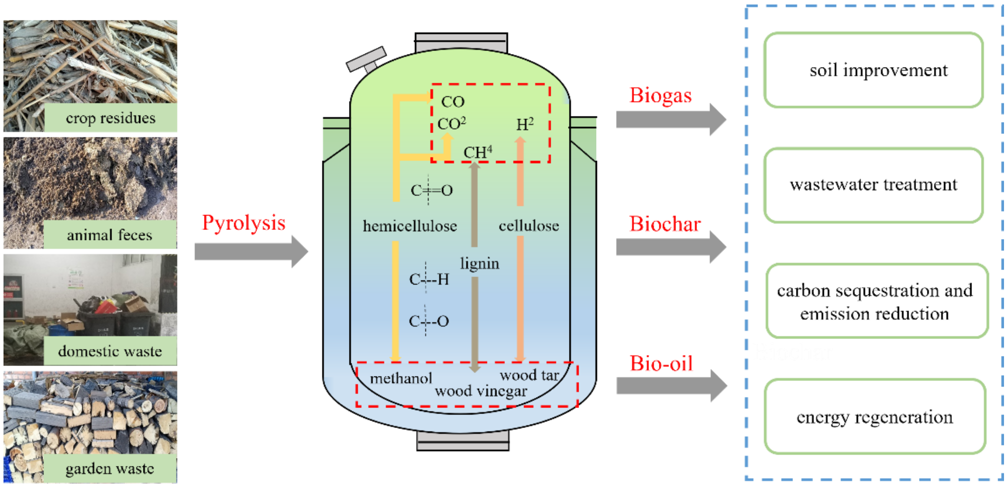

Figure 1. The preparation process of biochar.

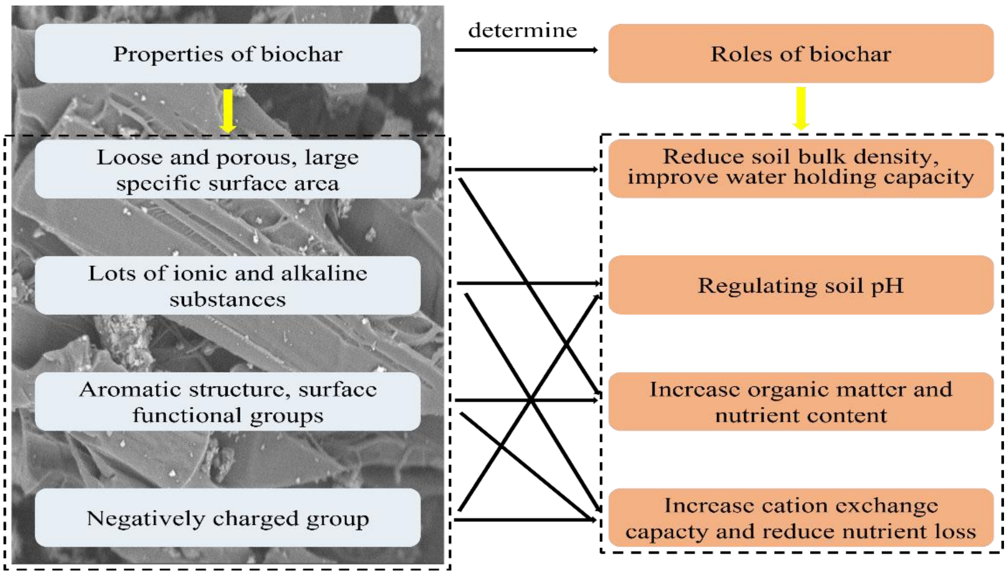

Figure 2. Effects of biochar on soil physical properties.

In addition, a key aspect in soil quality improvement is the decomposition and transformation of microorganisms. Soil microbial communities are one of the most sensitive soil properties to changes in a soil environment and a critical index of soil properties. They can significantly affect soil formation, soil physicochemical properties, and plant growth. The soil provides a place for soil microbes, which promote nutrients cycling in soil and crop development. Therefore, soil microorganisms are the significant driving force of biochemistry proceeding in soil, and are essential for maintaining the stability and ecological function of terrestrial ecosystems. In this paper, the impact of biochar application on community diversity, ecological functions of soil microbes, soil enzymes and their functional genes, and crop quality and yield are reviewed, providing some references for future related research.

2. Effects of Biochar on Soil Microbial Community Diversity

2.1. Effects on the Quantitative Characteristics of Soil Microbial Community

Soil microbial community biomass can reflect soil fertility and ecosystem productivity. Soil microbial diversity and abundance or biomass play a key role in ecosystem sustainability by keeping the basic functions of soil health through soil carbon and nutrient cycling. Biochar is rich in carbon and micronutrient elements for microbial growth. Its large specific surface and loose pore structure can provide a good and favorable growth environment for microorganisms, and also prevent some microorganisms in the pores from being preyed upon, which can effectively enhance soil microbial activity, and improve microbial biomass and diversity. Singh et al. [7] applied rice-husk biochar in field conditions to research its influence on soil microbes and rice yield, and found that the microbial biomass carbon, nitrogen, and phosphorus were higher compared to those of the control in different tests. As compared to control group, the mixture of the biochar and nitrogen fertilizer enhanced the total biomass of soybean rhizosphere microorganisms [8]. Hua et al. [9] also stated that modified biochar obviously raised the microbial biomass carbon and nitrogen. Ge et al. [10] conducted four treatments of biochar addition in moso bamboo plantation soils and found a significant increase in microbial biomass at 10–20 cm depth, while there was no obvious change at 0–10 cm. This may have been because pluralistic circumstances (such as soil water content and soil aggregates) partially offset the constructive results of biochar on microbial propagation in the topsoil, the fixation of recalcitrant substrates, and the downward migration of degradable portions of biochar with precipitation; the microorganisms also moved downward in the surface soil.

In addition to providing a good living space for microorganisms, microorganisms can also attach themselves to biochar to avoid overheating, drying, or leaching. Bacteria adhere to the surface of the biochar, hindering being leached, which increases the abundance of bacteria but does not significantly change the abundance of fungi, probably due to the existence of a hypha network [11]. Hale et al. [12] found that using pinewood biochar pyrolysized at 300 °C as the carrier of plant growth promoting rhizobacteria-*Enterobacter cloacae* UW5 could improve the survival of bacteria in the soil. Yang et al. [13] found that *Bacillus thuringiensis* was the most adsorbed by corncob biochar. The adsorption of biochar on microorganisms has a certain selectivity that may be relevant to the properties of microorganisms such as cell size and surface charge. Adsorption can be carried out by different mechanisms of hydrophobic adsorption or electrostatic adsorption [14].

The alkaline nature of biochar is an important factor in regulating soil pH, and the sensitivity of microbes to pH change varies with different types. Rousk et al. [15] reported that bacteria were more susceptible to pH than fungi were after minimizing the effect of factors other than pH. The relative bacterial abundance and diversity were greatly correlated with pH. The pH has significant direct effect on the bacterial community structure, possibly owing to the cramped pH range in which bacteria grow optimally. In contrast, the pH had less effect on fungal community structure, which is coincident with the pure cultivation consequence, indicating that the optimal pH range for fungal growth is usually larger. Most studies have confirmed that the utilization of biochar increases microbial abundance to a certain extent, but changes are still affected by various factors, thus showing different degrees of promoting and inhibiting effects. Li et al. [16] applied a water extract, organic extract, and residual solid after two extractions of corn straw biochar into purple soil with a biochar for a culture. After 30 days, the abundance and diversity of fungi increased, while there was no significant change in bacterial abundance. Anders et al. found that there was no positive impact on the microbial biomass under biochar application through greenhouse and field experiments [17].

2.2. Effects of Biochar on Soil Microbial Community Structure Characteristics

The utilization of biochar changes the physicochemical characteristics of the soil and the living environment of microbes, which leads to a development in the abundance of some dominant species or inhibiting the growth of certain pathogens. The improvement of soil specificity such as pH, water holding capacity, and soil nutrients is conducive to the propagation of microbes.

In an 8-year field trial, Qiao et al. [18] found that biochar addition caused significant changes in the bacterial community, with an increase in 10 genera and a decrease in 5 genera. Li et al. [19] found that biochar addition increased the relative abundance of phylum Proteobacteria at different nitrogen deposition levels, whereas it had different effects on Acidobacteria groups. According to the relevant reports, biochar also had a significant increase in the abundances of rhizosphere microorganism, with a 100-fold increase in *Brevundimonas* associated with the phosphorus cycling, and *Arthrobacter* and *Cupriavidus* related to sulfonate desulfurization [20]. Xu et al. [21] found that the increase in bacterial diversity was directly proportional to the addition proportion of biochar. The relative abundance of Gemmatimonadetes, Acidobacteria, and Chloroflexi decreased, whereas the relative abundance of Actinobacteria, Proteobacteria, and Bacteroidetes increased. Liang et al. [22] reported that biochar could improve the relative abundance of functional microbes such as *Nitrosomonas* and *Thauera*, which boosted nitrogen cycling, and reduced nitrous oxide release.The biochar did not transform the relative abundance of most bacteria in phaeozems at the phylum level, while the relative abundance of other bacterial groups (e.g., Actinobacteria and Anaerolineae) degraded aromatic compounds, increased in both soils at a different pH found by Sheng and Zhu [23]. On the basis of phospholipid fatty acid (PLFA) analysis, biochar addition pyrolysized at 300 and 700 °C increased soil pH with significant increases in Gram-positive bacteria and -negative bacteria, actinobacteria, and fungi, as studied by Luo et al. [24].

3. Effects of Biochar on Ecological Function of Soil Microorganisms

Soil microorganisms have an immense influence on the soil metabolism and the growth of plants, including the decomposition, recycling, and transformation of nutrient elements, and the promotion (or inhibition) of plant growth. The utilization of biochar in soil impacts the function of microorganisms [25]. Chen et al. [26] researched the influence of biochar on soil nitrogen leaching and retention, and the microbial mechanism in tea plantations of 20 and 60 years planting age, and showed that the most significant effect of slowing nitrogen leaching and increasing total nitrogen content was at biochar addition of 6%. Soil enzyme activity and microbial biomass increased, and the bacterial community changed. The results further indicated that the utilization of biochar increased the microbial nitrogen demand, promoted soil nitrogen cycling, and enhanced the fixation of microbial nitrogen. Abbruzzini et al. [27] applied biochar to tropical soils where wheat was grown, and found that the usage of biochar reduced nitrous oxide (N_2O) emissions, increased 15^N content in grains, improved nitrogen utilization, and increased the efficiency with which plants could obtain nitrogen and convert it into food yield, thus improving crop performance.

Carbon sequestration also plays an important role of soil microorganisms. Carbon sequestration includes increasing the synthesis of organic matter and reducing the decomposition of soil carbon, which reduces greenhouse gas emissions [28]. Sheng et al. [23] applied biochar in different proportions to ferralsol and phaeozems. The abundance of oligotrophic bacteria in black soil was increased, and carbon dioxide (CO_2) emissions decreased due to the adsorption of biochar. However, the growth of Bacteroidetes and Gemmatimonadetes, and the decline of Acidobacteria were observed, which were caused by the increase in CO_2 emissions. Yang et al. [29] found that biochar addition lessened CO_2 emissions by 18–25% during the first year, and 19–41% in the second year compared to control in a two-year field trial, and that methane (CH_4) emissions were significantly reduced with 15 and 30 t ha^{-1} applications. The addition of 30 and 45 t ha^{-1} markedly increased the amount of carbon sequestration at 0–15 cm depth, indicating that biochar has a positive function in lessening discharged greenhouse gases and improving soil carbon sequestration.

In addition to utilizing organic matter, microorganisms can effectively degrade some pollutants in soil to reduce residual toxins. Bashir et al. [30] reported that sunflower planted in wastewater-irrigated soil that was treated with four plant types of biochar could lessen the mobility of Cd in the soil, and the assimilation of Cd in the plant buds was also effectively decreased. Cd, As, and Pb concentrated in polymetallic-contaminated soils were significantly reduced after biochar addition [31]. The utilization of biochar also significantly promoted the removal of pyrene and benzo pyrene in both rhizosphere and nonrhizosphere soils, but did not promote the dispersion of phenanthrene [32]. Studies on the elimination of polycyclic aromatic hydrocarbons (PAHs) in the soil with the combination of different biochar and tillage systems indicated that the bioaccumulation rate of PAHs was the lowest with 2% corn straw-derived biochar pyrolyzed at 300 °C in a paddy-upland rotation cropping system. The results also showed that the degradation efficiency of PAHs was significantly greater than that under continuous upland cropping mode [33].

Microorganisms can reduce the decomposition of organic matter by forming soil aggregates, which greatly influences carbon sequestration and soil fertility improvement. Studies found that corn stalk biochar had an active influence on Actinobacteria and Acidobacteria, which could ameliorate the stability of soil aggregates [34]. Li et al. [35] compared changes in bulk density and aggregate stability after 2 and 5 years of biochar application, and indicated that the increase in soil organic carbon was the highest after 5 years with a biochar addition of 60 $t \cdot hm^{-2}$. Soil bulk density decreased significantly at 20–30 cm in depth, and aggregate stability and aggregate content with particle size greater than 0.25 mm increased significantly.

4. Effects of Biochar on Soil Enzymes

Soil enzymes is the general term for all enzymes in the soil. Soil enzymes dominate the biochemical process of the soil involved in the decomposition and transformation of various animal, plant, and microbial residues, and the redox reaction of inorganic and organic in the soil to promote soil carbon, nitrogen, phosphorus, and other nutrients' cycle transformation [14]. The porous structure of biochar can house an enzymatic reaction, and the enzymatic substrate attaches to the surface of biochar, thus enhancing the process of the enzymatic reaction [14]. The response of enzymes to the addition of biochar is not determined by a single factor, but by comprehensive factors such as biochar pyrolysis temperature, raw materials, application ratio, soil structure, and even the measured enzyme [36].

Nitrogen is necessary for plant growth, but some forms of nitrogen cannot be directly absorbed by plants, which requires the participation of some soil enzymes. Enzymes, including protease, urease, N-acetyl-β-glucosaminidase, nitrate reductase and nitrite reductase, are all related to nitrogen transformation in soil [37]. A previous study indicated that biochar mingled with nitrogen fertilizer could significantly improve urease activity with PLFA analysis [38]. When biochar mixed with different nitrogen sources was applied to paddy soil, the combination of nitrogen fertilizer and biochar enhanced urease activity, which may have been related to the increase in the microbial biomass nitrogen pool [39]. According to report by Liu et al. [40], the addition of compost combined with biochar greatly decreased the activity of nitrite reductase, and heightened the activity of nitrate reductase. In a test on the impact of apple branch biochar on soil, soil nitrate reductase activity decreased after 0–50 mg NO^{3-}-N kg^{-1} treatment, while soil nitrate reductase activity and root activity significantly increased under 1% biochar combined with 0–300 mg NO^{3-}-N kg^{-1} [41]. Through the influence of acid-activated biochar on soil enzyme activity, Ameur et al. [42] concluded that, in contrast with the control, the activities of protease and exochitinase improved after a month, and only protease activity increased after applying biochar for 7 and 22 months, while exochitinase activity decreased.

The activities of enzymes such as sucrase, cellulase, phenol oxidase, and peroxidase can characterize the conversion efficiency of soil carbon, and they directly participate in the mineralization and accumulation of soil organic matter to provide energy for the organisms in the soil. According to report by Wang et al. [43], the utilization of biochar increased the activity of catalase and polyphenol oxidase. Lopes et al. [44] determined that the application of biochar increased the activity of β-glucosidase in sugarcane soils, which was probably related to the escalation in carbon utilization bolstered by biochar, and the existence of volatile compounds in biochar. Adding biochar could also notably increase the activity of the soil sucrase and catalase, which are more susceptible to wood biochar [45]. Zhang et al. [46] found that the activity of catechol 2,3-dioxygenase and ligninolytic enzymes was reduced with the increase in heat-treated temperature after plant residue biochar under different treated temperatures (250, 400, and 600 °C) was applied in soils. Khadem et al. [47] applied corn straw biochar at three temperatures to sandy and clayey soils to measure soil enzyme activity, and established that the biochar addition markedly improved the activity of catalase and cellulase, but declined with the increase in pyrolytic temperature. The increase in enzyme activity in sandy soil was also more obvious. Adding biochar to a tea garden can also significantly promote the activity of sucrase and catalase [48].

Enzymes related to the conversion of phosphorus and sulfur elements in soil are also affected by biochar. Khadem et al. [49] added two types of corn biochar (400 and 600 °C) to two kinds of calcareous soils. A 3.1–4.4 time increase in alkaline phosphatase activity was detected after 90 days in the soil with biochar and residue, depending on the carbonization temperature and soil texture. The significant influence of biochar on soil alkaline phosphatase activity was better at a lower pyrolysized temperature than that with a high temperature, and greater in sandy loam than that in clayey soil. Fine particle biochar decreased the phosphatase activity of paddy soil and red soil [50]. Lopes et al. [44] reported that the activities of β-glucosidase, acid phosphatase, arylsulfatase, urease, and the total soil microbial quality were improved at 30 t hm^{-2} application of biochar. However, their activities were decreased with a higher supplemental level over time. An NPK fertilizer mixed with biochar increased the activities of urease, β-glucosidase, and arylsulfatase, but decreased the activity of acid phosphatase.

5. Effects of Biochar on Microbial Functional Genes

Soil microbes participate in a series of ecological processes in the soil through enzymes, and the transcription and expression of related functional genes regulate the activity of enzymes, which is an important index to understand the functional diversity of microbes and soil functions. The regulation mechanism of biochar on rhizosphere soil microecology is shown in Figure 3.

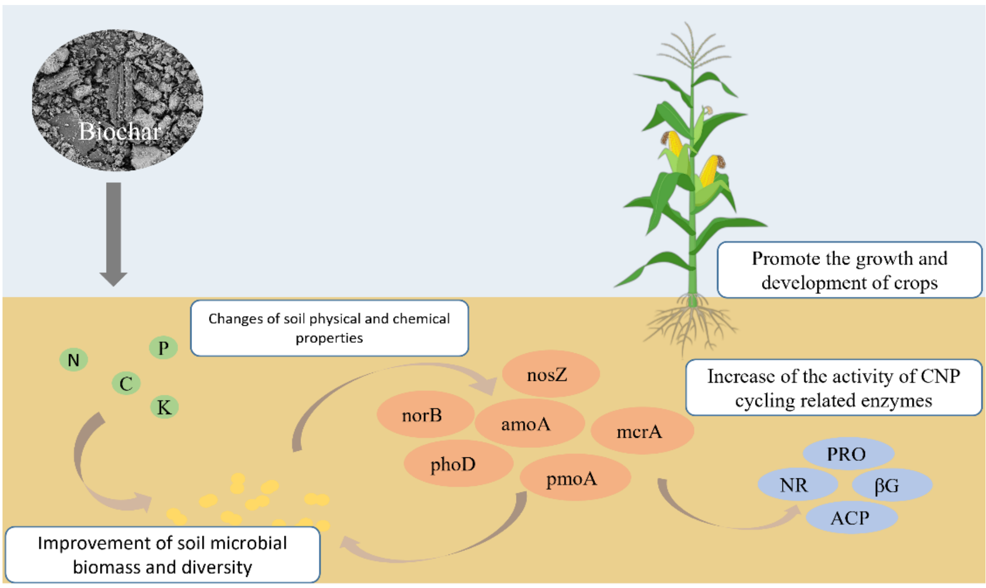

Figure 3. Regulation mechanism of biochar on rhizosphere soil microecology. Note: PRO: protease; NR: nitrate reductase; βG: β-glucuronidase; ACP: acid phosphatase.

The main functional genes involved in soil nitrogen cycling are nitric oxide (NO) reductase *norB*, N_2O reductase *nosZ*, nitrite reductase *nirS* and *nirK*, ammonia monooxygenase *amoA* and nitrogenase ferritin *nifH*. The study of Liu et al. confirmed that the addition of compost prominently raised the abundance of *nirS*, *nosZ*, *narG*, while the abundance of *nirK* and *nirS* may be susceptible to the addition of compost and biochar [40]. Liu et al. [51] conducted straw returning and biochar application, and found that, during the maize season, the copy amounts of ammonia-oxidizing archaea (AOA), ammonia-oxidizing bacteria (AOB), *nirK*, *nirS* and *nosZ* gene increased due to biochar application, and straw returning reduced the copy amounts of AOB, *nirK*, *nirS* and *nosZ*. N_2O emission was primarily affected by AOB and *nosZ*, while it was primarily influenced by AOB when planting wheat. He et al. [52] applied biochar to acidic and alkaline soils for four years, and found that the copies of AOA and AOB in acidic soils were more than those in alkaline soils. Adding biochar enhanced nitrification in acidic soils, which may have been due to the notable addition in the abundance of AOB and the elimination of some strictly acidophile AOA groups. Sole mineral fertilizer utilization and biochar combined with mineral fertilizer both increased the copy amounts of *amoA* in AOB, but decreased the copy amounts of *amoA* in AOA, *nirS* and *nosZ* genes. Compared with straw and mineral fertilizer, biochar and mineral fertilizer increased the community diversity of *nirK* and *nosZ*, but declined the community diversity of *nirS* [53]. According to report by Liu et al. [54], a biochar addition of 2% could markedly reduce the N_2O emissions of autotrophic nitrification and heterotrophic nitrification by 20.6 and 15.7%, respectively. A biochar addition of 5% could significantly reduce the N_2O emissions of heterotrophic nitrification, and had no significant effect on autotrophic nitrification. A biochar addition of 2% could markedly increase the abundance of denitrifying *Rhodococcus* of *nirK*-type and *Cupriavidus* and *Pseudomonas* of *nosZ*-type. Biochar immobilized and adsorbed inorganic nitrogen, which was one reason for the suppression of N_2O emission by biochar in the process of nitrification, and its catalytic role on the two bacteria above for denitrification.

Functional genes participate in the cycle and transformation of other elements in soil will be regulated by biochar similarly. After applying biochar to paddy soil, unlike chemical fertilizer solely, biochar utilization reduced the abundance of methanogenic archaea (*mcrA*), but increased the abundance of methanotrophic bacteria (*pmoA*), thereby reducing the ratio of *mcrA*/*pmoA*. CH_4 emissions were markedly greatly relevant to the abundance of *mcrA* gene, but not to the abundance of *pmoA* gene. Therefore, the application of biochar could reduce CH_4 emissions by reducing the abundance of methane archaea in paddy soil [55]. Han et al. [56] found that the decrease in CH_4 emissions was mainly due to the decrease in methanogenic activity, the increase in CH_4 oxidation activity, and the abundance of the methanogenic *pmoA* gene. Huang et al. [57] used biochar to improve soil in tobacco rice rotation and indicated that, when rice was planted, the copy number of *pmoA* in soil increased with the increase in biochar addition, thus reducing CH_4 emissions. CH_4 emissions increased with the increase in the copy number of 16S rDNA gene in methanogenic archaea. Tian et al. [58] found that, under a low phosphorus input, adding biochar was beneficial to the formation of the *phoD* gene community and preferentially enhanced the phosphate mineralization ability of this group, thus improving the bioavailability of phosphorus and the acquisition of phosphorus by plants.

6. Effects of Biochar on Crop Yield and Quality

Soil quality has long been improved by ploughing and fertilizing. In recent years, as an excellent soil conditioner, biochar has generally been applied in the agricultural field to ameliorate soil quality and fertility, and produce better crops. Crop yield could be improved with biochar addition to some degree. In a four-year wheat-maize rotation field experiment, the plant height and aboveground biomass of wheat and corn were the highest at a 16 t ha^{-1} mixture of straw biochar and fertilizer. The grain number per spike and 1000 grain weight of wheat and maize managed with biochar were markedly higher than those of other treatments [59]. A field experiment was conducted in a subhumid area of Kenya for over 10 years to examine the influence of biochar addition on yields in corn-soybean rotation. Soybean and maize yields were markedly increased due to biochar addition. Most importantly, corn and soybean yields were influenced by biochar for a decade [60]. Biochar also influenced rapeseed production for 5 consecutive years, with rapeseed yield after being amended with biochar increasing significantly in the first year, but then decreasing. Thus, soil fertility and rapeseed yield were substantially improved under biochar treatment, but the improvement was not permanent [61]. In a three-year experiment on the response of rice yield to biochar addition, a biochar application of 10–15% increased rice yield by 29.1–34.2% in the first year, 15–20% application increased the yield by 29.6–96.0%, but there was almost no increase in the third year. The rice yield in the first year was higher than that in the next two years, which was related to local meteorological factors. The application of 10–15% straw biochar and the periodic supplementation of biochar were beneficial to increasing rice yield [62].

The optimization of quality and quantity is the top priority for the future development of cash crop industries. After using biochar, Wang et al. [43] found that some growth targets of seedlings were markedly boosted, the abundance of soil-borne pathogen *Fusarium solani* was decreased, and soil enzyme activity was increased. These effects jointly promoted plant growth. Sani et al. [63] found that, under reduced NPK fertilizer application, the blended utilization of Trichoderma and biochar obviously increased the yield of tomatoes, and also effectively increased the contents of soluble solids, lycopene, and ascorbic acid in tomatoes, thus improving the nutritional and functional quality of the fruits. Solaiman et al. [64] found that poultry litter biochar combined with inorganic nitrogen and phosphate fertilizer could improve cucumber yield, nutrient content, and mycorrhizal fungus colonization rate, and reduce the negative effects of macro and trace element deficiency stress on cucumber growth. However, in some related studies, biochar had no obvious influence on crop harvest. Yakubu et al. [65] planted okra in sandy clay loam during the dry season. Under deficit irrigation treatment, 10 t hm^{-2} biochar obviously increased okra fresh fruit harvest by 67%, but a 5 t hm^{-2} addition had no obvious influence on okra harvest. In a pot experiment, the application of peanut-shell biochar alone or integrated with nitrogen fertilizer had no significant impact on greenstuff harvest, while the utilization of modified biochar mixed with nitrogen fertilizer reduced greenstuff yield, possibly due to the inhibition of excessive nutrients on the root morphology [66]. Farrar et al. [67] found that, compared with other treatments, high-dose biochar increased root mass fraction and plant height, but reduced the number of stems. After biochar application, the harvest, quality, and commercial value did not change greatly.

7. Prospects

As a new type of soil conditioner, biochar shows great potential for addressing questions concerning soil health, and achieving the high-class and sustainable development of agriculture. Fertilizing biochar changes the soil's physicochemical properties, increases its organic and nutrient matter, promotes the enhancement of enzymatic activity, cooperates with and promotes enzymatic reactions, and optimizes soil microbial community structures, which enriches diversity and reinforces the mutual effect between microorganisms and the crop root system, thus improving crop yield and quality. Therefore, it is essential to systemically study biochar by returning to the field and conducting further research to determine many uncertain factors of biochar application.

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