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Review

Research Progress on Effects of Biochar on Soil Environment and Crop Nutrient Absorption and Utilization

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Abstract: As a by-product generated from the pyrolysis of biomass, biochar is extraordinary for improving the soil environment of agricultural fields, improving soil fertility, and promoting nutrient uptake and the utilization of crops. In recent years, breakthroughs in progress have been made regarding the fertility value of biochar and in investigations into the physicochemical properties of soil and into plant nutrient utilization. This review focuses on the physicochemical and biological properties of soil, on soil pollution remediation, on greenhouse gas emissions, and on the effects of biochar on the uptake and utilization of soil nutrients and plant nutrients, as well as on the preparation of biochar, and on biochar produced under different conditions. The results of the relevant studies show that the main characteristics of biochar depend on the biochemical properties and pyrolysis temperature of raw materials, which play an important role in nutrient transport and transformation in the soil. At low temperatures (≤400 °C), the biochar prepared from manure and waste contains a large amount of nitrogen, which can be used as a nutrient source for plants. In addition, biochar enhances soil fertilizer retention by reducing soil nutrient loss, which in turn promotes nutrient uptake and utilization by crops. By controlling pyrolysis temperature and by optimizing biochar input, one can effectively reduce soil respiration, as well as reduce carbon emissions to achieve the goal of controlling carbon sources and increasing carbon sinks. Therefore, a long-term series of mapping studies on the effects of biochar application on agricultural ecosystems should be conducted, which in turn, it is hoped, will provide a theoretical reference for the physiological and ecological effects of biochar croplands.

Keywords: biochar; soil; soil nutrients; pyrolysis; microbes

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1. Introduction

At present, with the increase of global temperature and fertilizer application, the utilization efficiency of nutrients in farmland soil has gradually reduced and problems such as the decrease in productivity of cultivated land and the increase of pollutants in the soil ecological environment have become the focus of attention in terms of the current agricultural ecosystem. In line with the need for sustainable agricultural development, an increasing number of scholars are studying the use of Biochar in reducing the impact of the above problems. Biochar is rich in carbon, highly porous, has a high specific surface area and rich functional groups, and has good physical and chemical adsorption capacity. It plays an important role in improving soil quality in agricultural fields, improving water use and crop productivity, reducing greenhouse gas emissions and in climate change mitigation. In recent years, biochar has attracted much attention in the scientific community as a nutrient modulator of soil and a modulator of plant nutrient uptake and utilization [1–3]. Currently, much research on biochar has focused on soil contaminant control and remediation, crop growth, greenhouse gas abatement, soil fertility, soil micro-organisms, and so on [4–6]. The application of biochar affects soil pH, capacity, water retention, and cation interactions [7], and alters a soil's microbial community [8], its capacity for carbon fixation [9], and the availability of nutrients such as nitrogen, phosphorus, and potassium, reducing drought and salt tolerance stress in plants [10,11], and more obviously affecting soil available nitrogen [12], nitrogen leaching [13], soil nitrogen cycling [14], plant growth and nutrient uptake [15]. These effects are mainly due to the enhancement of soil fertility by increasing soil nutrient content and nutrient mobility [16].

In recent years, many scholars in China and abroad have undertaken substantial research on the preparation and properties of biochar and its application in agricultural and ecological environments, but a complete theoretical system has not yet been formed to explain the effects of biochar on the soil environment and the uptake and utilization of crop nutrients. Therefore, based on previous studies, this paper summarizes the effects of biochar on the soil environment, on soil metal pollution and soil remediation, on soil nutrient content and on plant nutrient uptake and utilization, intending to provide a theoretical reference for understanding the physiological and ecological effects of biochar on farmland.

2. Preparation and Characterization of Biochar

2.1. Preparation of Biochar

With the rapid development of the economy and the remarkable improvement of people's living standards, people are paying increasing attention to the environmental quality of the production areas of agriculture, and the harmless and resourceful uses of agricultural waste have become a focus of attention. Agricultural waste mainly includes crop residues from agricultural cultivation, by-products from the processing of agricultural products and livestock manure from farming. With the demands of the times, the traditional methods of treating and disposing of these agricultural wastes (returning them to the field, composting, etc.) have begun to face challenges. In recent years, biomass charring technology has been recognized as a promising new method of agricultural waste treatment. The raw materials for biochar preparation are composed of biomass such as manure, wood materials, industrial waste materials and crop straw, and the nutrient composition of the different biochar from which the raw materials are prepared also varies [17]. Biochar raw materials undergo high temperature cleavage under anaerobic and aerobic conditions to produce aromatic hydrocarbon compounds with strong stability, high carbon content and porosity. With increasing pyrolysis temperature under oxygen-free conditions, biochar feedstock is also gradually thermally separated, volatilized, and forms carbonization particles with high porosity and an irregular, rough surface. As a result, it can be divided into the following groups of biochar, which differ in their physical properties: (1) peanut shell pyrolyzed at low temperature of $\leq$400 degrees, which is rich in oxygen-containing functional groups and mineral elements, and is suitable for acidic soil amendment [18]; (2) Miscanthus pyrolyzed at low temperature, with its highest solid carbon capacity obtained under a pyrolysis temperature of $\leq$450 degrees [9]; and (3) xylan, with a pyrolysis temperature between $\leq$300 and $\geq$500 degrees, the surface of which starts to show stomata which are dense and uniform, with strong adsorption, and with the abilities to promote nutrient exchange between soil and plants and to improve soil fertility (Figure 1) [19]. However, the nutrient composition of biochar depends mainly on the feedstock properties and the pyrolysis temperature conditions at which the biochar was prepared, with lower pyrolysis temperatures [20] incurring improved pyrolysis effects for biochar preparation and higher soil nutrient utilization. For biochar that is produced using a preparation process that includes both increasing carbonization temperature and enhancements to the organic component's C element content, electrical conductivity and water holding capacity [21,22], the Na^+ and K^+ trend was not obvious, and the hydrophilicity weakened as the aromaticity gradually enhanced [15].

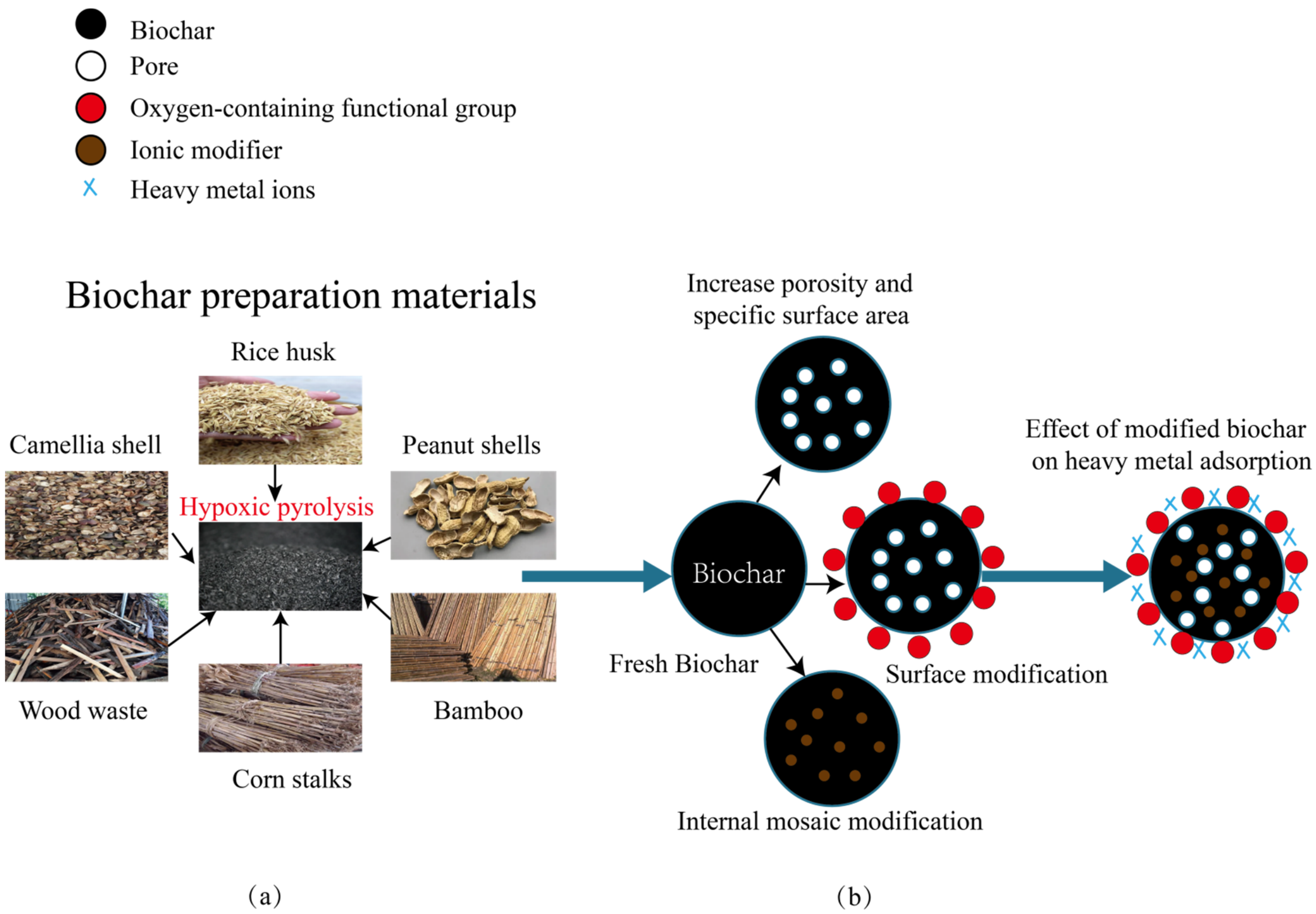

Figure 1. Preparation and modification of biochar. (**a**) Biochar preparation material, and (**b**) main functions and modification of biochar.

2.2. Characteristics of Biochar

Biochar is a product generated after the decomposition of organic and inorganic matter [23]. The difference between biochar and charcoal is that charcoal is an energy material capable of producing thermal energy, while biochar is commonly used to change soil properties and nutrient uptake, thereby improving environmental ecosystems [24]. It has been found through a study with black soil in the Amazon region that biochar has similar characteristics to the black soil found in the Amazon region and so many related studies about biochar characterization and its application to soil have been conducted [25]. Biochar has a strong adsorption capacity [26], and the physical adsorption of biochar occurs mainly within the pores and on the internal surface area. Additionally, there is a positive correlation between the internal surface area of biochar and its adsorption capacity (Table 1). Biochar has value in improving and enhancing soil water storage capacity and increasing crop yields with properties such as specific surface area, porosity, pH, cation exchange capacity (CEC), electrical conductivity (EC) and surface functional groups (e.g., -COOH, -OH, C=O, phenol-OH and -CHO groups) [27].

In summary, the main characteristics of biochar depend on the biochemical properties of the feedstock and pyrolysis temperature, and the reasons that cause these properties to change are environmental factors, soil properties, and planting variety [29,30].

Table 1. Physical properties of biochar derived from different feedstock and pyrolysis conditions [28].

Feedstock Types	Pyrolysis Temperature/°C	Surface Area/($cm^2 \cdot g^{-1}$)	Pore Volume/($mL \cdot g^{-1}$)	Pore Diameter/nm
Banana leaf (BL)	350	27.15	0.060	9.00
	500	28.90	0.062	8.32
	650	234.02	0.164	2.84
Banana stalk (BS)	350	7.19	0.014	25.59
	500	2.88	0.015	20.54
	650	29.02	0.045	6.22
Banana pseudo stem (BP)	350	2.58	0.018	26.32
	500	4.58	0.035	27.27
	650	5.33	0.035	24.63
Sugarcane leaf (SL)	350	8.26	0.032	23.58
	500	6.97	0.009	8.23
	650	71.28	0.017	17.17
Sugarcane stalk (SS)	350	1.21	0.007	23.45
	500	3.04	0.011	14.90
	650	3.88	0.012	12.17
Cassava stem (CS)	350	9.41	0.020	23.48
	500	48.92	0.054	4.64
	650	43.59	0.049	4.52
Mulberry stalk (MS)	350	22.62	0.023	4.83
	500	222.77	0.123	2.24
	650	276.14	0.165	2.40
Eucalyptus branches (EB)	350	292.60	0.173	2.59
	500	261.54	0.155	2.40
	650	388.77	0.187	1.90
Peach branches (PB)	450	4060.00	1.011	9955.10
Willow branches (WB)	450	257,550.00	1.082	168.00
Apricot branches (AB)	450	315,690.00	0.998	126.50

3. Impact of Biochar on the Soil Environment

Biochar can enhance soil nutrient uptake and utilization mainly because (1) biochar increases soil water holding capacity and improves soil physical properties [31]; (2) biochar improves soil trace element and cation exchange capacities [32]; and (3) Biochar has short-term effects on soil microbial communities and nitrogen-associated bacteria [33].

3.1. Effects of Biochar on Soil Physicochemical Properties

3.1.1. Effects of Biochar on Soil Physical Properties

Biochar and N fertilization studies have shown that biochar application in a 0–20 cm soil layer can reduce soil capacity weight, which in turn increases soil porosity and interacts with N fertilization [34]. At the same time, the soil aggregate structure can also be significantly changed after biochar application in agricultural fields, so that the 0.5–0.25 mm and 1–0.5 mm particle size water stable aggregate contents in soils are significantly improved, and the biochar can enhance soil quality, play the role of carbon sequestration, promote soil aggregate formation and organic carbon stability [35]. Applying biochar to acidic soils, the amount of rice husk biochar applied over three years at 6–12 t ha^{-1} could effectively improve and increase the optimal soil quality index (SQI:0.337–0.616, with a mean value of 0.462.), further indicating that long-term biochar application can improve soil physical properties [36]. In arid and semi-arid areas, total soil porosity, capillary porosity, hygroscopic coefficient, wilting moisture, saturated water content and field water holding capacity increased with increasing biochar application rates of 2%, 5% and 10% (ratios were mixed according to the percentage of the mass of biochar to soil) [37]. In areas prone to waterlogging stress, the application of biochar significantly reduced the soil capacity of the rice–wheat rotation, facilitating the downward movement of water, promoting the early growth of wheat and resisting stain stress during the critical wheat fertility period [38]. In addition, the application of biochar in sandy loam soils facilitates an increase in soil water storage compared with loam and clay soils [17]. Biochar has a positive response to soil surface area. This is related to the type of biochar [39]. Studies have shown that the surface area of soil applied with biochar is three times greater than the surface area soil to which biochar is not applied [40].

To sum up, biochar raw materials have large porosity and specific surface area after high temperature cracking [41]. The small particles of biochar can better combine with the soil to form a tiny agglomerate structure and improve the adhesion of water in the soil, thus increasing its water content. Additionally, biochar can change the shrinkage of the soil after application due to its well-developed pore structure and huge specific surface area. Therefore, the rational application of biochar can effectively improve soil water holding capacity and improve crop uptake and use efficiency for soil moisture and water-soluble nutrients.

3.1.2. Effects on Soil Chemical Properties

Biochar has a positive effect on the chemical properties of amended soils and produces important effects on soil nutrient composition. The addition of suitable straw biochar increases soil conductivity (EC), cation exchange (CEC), oxygenated organic C (OC), microbial biomass C (MBC), dissolved organic matter (DOC) and available nutrients (NPK). Not only is it able to change a soil's acid–base properties, but also to increase soil C-N content, increase soil nutrient content and increase crop yield [42,43]. The surface of biochar is rich in oxygen-containing groups and has a high ion adsorption and exchange capacity, which can adsorb ammonium nitrogen, nitrate nitrogen, soluble nitrogen and soluble phosphorus in the soil and reduce the loss of nutrients. The addition of biochar to the soil thus promotes the absorption and adsorption of nutrients [44,45]. Studies have shown that the dense soil structure of arable land is modified by biochar, creating environmental conditions conducive to microbial growth and reproduction, and activating the nutrients fixed in the soil, indicating that the addition of biochar has a catalytic effect on the mineralization of nitrogen in arable soil [46,47]. At the same time, crop yield increases with relation to available P, K ions, and alkali saturation in the crop and is associated with improved retention of soil cations and soil nitrate N with increasing biochar input [48].

In summary, the soil properties after biochar amendment depend on the soil type, application environment and the amount of biochar applied. When biochar was applied at 8% (200 t ha^{-1}), it significantly increased soil pH, moisture, total nitrogen, total phosphorus, and effective potassium, but decreased soil bulk and total potassium content [49]. The results of the study show that the application of biochar treatment increased the number of water-stable soil aggregates, accelerated the content of quick-acting nutrients in the soil, enhanced the water and fertility retention capacity of the soil, and improved the growing environment of rye and, boosting its growth [50].

3.2. Effect of Biochar on Soil Microbial Properties

Because biochar is of high porosity, it provides a favourable growth environment for soil microbes (*fungi*, *bacteria*, *actinomycetes*, etc.) meaning that the application of biochar can effectively improve the soil microbial environment [51]. A four-year crop rotation system of different types of biochar applied to wheat and maize found that, compared with conventional fertilizer control, the fungal population decreased by 21.9% in the digestate treatment and increased by 33.3% in the biochar treatment; however, the bacterial population increased by 258% and 121% in the digestate and biochar treatments respectively, the actinomycete population increased by 95.1% and 29.6% respectively, wheat yield increased by 8.46% and 23.47%, respectively, and maize yield increased by 18% and 15.46%, respectively [52]. Based on a seven-year pilot study using a quantitative polymerase chain reaction and 454 high-throughput pyrosequencing, it was shown that straw biochar significantly increased the abundance and microbial diversity of AOB during the growing season of wheat, while after the addition of straw and straw biochar, soil nitrification activity was positively correlated with the abundance of AOB in rice and wheat, but not with AOA [53]. The abundance of soil fungi measured using quantitative real-time PCR shows that the addition of biochar had no effect on the fungal community diversity and had a significant effect on the community composition in northeast black soil. Additionally, the community changes were mainly reflected at the genus and operational taxonomic unit levels, which indicates that long-term application of biochar changed the soil fungal community [54]. Application of straw, biochar and nanocarbon in saline soils effectively suppressed the soil's carbon-fixing bacterial community diversity and microbial species abundance [55]. Under long-term drought and frequent wet and dry cycling conditions, the application of biochar increased soil microbial biomass, changed the composition of the soil microbial community, and increased the soil nutrient level, which was beneficial for maintaining soil microbial numbers and reducing the effects of soil water stress on the soil microbial community [56]. Biochar application also significantly increased soil bacterial diversity, depleted the relative abundance of pyrolytic carbon nitrifying bacteria and bacteria, improved the abundance of soil Bacillus, *Pseudomonas and Streptomyces* as well as the bacterial antagonism to *P. capsici*, and the relative abundance of *Ascomycetes* was most affected by biochar and fertilizer in the soil [57,58]. The linear relationship between soil carbon mineralization rate and dehydrogenase and *β-glucosidase* indicates that biochar application significantly increased carbon mineralization and soil enzyme activity and enhanced the potential for soil carbon sequestration [59].

In conclusion, biochar application exerted a large effect on soil micro-organisms, and this effect may be related to cropland soil type, biochar species and biochar application. Biochar can optimize soil structure and influence soil physicochemical properties, while biochar applied to soil can promote the survival and reproduction of soil microbial communities and increase the reproduction capacity of plant root fungi [60], thus improving soil microbial activity, community structure and functional diversity, and, ultimately, crop yield and quality. In addition, changes in biochar application times can also have impacts on soil microbial abundances and numbers, which all require systematic pilot studies for a more in-depth understanding of the effects of biochar on soil micro-organisms.

4. Effect of Biochar on Soil Metal Pollution and Soil Remediation

4.1. Effect of Biochar on Soil Metal Pollution

Heavy metal contamination of soil has adverse effects on the agricultural ecosystem and food security production. The application of biochar may not only promote the reduction of oxidized pollutants but also participate in element cycling in terrestrial, groundwater, or wastewater ecosystems [61,62]. Biochar has a large porosity and abundant oxygen-containing functional groups, thus reducing the effectiveness of the migration and bio-availability of soil heavy metals, indicating that biochar can control soil acidity, alkalinity, salt alkalinity, and can remediate contaminated soils while increasing soil organic C and moisture retention [63]. The application of biochar to acidic and alkaline soils significantly increased the release of K, P, and Mg from soils by approximately 40–50 fold, and the release of K, P, and Mg nutrients from alkaline soils was higher than that from acidic soils [64]. The study showed that biochar amendment increased the total amount of heavy metals in the soil, but 43–97% of the heavy metals in the improved soil were concentrated in the less bio-available residual fraction. Therefore, the addition of biochar can significantly reduce the accumulation of heavy metals in lawn biomass at a rate of 50%, indicating that sewage sludge biochar is a potential regulator for improving urban soils [65]. In terms of soil heavy metal immobilization and retention, biochar preparation feedstocks produced by pyrolysis and gasification processes have impacts on metal and metal immobilization in soils. High pH, highly condensed carbon as well as high inorganic minerals (exchangeable cations) are favourable for Pb immobilization, while abundant surface functionality and a lesser amount of negative changes to the carbon surface contribute to retention, while the large surface area of biochar amendment plays a role in contaminant retention [66]. The feasibility of using biochar as a way to significantly reduce the environmental risk of heavy metal contamination of soils has been demonstrated by the generally decreased levels of several heavy metals, including Cu, Zn, Cr, Ni, Pb, and Cd, in a mixed biochar under pyrolysis conditions of corn straw (CS) and pig manure (SM). The total concentration of the six heavy metals was lower in the mixed biochar at the same temperature compared with the added CS, due to the "dilution effect", resulting in a lower heavy metal content. The optimum conditions to reduce the metal mobility and metal-related environmental risk of pig manure biochar are a higher addition rate of biochar from maize straw (CS/SM ratio 3:1) and a higher pyrolysis temperature (700 °C) [67]. Biochar application with cationic zeolites was effective in reducing the impact of Ni pollution on sunflower, maize roots, and shoots, resulting in improved biomass, grain yield, physiology, biochemistry, and antioxidant defense against mechanical crops, and remediation of Ni-contaminated soils [68]. In heavily polluted soils, the addition of bamboo and rice straw biochar can be used for in situ remediation by immobilizing metals, thereby reducing CD, Cu, Pb, and Zn uptake in the soil, a pH of 6.0–6.5 in soils can contribute to reducing metal toxicity, and the enhanced precipitation and adsorption of heavy metals in biochar treatment will contribute to reducing metal solubility and bio-availability [69].

4.2. Impact of Biochar on Farmland Restoration

Biochar has the characteristics of a large specific surface area and more oxygen-containing functional groups on the surface, so it has a positive effect on soil fixation and heavy metal adsorption and acting to purify the agricultural environment, reduce the toxicity of agricultural soils, and promote crop growth through the improved activity of functional groups. Biochar prepared from different biomass raw materials showed different effects on agricultural soil remediation. The use of biochar-loaded micro-organisms to treat soil containing heavy metal contamination can take advantage of both biological and adsorption methods. Moreover, the rich pore structure of biochar can adsorb Cd while providing a habitat for micro-organisms [70,71]. The remediation effects of different combinations of clay minerals and biochar on Pb and Cd in agricultural soils were followed, and the results show that seafoam with biochar and artificial zeolite with biochar were more suitable for the remediation of agricultural soils with combined Pb and Cd pollution [72]. A large number of studies have confirmed that, though woody biochar can significantly increase soil pH, CEC, and organic matter content, it can also play a role in improving the soil environment, reducing crop poisoning by agricultural pollution, and promoting crop growth and yield [73]. Meanwhile, it has also been found that crop straw and pig manure had better efficacy than mixed biochar with 1:1 mixture biochar quality, which could obviously reduce malondialdehyde (MDA) content within ryegrass plants, with an increase in soluble protein and photosynthetic pigment content. This study shows that mixed biochar can effectively alleviate the damage of uranium on the *Lolium perenne*, as well as promote the growth of plants and uranium enrichment [74].

5. Effect of Biochar on Soil Nutrient Content and Plant Nutrient Uptake and Utilization

5.1. Effect of Biochar on Soil Fertility

5.1.1. Effect of Biochar on Soil Nitrogen

Though nitrogen is an essential nutrient element for plant growth and development, it is also the first factor limiting plant growth and yield formation (Figure 2). The multi oligomerization of nitrogen plays a crucial role in crop yield increase, and an appropriate N application can promote chlorophyll synthesis in the plant body, which in turn enhances photosynthesis, provides sufficient nutrients to plants, and promotes plant growth. However, once nitrogen fertilization is applied in excess, the stress resistance ability of the crop decreases, and it is highly susceptible to pests, disease and freezing injury. Nitrogen also aggravates soil acidification, saline alkalization, causes pollution and damage to the agricultural ecological environment and will also affect crop yield [75].

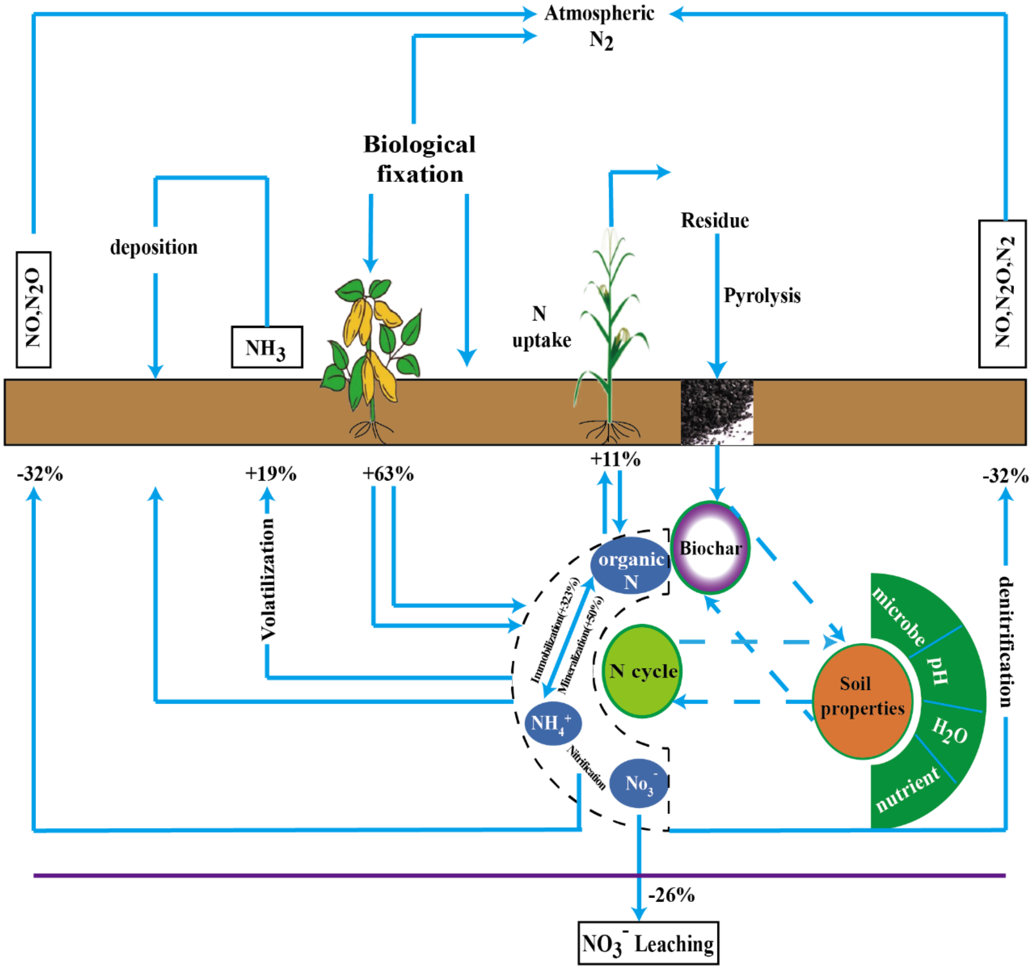

Figure 2. Conceptual framework of the biochar-mediated N cycle [75].

Biochar, because of its characteristically large surface area and fenestrated pore structure, can adsorb retained inorganic N ions by cation exchange after application to soil, reducing N loss and runoff in the soil, and also reducing nutrient loss by increasing water holding capacity [76,77]. Additionally, the leaching effects of biochar on soil nutrients differed considerably by soil type. We found that the leaching effect after biochar application was more significant on sandy loam soil than on clay planted with rice [12], while the biochar controlled the loss of nitrate nitrogen better on sandy loam soil than on control clay, which may be related to soil properties. In addition, biochar, when applied to soil, also increases N retention and biomass uptake, significantly enhancing the nitrogen cycle and improving soil mineral quality and N fertilizer utilization [78,79]. Biochar nutrient elements migrate in soils and available nutrients are taken up and utilized by crops at all reproductive stages [36]. To sum up, when studying the effect of biochar on soil nitrogen, we should take into account the external conditions of soil type and application amount of biochar.

5.1.2. Effect of Biochar on Soil Trace Elements

Biochar contains a large number of micronutrients such as Fe, Cu, B, Zn, and Mn. Studies have shown that the contents of Cd, Cu, Pb, and Zn between the oilseed rape subsurface and the above ground showed a gradually decreasing trend. With the amount of applied biochar, the transport coefficients of Cd, Cu, and Zn in the above ground showed a gradually increasing trend, and the application of biochar and carbon-based manure increased the transport of Cd, Cu, and Zn to the above ground in soils [80]. Under the conditions of an equal amount of straw and equal amounts of nitrogen, phosphorus and potassium nutrients, continuous application of biochar and straw can effectively increase the exchangeable Ca^{2+}, Mg^{2+} and K^{+} content in the exchangeable salt base, which in turn has a positive effect on the soil exchangeable salt base and cation exchange performance, increasing the amount of soil cation exchange and total exchangeable salt base, and enhancing the fertilizer retention and supply performance of the soil [81]. However, the concentrations of B, Mn, Mo, and Na significantly correlated with plant uptake in barley seedlings grown in a sand medium with biochar input and 0.01 M $CaCl_2$ extract [10]. In summary, the effects of biochar on nutrient ion retention and release indicate that before biochar application to soil, the adsorption capacity of biochar for nutrients should be determined, and different types of biochar differ in their adsorption capacities.

5.2. Biochar Impacts on Greenhouse Gas Emissions from Agricultural Land

The effects of different sources, pyrolysis temperatures, and application rates of biochar feedstocks on greenhouse gas emissions from agricultural fields also differ [82], and biochar undergoes high-temperature cleavage under anoxic or oxic conditions to obtain a stable and highly aromatic solid-state, carbon rich, and porous material, one which can sequester the decomposed carbon, achieve the fixation of CO_2, and reduce greenhouse gas emissions. Agricultural biochar amendment significantly reduced CH_4 and N_2O emissions, increased the carbon stocks of rice and wheat by 10.3%, reduced greenhouse gas emissions by 10.4%, and had a positive effect on greenhouse gas emissions, reducing N_2O production and counteracting 60% of CH_4 oxidation activity [83]. The role of biochar in reducing N_2O emissions and ammonia leaching from soils was enhanced over time when biochar was applied to agricultural fields, and nutrient sorption was enhanced through oxidation reactions [84]. Biochar can inhibit soil N_2O emission, improve nitrogen fertilizer utilization rate, promote soil nitrification rate, improve soil fixation of NH_4^+/NH_3 and NO_3^-, improve soil microbial nitrogen fixation, etc. [85,86]; however, some studies have shown that biochar can promote soil N_2O emission, inhibit soil nitrification rate, and does not have NO_3^- fixation capacity [87,88]. This is mainly related to the type and ageing process of biochar, as well as the soil type and its moisture porosity (Figure 3). By optimizing the amount of biochar applied and controlling the pyrolysis temperature, it is possible to reduce the emission of carbon from soil to the atmosphere during soil respiration and microbial decomposition, causing environmental pollution, health hazards, and the greenhouse effect and thereby modifying the impact of climate change [89]. The source of biochar feedstock, pyrolysis temperature and application rate affects NH_3 volatilization, and the application rate of biochar prepared under low and high temperature conditions can reduce NH_3 volatilization more substantially; however, poultry manure biochar prepared under low temperature conditions leads to increased soil N_2O emissions and increased NO_3-N leaching. [90]. Biochar feedstock (poultry manure, green waste compost and wheat straw), pyrolysis temperature (250, 350, 450, 500 and 700 °C) and application rate (1% and 2%) all affected NH_3 volatilization from soil. Poultry manure biochar reduced NH_3 volatilization by an average of 53%, while biochar prepared from green waste compost and wheat straw reduced NH_3 volatilization by 38% and 35%, respectively [91].

5.3. Effect of Biochar on Plant Nutrient Absorption and Utilization

Biochar inputs alter soil physicochemical properties, including pH, capacity weight, CEC, water retention, and bioactivity, which in turn affect soil nutrient retention. Biochar can significantly enhance soil resin soluble P and inorganic soluble P, thereby facilitating a nutrient increase in the soil available P, and the decline in P concentration is due to plant uptake of P rather than conversion of P concentration to a more stable form [92]. The biochar characteristics differed, as did the ^{15}N recovery, with an average of 6.8% ^{15}N recovery from roots and 10.9% to 26.1% ^{15}N recovery from leaf tissue when biochar containing adsorbed ^{15}N labelled ammonia entered the soil, with higher ^{15}N recovery from plants when ammonia was adsorbed by acidic biochar [93]. Pyrolysis of poultry manure biochar followed by amendment with NHO_3 or NHO_3+H_3PO_4 increased the concentrations of water-soluble P, K, CA, Mg, Fe, Zn, Cu, Mn and responded positively to increase available nutrients for plants and nutrients absorbed by plant growth [94]. Biochar application increased the mycorrhizal colonization of wheat roots up to 70% at a P application rate of 25 kg/hm^2, and soil pH plant and the mycorrhizal colonization value of biochar contributed to increased plant uptake of P and stem growth [95]. In summary, biochar application had a significant effect on CEC, soil pH, and soil organic matter, and was effective in reducing soil nutrient loss, thereby facilitating plant uptake and improving soil fertilization retention.

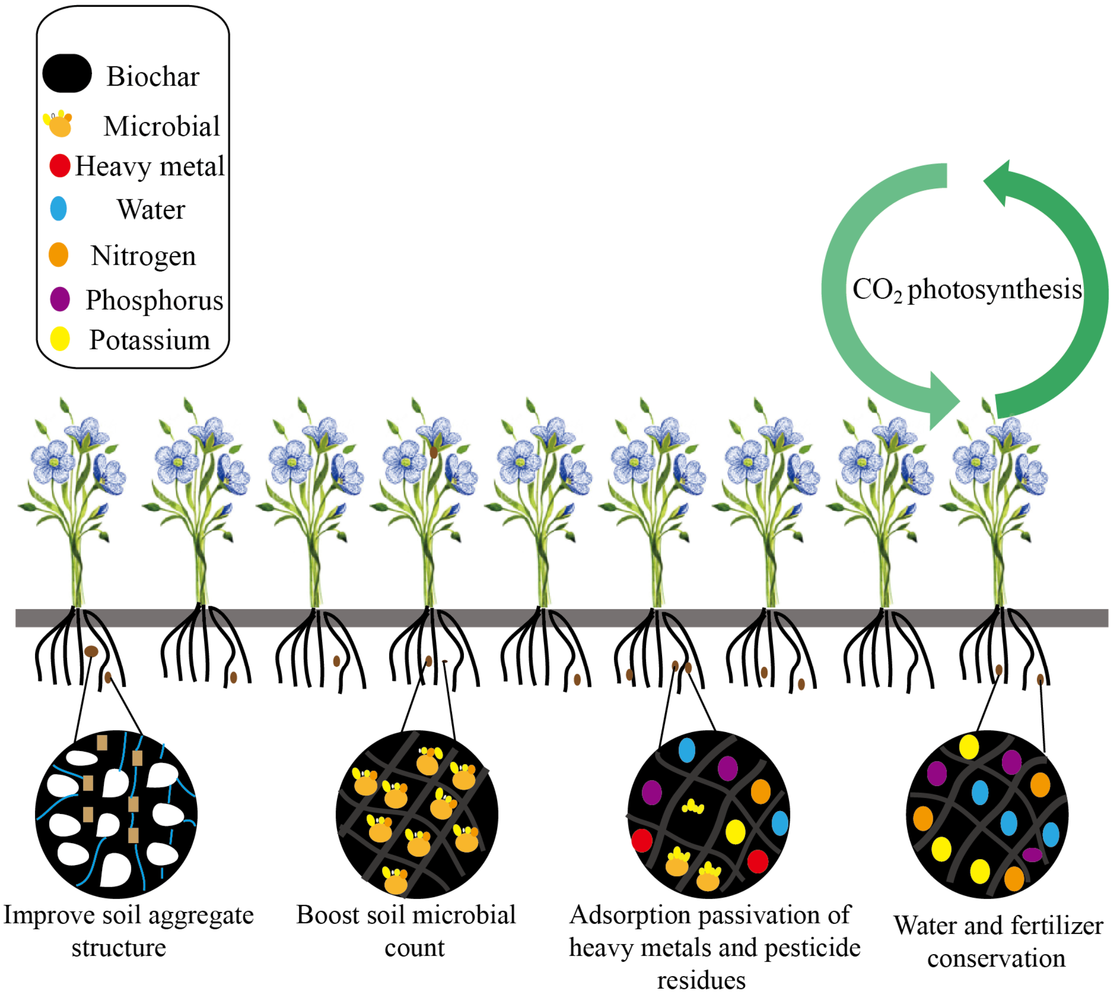

Figure 3. The effect of biochar on soil physicochemical properties.

6. Conclusions

In summary, biochar has unique physicochemical and biological properties that can affect the nutrient content of soils and improve the capacity of land production by changing soil capacity, pH, cation exchange, and soil microbial community. The effect of biochar on soil and plants is closely related to soil, plant type and soil fertility, and the application of biochar can reduce the drenching effect of the soil nutrients to achieve soil fertilization and water retention and improve the nutrient uptake efficiency of plants. Therefore, combining the major goals of agricultural sustainable development and resource conservation in China, future research and application should be focused on the following aspects:

(1) Biochar may have beneficial or detrimental effects on the composition of microbial communities after entering the soil environment, and there is a lack of research on the effects of biochar on the ecological functions of soil micro-organisms, which needs to be further investigated. Therefore, it is necessary to analyze and compare the structure of the

soil microbial community and its key gene expression, and to investigate the regulatory effect of biochar on soil nutrient transformation, to clarify the relationship between biochar and microbiological properties of agricultural soil.

(2) Through biochar application for the reduction of greenhouse gas emissions from agricultural fields, we investigated the relationship between biochar and the ecological environment of agricultural fields by cross application of different growth periods of plants, different fertilizers, and different soil types with different types of biochar to achieve greenhouse gas abatement while increasing yield.

(3) Biochar type, pyrolysis temperature, and soil type were collated to study the effect of different biochar types and different inputs on nutrient uptake and utilization efficiency in different soil types. This was undertaken in order to explore the regulation of uptake, utilization, transfer and distribution of plant nutrients by biochar, and to clarify the relationship between the regulatory mechanisms of biochar on plant nutrient utilization.

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