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Review

Advancements in Biochar Research Methods for Soil Pollution Remediation: Development and Applications

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Cite This: *ACS Omega* 2025, 10, 9854−9868

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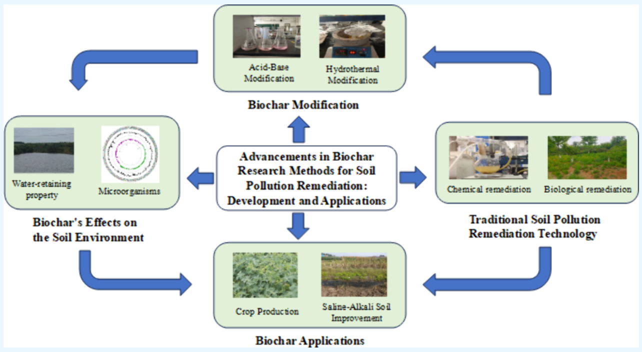
ABSTRACT: This review primarily focuses on the advancement of biochar research methods and their application in treating soil pollution and agriculture. Biochar, a novel material for soil treatment, shows great potential because of its high specific surface area, abundant functional groups, and well-developed pore structure. This work first introduces the current state and hazards of soil pollution and the limitations of traditional remediation technologies. It then discusses biochar research methods and advancements in biochar preparation techniques. This paper also discussed the application of biochar in the agricultural field. Although biochar has shown many advantages in soil remediation, technical and economic issues in its production remain to be resolved, and long-term environmental impacts and ecological safety need to be further evaluated. Future research should focus on the functional modification and application optimization of biochar to fully realize its potential in soil remediation and sustainable agricultural development.



1. INTRODUCTION

1.1. Current Status and Hazards of Soil Pollution.

Nowadays, with the continuous advancement of urbanization and economic development, human-generated pollutants enter the soil and accumulate continuously so that the content of pollutants exceeds the self-purification capacity of the soil, which results in soil pollution and the deterioration of the ecological environment. Environmental monitoring reveals that heavy metals, salts, and organic pollutants account for a significant proportion of soil pollutants, of which heavy metals are the most important pollutants.[1]

The sources of heavy metals mainly include rock weathering and geological processes, atmospheric deposition, sewage irrigation and excessive discharge, industrial solid waste piling, and the improper use of pesticides and fertilizers.[2] Heavy metals can migrate into natural systems through soil erosion and weathering, thus causing pollution.[3] The main characteristics of heavy metal pollution mainly include its high toxicity, wide distribution, convertibility, difficulty in degradation and irreversibility, which can destroy soil environments and indirectly affect plant growth.[4] Furthermore, due to the enrichment effect, heavy metals through the food chain will also harm human health and livestock health, thus causing double damage to agricultural economic development and human health.[5]

Salt pollution sources mainly include unreasonable agricultural irrigation and overuse of pesticides and fertilizers. Weathering, dissolution, wind erosion of rocks, and the transfer of salt from rock and soil layers to soil through surface water and wind action are also the causes of soil pollution. Nitrogen, phosphorus, and potassium in pesticides are the main elements of salt pollutants. Organic pollutants mainly include organochlorine, organophosphorus and other pollutants produced by excessive use of pesticides and fertilizers, as well as phenols, petroleum and other pollutants produced by industrial production, which remain in soil for a long time and may enter human body through the food chain, causing harm to human health.[6]

1.2. Traditional Soil Pollution Remediation Techniques.

1.2.1. Physical Remediation Techniques. Physical techniques for remediating contaminated soil are typically applied over large areas and mainly involve soil vapor extraction and electrokinetics. Soil gas phase extraction technology refers to the use of a vacuum pump to generate

Received: November 20, 2024
Revised: January 20, 2025
Accepted: February 19, 2025
Published: March 5, 2025

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https://doi.org/10.1021/acsomega.4c10533
ACS Omega 2025, 10, 9854−9868

Table 1. Advantages and Disadvantages of Traditional Soil Pollution Remediation Techniques

Soil Remediation Techniques	Advantages	Disadvantages
Physical Remediation	Wide application, secondary pollution can be controlled, simple process, low equipment requirements, low cost	Only treats surface-level pollution, some techniques need longer cycles
Chemical Remediation	Wide application, high pollutant removal efficiency, short cycles, quick results	May produce secondary pollution, high cost
Biological Remediation	Environmentally friendly, green, efficient, not easy to cause secondary pollution	Long treatment time, dependent on climate conditions, high requirements on site conditions, high equipment requirements, high cost

negative pressure to make air flow through the pores of contaminated soil, desorb, and carry volatile and semivolatile pollutants out of the gas well. This technology is suitable for the removal of organic pollutants.[7] This technique is effective for the removal of organic pollutants. The thermally enhanced gas extraction technology was used to repair benzene polluted soil in northeast China. The results showed that the removal efficiency of benzene and soil repair efficiency of thermal enhanced gas extraction technology were significantly higher than that of conventional soil gas extraction technology.[8]

Electrokinetic remediation involves placing electrodes in contaminated soil and using electric fields to migrate heavy metal ions toward the electrodes, where heavy metal are collected and removed.[9] A study has shown that the average removal rates of copper are in the range of 27.9−85.5% in copper-contaminated soil, while the average removal rates of zinc are in the range of 63.9−83.5% in zinc-contaminated soil through electrokinetic remediation.[10] It has been proven that the levels of lead and cadmium in the soil meet the standard "Soil Pollution Risk Control Standards for Soil Environmental Quality Construction Land" set by China (GB36600-2018) after electrokinetic remediation. EDTA solution is the best electrolyte, which has the advantages of economy and high efficiency.[11] However, there are three limiting problems of electrokinetic remediation, including the weak ability of dissolving metals, focusing effect and energy consumption.[12]

1.2.2. Chemical Remediation Techniques. Chemical remediation techniques mainly include chemical leaching, stabilization, solidification, and redox treatments. Chemical leaching technology refers to the dropping of acid, alkali, complexing agent and other chemicals into contaminated soil, so that the reagent reacts with the heavy metal ions in the soil to form a compound or complex, and then the dissolved heavy metals in the soil are removed by washing.[13] This method is suitable for areas with high pollution concentrations and easily soluble heavy metals. Studies have found that chemical leaching can change the pH value of the soil, reduce the total phosphorus and potassium content of the soil, and also significantly reduce the lead content of the soil.[14] According to a research, the optimum elution effect can be achieved by adding 2 mol/L hydrochloric acid when the soil-liquid ratio is 1:3 and the elution time is 1 h for 2 times, and the average removal rates of cadmium are 95.52%, and various forms of heavy in soil metals can be effectively removed.[15]

Stabilization and solidification treatment refers to the addition of phosphate, sulfate, lime and other additives in the soil, so that it can chemically react with heavy metals, convert them into more stable mineral forms, or form insoluble compounds with additives, thus reducing the bioavailability of heavy metals.[16] A research has found that stabilization and solidification treatment with hydraulic binders have a good effect on reducing the polluting power of metal, the removal rate of nickel is 98% and the removal rate of zinc is 99%.[17] This method is applicable to areas requiring long-term control of heavy metal pollution. Microscopic analysis and toxicity testing help to ensure successful stabilization and solidification.

Oxidation−reduction treatment, which uses oxidants or reductants to alter the valence state of heavy metals, reduces their toxicity and enhances stability. It was found that adding manganese oxide and hydrogen peroxide to soil was beneficial to convert hexavalent chromium into trivalent chromium, thus reducing the toxicity of chromium.[18] A research found that while the final pH of the system was in the range of 4.1−0.7, oxidation reduction potential varied from 230 millivolt to 629 millivolt, solubilization of chromium, zinc, copper, lead and cadmium in soil was in the range of 11%−99%, which is a good result for soil remediation.[19]

1.2.3. Biological Remediation Techniques. Biological methods for cleaning up contaminated sites include phytoremediation and microbial remediation. Phytoremediation refers to the use of plant roots to absorb heavy metals from the soil and transfer them to aboveground parts, and then these plants are harvested and treated safely to reduce the heavy metal content in the soil. Many experiments have shown that phytoremediation significantly reduces soil pollutants, and using a combination of plant species can enhance remediation effectiveness.[20] A research found that phytoremediation decreased the bioavailable cadmium and zinc concentrations in soil by 39.3% and 32.0% respectively, and increase the phytoextraction of cadmium by rice to 48.2% and 8.0% respectively, which means that the phytoremediation efficiency of cadmium−zinc contaminated soil could be improved by promoting the phytoextraction and immobilization of the metal.[21]

Microbial remediation refers to the transformation of heavy metal forms in soil through microbial metabolic activities to reduce its toxicity or increase its stability. Microorganisms can reduce heavy metal ions into insoluble forms or fix them through bioadsorption and complexation and decrease their mobility and bioavailability in the environment. Current studies have shown that many microorganisms can repair residual heavy metals in soil through their own metabolism and promote the secretion of plant hormones, improve soil structure and increase soil organic matter, thus promoting the natural recovery of ecosystems.[22] A research found that *Pseudomonas aeruginosa* had great bioremediation potential in restoring cadmium and lead in soil with the removal rates of 58.80% and 33.67% respectively.[23]

1.2.4. Characteristics of Traditional Soil Remediation Techniques. The advantages and disadvantages of traditional soil remediation techniques are listed in Table 1. Traditional remediation methods may destroy soil structure and fertility, and they are often less effective in treating heavy metal contamination.[24] Biochar can surpass many traditional methods for cleaning up polluted soil, but it faces limitations in raw material sources. Additionally, long-term use of biochar

https://doi.org/10.1021/acsomega.4c10533
ACS Omega 2025, 10, 9854−9868

leads to its aging, which might affect its effectiveness in treating soil pollution.[25]

2. DEVELOPMENT OF BIOCHAR RESEARCH METHODS

2.1. Introduction to Biochar. Biochar is a kind of refractory polymer with high stability and aromatics produced by pyrolysis carbonization of biomass under anaerobic or anoxic conditions.[26] The main component of biochar is the carbon molecule. The sources of biochar are diverse, including wood, straw, fruit shells, animal manure, and bones, as well as organic waste produced by industries such as garbage and sludge.[27] Scientists have been interested in the study of biochar, since they studied the black soil of the Amazon. Initial studies found that biochar possesses a large specific surface area, abundant surface functional groups and a developed pore structure.[28] Temperature, raw material type, and thermochemical conversion methods are the main factors affecting biochar yield and characteristics.[29]

The impact of adding biochar to soil on the form and mobility of heavy metals is significant as it reduces the acid-extractable fraction of heavy metals, thereby decreasing their bioavailability and aiding in their stabilization. The strong coordination capacity of the surface groups on biochar, along with ion exchange and electrostatic adsorption reactions, enables biochar to adsorb heavy metals from soil.[30] Biochar can increase the dry matter accumulation in the roots, lotus, and leaves of plants and reduce the loss of soil potassium and calcium ions. More importantly, biochar is better at removing heavy metals than other remediation techniques.[31] Nowadays, the combination of biochar and traditional soil pollution remediation technology becomes more and more popular and feasible, and more research has proved its advantages.

2.2. The Combination of Biochar and Traditional Soil Pollution Remediation Technology. *2.2.1. The Combination of Biochar and Physical Remediation Techniques.* A research used the combination of biochar and thermochemical processes to carry out an experiment and found that the content of cadmium, lead, and zinc in the root were lower than soil environmental quality standards. In addition, this pyrolysis process has the potential to treat heavy-metal-rich biomass, which is purified by vapor phase through condensation to produce agricultural grade biochar. Therefore, the combination of biochar and physical remediation techniques is feasible.[32]

2.2.2. The Combination of Biochar and Chemical Remediation Techniques. A research used the combination of biochar and electrochemical remediation to carry out an experiment and found that biochar combined with electrochemical technique significantly enhances the removal of phenanthrene from the sediment, mainly because the anode can be used as an electron acceptor to enhance the cometabolic degradation of phenanthrene by microorganisms in the sediment, and biochar can play a role as an electron transfer intermediate to enhance the extracellular electron transfer of microorganisms. Electrochemical techniques significantly affect the chemical form of lead in the sediment. The soluble lead in weak acid at the anode first increases and then decreases and slowly migrates to the cathode, where it is transformed into residual state. In this way, the in situ degradation of phenanthrene and the stabilization removal of lead in the sediment are realized.[33]

2.2.3. The Combination of Biochar and Biological Remediation Techniques. Some experiments have studied the effect of combining biochar and bioremediation technologies to repair soil pollution. A study found that there is an interaction between biochar and bacteria, and biochar has an important direct impact on bacteria by promoting extracellular electron transfer, an energy metabolic process that involves the transfer of electrons from intracellular oxidation to extracellular reduction. The combination of organisms and bacteria is feasible for several reasons. First, biochar acts as an electron shuttle that can both receive and transfer electrons from bacteria and transfer electrons to bacteria. Second, biochar can act as a medium of communication between bacteria, and biochar can act as a shelter for bacteria and help them resist stress. Third, biochar can help bacteria resist stress by changing the soil environment in which they live, Fourthly, bacteria can change the physical and chemical properties of biochar in order to maximize the impact.[34] Microorganisms can help plants cope with heavy metal stress while promoting plant protection and nutrient utilization. It also produces chemically sensitive substances that regulate plant growth and development and protect plants from pathogens; It helps plants adapt to alleviate stress and indirectly promotes plant remediation of metal-contaminated soil.[34]

2.3. Development of Biochar Preparation Methods. *2.3.1. Gasification.* In the early stages of research, gasification was a commonly used method for preparing biochar. Gasification refers to the process of using oxygen or oxygen-containing substances in the air as gasification agents under certain thermodynamic conditions to pyrolyze and redox polymers of biomass and finally transform into combustible gases with carbon monoxide, hydrogen, and methane as the main components. However, this method has drawbacks, including low reaction conversion rates, the escape of carbon monoxide into the atmosphere causing pollution, and low biochar yields.[35]

2.3.2. Pyrolysis. To overcome the limitations of gasification, the pyrolysis method then became the research hot spot and became the most widely used and most mature biochar material preparation method. Pyrolysis refers to the process of thermal decomposition of biomass into biochar, biological oil, and gas at a high temperature of 300−1000 °C in an oxygen-free environment. The obtained solid matter mainly contains carbon elements. It is a mixture of carbon, oxygen, nitrogen, calcium, and sulfur elements. Pyrolysis can be divided into fast and slow pyrolysis depending on the temperature, pressure, residence time, and heating rate. Rapid pyrolysis refers to the process of rapid heating of biomass raw materials under anaerobic conditions with medium reaction temperature and short steam residence time, in which the reaction temperature is generally set between 450−550 °C and the steam residence time is generally less than 2 s.[36] Slow pyrolysis refers to the use of low reaction temperature and large particle size of biomass for slow heating, in which the reaction temperature is generally set between 350−450 °C, the heating rate range is 0.1−0.8 °C per second and biomass particle size is greater than 1 millimeter.[37]

The pyrolysis temperature is a key factor influencing the yield, pore size distribution, and surface chemical properties of biochar. Excessive pyrolysis temperature will reduce the yield of biochar materials and the pore structure of products, increase the specific surface area of biochar, and change the functional group structure and oxygen content of the surface of biochar, thus weakening the adsorption capacity of biochar.

https://doi.org/10.1021/acsomega.4c10533
ACS Omega 2025, 10, 9854−9868

Table 2. Advantages and Disadvantages of the Activation Technology

Activation Technology	Advantages	Disadvantages
Acid Activation	Reacts at low temperatures, fast reaction speed, improves adsorption	High energy consumption, complex operations, high treatment costs, equipment corrosion risks
Alkali Activation	High catalytic efficiency, environmentally friendly	High equipment costs, equipment corrosion risks
Plasma Activation	Increases surface functional groups, enhances reactivity	High operational costs, low technological stability
Metal Impregnation	Effectively adsorbs heavy metal ions, improves soil structure	High cost, high technical requirements, uncertain long-term environmental impacts
Gas Activation	Simple preparation, increases adsorption efficiency	Inconsistent particle size, high ash content, difficulties in meeting environmental requirements

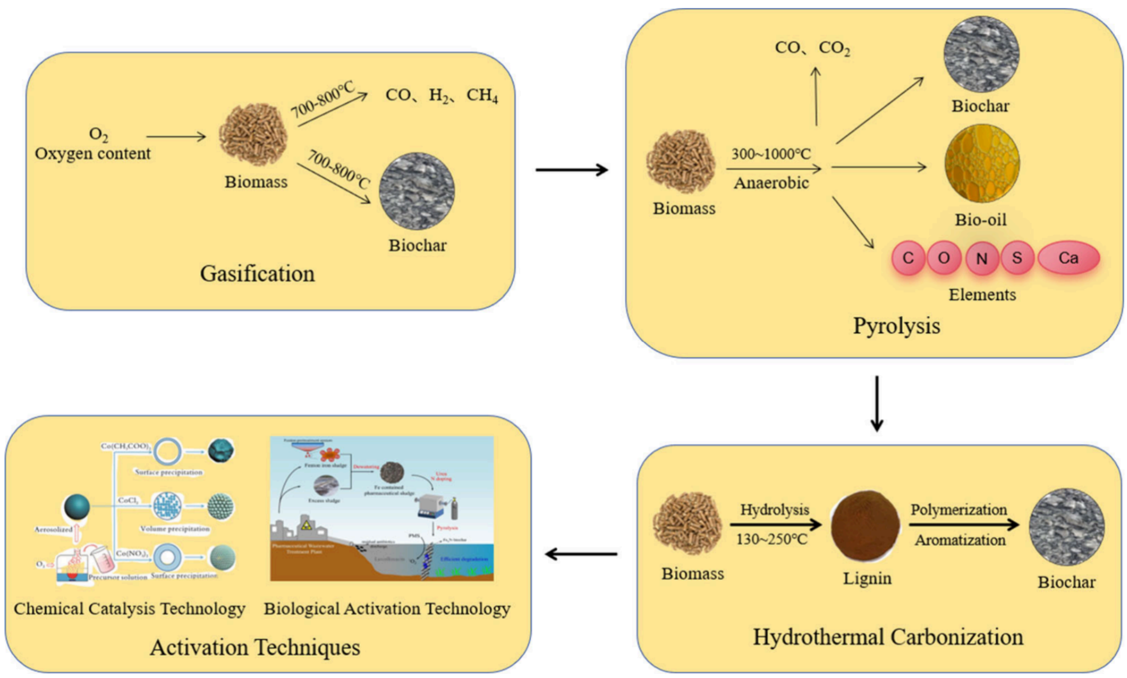

Figure 1. Diagram of the development of biochar preparation methods.

Additionally, the process requires high carrier gas purity and constant flow rates.[38]

2.3.3. Hydrothermal Carbonization. Hydrothermal carbonization refers to the process of converting biomass raw materials into carbon materials dominated by biochar under a certain temperature and pressure with water as the reaction medium. This method has gained popularity in recent research as a low-temperature alternative to pyrolysis and gasification, typically performed in the temperature range of 130–250 °C.[39] So it can replace the high temperature pyrolysis process.

The hydrothermal carbonization process is divided into three stages. First, the biomass raw material is hydrolyzed into monomer to reduce the pH value of the system. Then the monomer is dehydrated and causes a polymerization reaction. Finally, the aromatic reaction is carried out to form the final product.[40] This method has the advantages of low reaction temperature, low energy consumption, no secondary pollution, and strong stability and solves the problem of long pretreatment time and high cost of raw materials in the pyrolysis process of materials with high water content. Therefore, the preparation of biochar by a hydrothermal carbonization method is one of the current research hotspots.

A research study investigated the effect of different pyrolysis temperatures on biochar properties to explore the potential value of biochar structures for soil and water conservation applications. The biochar yield decreased from 41.32% to 29.45% with the increase in pyrolysis temperature. The ash content of biochar at 700 °C increased by 58.93% compared with that at 300 °C. The biochar prepared at 500 °C has abundant oxygen-containing functional groups and a more stable structure. Therefore, biochar prepared at higher pyrolysis temperatures is expected to be used in soil conservation in combination with its physical and chemical properties and characterized structure.[41]

2.3.4. Activation Techniques. To improve biochar's efficiency in treating soil pollutants and maximize its catalytic and stable properties, researchers have developed various biochar activation techniques. The activation techniques include acid activation, alkali activation, plasma activation, metal impregnation activation, and gas activation.

Each activation technique has its own advantages. Acid activation can not only effectively catalyze the dehydration and bond breaking reactions of cellulose and other substances in the pyrolysis process, and inhibit the formation of macromolecular organic byproducts such as tar, but also reduce the bond breaking temperature of functional groups.[42] Alkali activation is beneficial to increase the specific surface area and pore size of biochar, and it can generate positive charge to facilitate the adsorption of negatively charged substances, all of which are conducive to improving the catalytic efficiency of biochar.[43] In the process of plasma activation, low-temperature plasma can ionize or activate gas molecules and produce active

https://doi.org/10.1021/acsomega.4c10533
ACS Omega 2025, 10, 9854−9868

substances, particles, ions, and free radicals, etc. Various particles will collide with each other and a series of chemical reactions will occur, which is conducive to the adsorption effect of biochar.[44] Metal impregnation can promote the break of organic chemical bonds and the biochar impregnated with metal, metal oxides and metal salts has good electrostatic attraction, ion exchange and precipitation capacity, which is conducive to the fixation of heavy metals and the removal of new organic pollutants.[45] Gas activation increases the internal surface area by partially vaporizing the carbon skeleton, and provides abundant functional groups to the biochar surface.[46] The advantages and disadvantages of these activation techniques are summarized in Table 2. The development process of the biochar preparation method is shown in Figure 1.

2.4. Biochar Modification. Nowadays, biochar production technology is quite mature. Any organic material with a high carbon content and a low inorganic content can be used to produce biochar. To improve biochar's pore structure, surface area, and functional groups, modification methods have been widely researched. Biochar modification can also reduce soil remediation costs. Common biochar modification methods include metal modification, organic modification, acid−base modification, microwave modification, high-temperature heat treatment, hydrothermal modification and microbial modification.[47]

2.4.1. Metal Modification. Metal modification refers to load metal ions onto the surface of biochar, change its surface structure, and increase its specific surface area and pore volume. The modified biochar needs to be pickled to remove residual metal ions. Studies have found that biochar modified with magnesium−aluminum hydrotalcite can significantly reduce the content of cadmium in soil and the enrichment capacity of cadmium in soil. Metal oxide modified biochar can make full use of soil nutrients and improve the quality of spinach and other plants.[48] Additionally, biochar modified by nickel and zinc can enhance its aromatics, weaken its hydrophilicity, and increase the specific surface area and the number of oxygen-containing functional groups. Moreover, the adsorption capacity of zinc-modified biochar is stronger than that of nickel-modified biochar, and the removal rate of ciprofloxacin is greater.[49]

2.4.2. Organic Modification. Organic modification can increase the number of functional groups and adsorption sites on the surface of biochar so as to improve the adsorption capacity of biochar for pollutants. The results showed that methanol can dissolve organic compounds that block the pores of biochar, reduce the number of carbonyl groups on the surface of biochar, increase the number of ester groups and hydroxyl groups, transfer oxygen atoms on the surface of methanol-modified biochar from high energy to low energy, increase the electron density of oxygen atoms, and promote the formation of hydrogen bonds between biochar and pollutants, thus enhancing the adsorption capacity of pollutants. After persulfidation, the aromatics of biochar decreased, the polarity increased, and the structure of surface functional groups changed. Adding sodium hydroxide and anhydrous ethanol to the shell powder can increase the number of oxygen-containing functional groups and increase the specific surface area.[50]

2.4.3. Acid−Base Modification. Acid modification removes impurities from the biochar surface and introduces acid binding sites for pollutant adsorption, while alkali modification increases the number of oxygen-containing groups like hydroxyl and carboxyl, enhancing biochar's adsorption capacity. A study shows that the specific surface area of biochar is increased several times compared to that of the original biochar, and the adsorption ability of biochar to pollutants is improved after acid−base modification. Compared with alkali-modified biochar, acid-modified biochar has a better adsorption effect on hexavalent chromium. Due to the positive charge on the surface of alkali-modified biochar, there is electrostatic attraction between hexavalent chromium and biochar, which is conducive to the combination of hexavalent chromium and biochar. However, acid-modified biochar has small porosity and small quantity, so its adsorption effect on heavy metals is not as significant as that of alkali-modified biochar.[51]

2.4.4. Microwave Modification. Microwave modification refers to the rapid heating of porous biochar through microwave heating. This method can form new pores in porous biochar, and the thermal effect of pores causes changes in pore structure, and the number and types of some surface functional groups also change. Research has shown that microwave heating can still maintain the porous structure of biochar and organic pollutants can be decomposed and desorbed by heating, which makes it easy to control the heating temperature. Microwave can quickly heat biochar, so the modification time of microwave modification is relatively short compared with other modification methods, so it can show higher adsorption efficiency.[52]

2.4.5. High-Temperature Heat Treatment Modification. High-temperature heat treatment modification refers to heating biochar in an inert gas to alter its pore structure. After treatment, the surface area of the biochar increases, thus, enhancing its adsorption capacity. At the same pyrolysis temperature, biomass is the main influencing factor. For the same substance, the pyrolysis temperature is the main factor. A study showed that orange peel biomass had the most significant adsorption effect on cadmium ion at 500 °C, which was stronger than that of peanut shell biomass.[53]

2.4.6. Hydrothermal Modification. Hydrothermal modification refers to hydrothermal heat treatment at 120−200 °C in a high temperature and high pressure water environment, so that the efficiency of secondary activation is higher. The modified biochar with high specific surface area and large porosity was obtained by water heat treatment to dredge the pore size and adjust the pore structure so as to improve its adsorption capacity. Studies have shown that in the process of hydrothermal modification, the number of oxygen-containing functional groups, the number of acidic functional groups and the content of carbon on the surface of biochar increased, and adding hydrothermal modified biochar to soil could reduce the toxicity of chromium.[54] In addition, the amount of pure bamboo biochar adsorbed tetracycline hydrochloride was very low and the effect was poor, but the effect of bamboo biochar modified by potassium permanganate and potassium carbonate hydrothermal method was more significant.[55]

2.4.7. Microbial Modification. Microbial modification refers to the modification of biochar by using the function of microorganisms. Microorganisms are usually cultivated in the pores of biochar and provided with ideal temperature and organic nutrients to enable microorganisms to play their roles. Studies have shown that the specific surface area of biochar modified by phosphorus solubilizing microorganisms increased greatly, and the amount of nutrient elements released increased.[56] Additionally, compared with nonbiological

https://doi.org/10.1021/acsomega.4c10533
ACS Omega 2025, 10, 9854−9868

modified biochar, microbial modified biochar can enrich the beneficial microbial community in soil, promote the colonization and growth of microorganisms, enhance its ecological function, increase the pore size of biochar and increase the specific surface area and adsorption capacity of biochar.[57] The schematic diagram of microbial modification is shown in Figure 2.

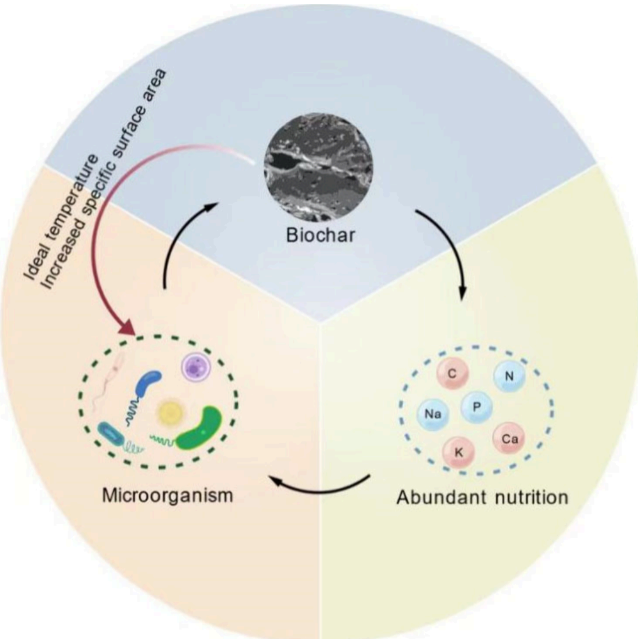

Figure 2. Microbial modification diagram.

2.4.8. Characteristics of Various Biochar Modification Methods. The advantages and disadvantages of various biochar modification methods are summarized in Table 3.

3. BIOCHAR'S EFFECTS ON THE SOIL ENVIRONMENT

3.1. Biochar's Effects on Soil Physical and Chemical Parameters.

3.1.1. pH. Biochar significantly increases the soil pH value. In most cases, biochar is alkaline because of the presence of ash, carbonates, and alkaline cations produced during pyrolysis. As the ash in biochar contains soluble base ions such as calcium, magnesium, potassium, and sodium, the addition of the soil increases the base saturation of the soil, and the base ions can be exchanged to reduce the concentration of soil hydrogen ions. After the biochar is added to the soil, the alkaline substances in the biochar are released to neutralize part of the soil acidity, thus increasing the pH of the soil. Some studies have suggested that biochar can improve acidic soil by reacting with hydrogen ions in soil to increase soil pH due to its structure including negatively charged phenol and hydroxyl groups.[58]

3.1.2. Cation Exchange Capacity. Biochar's large surface area and surface oxidation significantly increase the number of oxygen-containing functional groups, thus enhancing its ability to adsorb cations. Therefore, adding biochar to soil increases the cation exchange capacity. This also means that biochar can reduce nutrient leaching and increase the efficiency of nutrient recycling. Research showed that the addition of biochar to highly weathered tropical soils can increase the cation exchange capacity by 50%, and even low biochar input can increase the soil cation exchange capacity.[59]

3.1.3. Organic Matter and Carbon Content. Biochar contains high levels of organic matter and carbon, so adding biochar to soil increases the organic carbon content, thus improving soil humus and organic matter. Biochar enriches a large amount of nitrogen, phosphorus, potassium, calcium and other nutrients in biomass, which can be retained in the soil for a long time and transform the originally unstable organic carbon into a stable form of biochar, thus achieving effective carbon storage in the soil and increasing the carbon content in the soil.[60] Current studies have found that the more biochar is applied to the soil of yellow rape, black rape, and Indian mustard, the greater the content of organic matter and carbon will be. This is because the carbon content in biochar is the highest. In the planting process, biochar can coupling carbon with yellow rape, thus alleviating the decomposition of soil organic matter and increasing the organic matter content.[61]

3.1.4. Ash Content. The change of the ash content mainly depends on the raw material and pyrolysis temperature. High ash content is related to alkaline functional groups, while acidic functional groups on the surface of biochar volatilize faster with an increasing pyrolysis temperature, which increases the proportion of ash and further prevents nutrient loss. Since the ash in biochar contains mineral elements such as calcium,

Table 3. Advantages and Disadvantages of Biochar Modification Methods

Biochar Modification Methods	Advantages	Disadvantages
Metal Modification	Increases surface area, improves pore structure, enhances heavy metal adsorption, promotes biochar adsorption of heavy metal ions, improves the selectivity of biochar to heavy metals	High cost, potential secondary pollution
Organic Modification	Increases organic carbon content, improves adsorption efficiency, prevents soil phosphorus leaching, improves soil physical and chemical properties	High cost, high technical requirements, potential secondary pollution
Acid−Base Modification	Increases surface functional groups, enhances chemical stability, improves adsorption properties	High cost, potential secondary pollution
Microwave Modification	Shorter modification time, lower energy consumption, green and environmentally friendly	High equipment cost, complex operation
High-Temperature Modification	Increases surface area, improves adsorption efficiency	High energy consumption, high technical requirements, high processing cost
Hydrothermal Modification	Low energy consumption, environmentally friendly, easy to control temperature, pressure, reaction time and other parameters	Complex operation, high cost, limited applicability
Microbial Modification	Enhances soil fertility, maintains soil fertility, promotes plant growth, improves pore structure	Some pollutants may inhibit microbial growth, complex modification process

https://doi.org/10.1021/acsomega.4c10533
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magnesium, potassium, sodium, and other oxides, the addition of biochar to the soil will increase the ash content and provide nutrients for crop growth. Under the condition of 550 °C, organic matter in biochar will dehydrate and accumulate mineral elements such as potassium, sodium, and calcium, thus increasing the ash content of biochar. This research showed that the ash content of rice straw biochar is higher than that of corn straw biochar and wheat straw biochar because of the higher content of cellulose and lignin in rice straw.[62]

3.1.5. Surface Area and Porosity. Biomass raw materials contain more hydrogen and oxygen elements. In the pyrolysis carbonization of raw materials, the removal of hydrogen and oxygen elements causes the carbonization of residual carbon elements and the formation of a pore structure. The disappearance of the original structure of biomass materials and the dehydration pyrolysis reaction led to the escape of water and volatile fractions, which formed a porous carbon frame structure. Therefore, the addition of biochar in the soil increases the space between the soils, which makes the soil structure more loose, thus effectively reducing the soil bulk density, improving the soil porosity and specific surface area, enhancing the binding force between soil particles, and making the soil structure more stable, thus increasing the adsorption and retention of small molecular substances in the soil. It is more conducive to the growth, development, and stability of plants, especially roots. The increase of soil porosity is conducive to leaching of soil salt during precipitation, reducing salt content, and improving saline-alkali soil. Some studies have found that straw biochar with smaller particle size contains larger specific surface area and porosity and more abundant pore structure. Adding biochar to soil can greatly reduce soil volume mass, increase porosity and effectively improve soil structure.[63]

3.1.6. Electrical Conductivity and Particle Size. In soil pollution remediation, biochar with particle sizes ranging from 0.5 mm to 5.0 mm is generally used. The main component of biochar is carbon molecules, and carbon is a nonmetallic element. Additionally, the salt concentration on the surface of biochar is lower, so the electrical conductivity of biochar is lower. By addition of biochar to the soil, the electrical conductivity of the soil can be reduced, thereby promoting the growth of crops in the soil. With the increase of biochar, the electrical conductivity in the soil increased, indicating that biochar can effectively adsorb salt ions.[64] Additionally, biochar can inhibit the infiltration of water in karst slope soil, and the effect of using large-particle biochar is more significant.[65]

3.1.7. Air Permeability and Water Retention. Adding biochar to soil can increase the specific surface area of soil, effectively reduce the bulk density and density of soil, increase the total porosity of soil, facilitate the air circulation in soil, and improve the permeability of soil. This can also change the percolation pattern and retention time of soil water, so that biochar can effectively retain water in the soil and plants can fully absorb water. In the gravity drainage balance, more water can be retained, there is a greater water retention potential and surface area, water diffusivity decreases, and water retention of soil increases. The addition of biochar to the soil can produce a larger aggregate, which enhances the adsorption and retention of nutrient ions in the soil, so that it is not easy to lose with water washing, thus ensuring the water retention of the soil. It was found that in the process of rice planting, adding biochar to soil can achieve the effect of water retention and fertilizer preservation, and the rice yield is significantly improved, and the soil permeability is also improved.[66]

3.2. Biochar's Effects on Soil Microorganisms.

3.2.1. Changes in Microbial Habitat and Nutrients. The pore structure of biochar is very developed; the pores are responsible for the diffusion of substances, mass transfer, and space provision, so biochar can provide more space for microorganisms to settle, grow, and reproduce. Biochar contains a lot of nitrogen, phosphorus, potassium, sodium, carbon and other nutrients, which can directly provide nutrients for the growth of microorganisms.[67] The surface of biochar is rich in various functional groups, which can adsorb inorganic anions and nutrient cations, thus indirectly providing nutrients for microorganisms indirectly. It is conducive to the metabolic activities of soil microorganisms. Studies indicate that the addition of biochar to soil can promote the nutrient absorption of peach trees. The modified biochar of wheat straw charcoal and Chinese fir charcoal can significantly increase the nutrient content of leaves and fruits in some growth periods of yellow peach.[68]

3.2.2. Changes in Microbial Enzyme Activity. Soil enzymes are secreted by animals, plants, and microorganisms or decomposed by residues and participate in various biochemical reactions in soil, which reflects the active degree of biochemical reactions in soil, soil quality, and nutrient cycling state. Biochar can significantly affect the activities of many enzymes and microorganisms involved in the cycling of carbon, nitrogen, phosphorus, and other nutrients in soil. Because biochar has water and heat retention properties, it can provide more favorable hydrothermal conditions for biochemical reactions. The air in the pores provides sufficient oxygen for the aerobic reaction, thus inhibiting the anaerobic reaction. The adsorption of biochar on the reaction substrate is convenient for enzyme binding and enzymatic reaction, thus improving the enzyme activity.[69] Studies show that rice straw biochar, wheat straw biochar, and *Cunninghamia lanceolata* biochar could promote soil carbon, nitrogen, and phosphorus cycling, which was beneficial to soil fertility and enzyme activities. The best effect was achieved when wheat straw biochar was applied at 20 tons per hectare.[70]

3.2.3. Changes in Microbial Community Structure and Biodiversity. It has been found that biochar treatment can significantly increase the soil fungal abundance and diversity index and change the fungal community structure by improving the physical and chemical properties of soil.[71] Experiments have shown that the addition of biochar to soil can affect the nitrogen cycle by changing the community structure of ammonia-oxidizing bacteria. The abundance of ammonia-oxidizing bacteria increased significantly, and the growth of ammonia-oxidizing archaea was inhibited after adding alkaline rice straw biochar to acidic soil. The effect of biochar on ammonia-oxidizing bacteria and ammonia-oxidizing archaea promoted nitrosation, directly or indirectly promoted nitrogen cycling in soil, and reduced nitrous oxide emissions.[72]

In addition, the addition of biochar to soil can affect the carbon and phosphorus cycles by changing the structure of the soil microbial communities. Biochar can promote the growth of phosphorus solubilizing bacteria, facilitate the transformation of insoluble phosphorus into soluble phosphorus in soil, and increase the available phosphorus content in soil. By an increase in the number of bacteria that can act on the refractory carbon compounds, the soil carbon flux is regulated and the decomposition of various carbon compounds into soil

https://doi.org/10.1021/acsomega.4c10533
ACS Omega 2025, 10, 9854−9868

microbial carbon sources is promoted. Biochar can affect the bioavailability of inorganic phosphorus by promoting the growth of *Sporangium* and *Bacteriaceae* microorganisms. Therefore, changing the number and community structure of different functional microorganisms in soil is one of the important mechanisms by which biochar affects soil carbon, nitrogen and phosphorus cycles.[73] A research found that rice stalk biochar can improve the diversity of bacterial and fungal communities in soil and increase the abundance of dominant groups through experiments.[74] The functional strains mainly include *Bacillus*, *Streptomyces*, *Aspergillus*, *Actinomycetes*, *Methanogenus*, etc. The functions of these strains are shown in Table 4.[75]

Table 4. Effects of Soil Functional Bacteria

Soil Functional Bacteria	Effects
Bacillus	Participate in the decomposition of organic matter and nutrient cycling to maintain the stability of soil ecosystems
Streptomyces	Participate in the decomposition of organic matter and nutrient cycling, and protects plants from pathogens by producing antibiotics
Aspergillus	Decompose organic matter, promote nutrient circulation, and produce beneficial metabolites to promote plant growth
Actinomycetes	Participate in the decomposition of organic matter and nutrient cycle, produce a variety of bioactive secondary metabolites, maintain soil ecological balance and normal plant growth
Methanogenus	Participate in methane biosynthesis and plays a major role in soil carbon cycle and global climate change

4. APPLICATION OF BIOCHAR IN AGRICULTURE

4.1. Application of Biochar in Pollutant Removal from Soil. *4.1.1. Application in Saline-Alkali Soil Improvement.* In the process of saline-alkali land improvement, many studies have considered the integrated application of biochar and other soil amendments. Biochar is a highly effective soil modifier. The combination of biochar and other modifiers such as organic fertilizer, lime, and gypsum can improve the physical, chemical, and biological properties of soil more comprehensively. The combination of biochar and organic fertilizer not only improves soil nutrient level, but also increases soil organic matter content, thus improving soil structure and increasing soil biodiversity.[76] The pore structure of biochar can improve the utilization rate of nutrients in organic fertilizer and reduce the loss of nutrients. In addition, biochar combined with lime or gypsum can raise the pH of the soil, and the adsorption properties of biochar also help reduce the accumulation of salt that may be caused by these inorganic amendments, thus making the soil environment more suitable for plant growth.[77]

For specific saline-alkali soil characteristics, tests can be conducted to determine the best ratio of biochar and other amendments as well as the depth and frequency of application. The rational proportion and application of biochar and other amendments can improve the physical and chemical properties and biological activity of soil, thus helping to restore and enhance the agricultural productivity and ecological function of saline-alkali land.[78]

A research has found that acidified palm fruit branch biochar application has significant long-term benefits in improving soil structure and hydrothermal properties through a three-year cotton field experiment, which can solve the problem of saline-alkali soil improvement. Biochar application can increase sand content in the range of 1.6−8.4% and increase the water holding capacity in the range of 6.5−16.7%. The optimal biochar application range was 15−20 tons per hectare under sufficient irrigation, while the optimal range was 20−25 tons per hectare under low irrigation.[79] A research used Alterniflora root to make biochar and carried out a pot experiment with mixed microbial agent. It was found that soil salt content was decreased by 45.49%, soil enzyme activity was increased by 20%, and soil organic matter content was increased by 40%.[80] A research used corn stalk biochar and coastal saline soil to carry out pot experiment, and found that the biomass of root and tip of licorice increased by 80% and 41% respectively.[81] A research used straw stalk biochar and coastal saline soil to carry out pot experiment, and found that rice yield was increased by 9.65% and soil available phosphorus content was increased in the range of 21−110%.[82] Therefore, biochar has a significant effect on saline-alkali soil improvement.

4.1.2. Application in Heavy Metal Removal from Soil. The current study showed that adding biochar to soil can reduce the activity of heavy metal ions in soil and reduce the enrichment effect of heavy metal ions in crops, thereby improving soil quality and crop quality.[83] Mechanisms include the following points. First, the surface negative charge of biochar produces electrostatic adsorption of heavy metal cations. Second, the large surface area and rich functional groups of biochar are beneficial to its adsorption of heavy metals. Third, ash and heavy metal ions in biochar form precipitation.[84]

Nowadays, there are many experiments to study the effect of biochar on soil heavy metal pollution. The addition of wheat straw biochar to paddy fields effectively fixed the heavy metal cadmium, reduced the cadmium content in rice plants, and showed a better growth trend of rice.[85] Adding peanut shell biochar to soil can significantly increase the content of soil organic matter, and the content of soil alkali-hydrolyzed nitrogen, available phosphorus and available potassium.[86] At the same time, the activities of urease, phosphatase, catalase, and sucrase in soil and the number of bacteria, actinomyces, and fungi in soil increased significantly, which reduced the availability of chromium in soil.[87] The preparation of iron-modified sepiolite and iron−manganese modified sepiolite with sepiolite as matrix material can both reduce the bioavailability of cadmium in soil, and with the increase of the amount of biochar, it has the effect of simultaneously passivating cadmium and arsenic in soil, which reduces the bioavailability of manganese, zinc, and copper in soil.[88] The combined addition of bagasse biochar and other substances to soil can reduce the mobility of trivalent chromium and tetravalent chromium, reduce the concentration of bioavailable cadmium in soil and reduce the absorption of trivalent chromium and tetravalent chromium by corn.[89] A research used bagasse biochar and soil to carry out an experiment on a farm in Guangdong Province, and found that cadmium was decreased by 62−76%, lead was decreased by 17.3−49.1% and copper was decreased by 15−38%.[90] A research use English broadleaf hardwood to make biochar, and found that the concentration of nickel and zinc in the soil decreased by 83−98% in three years.[91] A research used oak biochar and soil to carry out an experiment, and found that the content of acid-soluble cadmium was reduced from 80% to 69% and the content of acid-soluble zinc was reduced from 21% to 19%.[92]

4.1.3. Application in Organic Pesticide Removal. Studies have shown that the synergistic enhancement effect of biochar

https://doi.org/10.1021/acsomega.4c10533
ACS Omega 2025, 10, 9854−9868

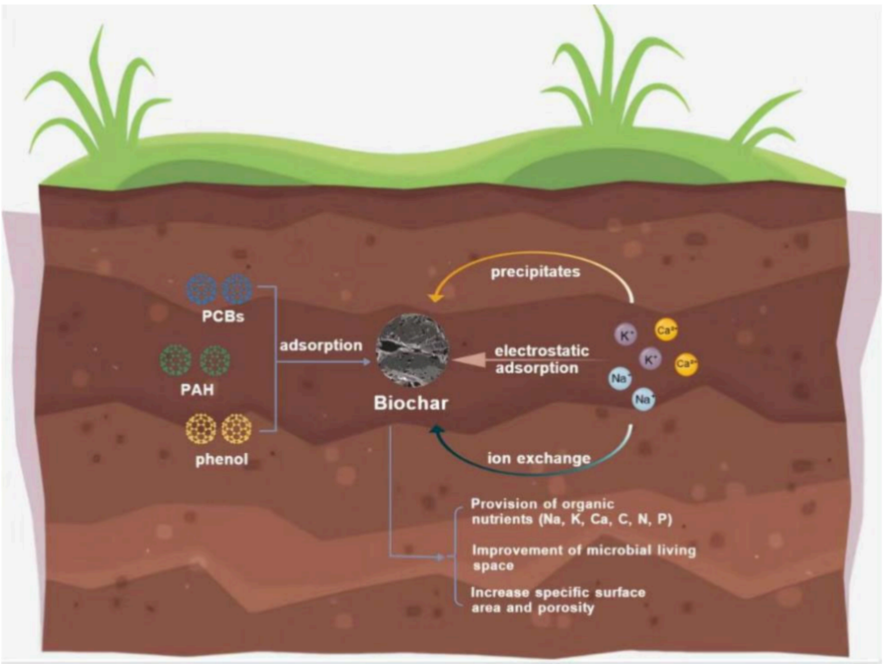

Figure 3. Diagram of the mechanism of biochar modification of contaminated soil.

and other materials can effectively remove organic pollutants such as polychlorinated biphenyls, polycyclic aromatic hydrocarbons, and phenols in soil. Iron modified biochar has a good adsorption effect on benzene and chlorobenzene, and it can completely remove benzene and chlorobenzene under neutral and acidic conditions.[93] The removal rate of tetracycline was 94.72% when modified biogas residue biochar was added to soil under acidic condition.[94] Under the neutral condition, 2.60 mmol of persulfate per liter was used, and zerovalent iron and biochar with a mass ratio of 3:1 were added. Finally, the removal rate of phenol was 89%. The adsorption effect of titanium-alkali-modified biochar was better than that of original biochar, and the removal rate of enrofloxacin reached 77.14%. The removal mechanisms of organic pollutants include physical adsorption, electrostatic interaction, $\pi-\pi$ interaction, Fenton oxidation, and photocatalytic degradation, which varies by biochar species.[95]

A study compared the effects of peanut shell biochar to those of modified biochar. Peanut shell contains a large number of organic compounds, including lignin, cellulose and protein, so peanut shell biochar shows a higher adsorption affinity for atrazine produced by organic pesticides, and modified biochar has a higher surface area and more aromatic structure, which can improve the adsorption capacity of biochar for pollutants.[96] In addition, the addition of biochar is conducive to the growth of microorganisms in the soil, enhance the metabolic capacity of microorganisms and indirectly promote the degradation of atrazine.[97] The improvement mechanism of biochar on contaminated soil is shown in Figure 3.

4.2. Application of Biochar in Crop Production.

4.2.1. Effects of Biochar on Crop Growth. In addition to removing soil pollutants, improving soil physical and chemical properties and structure, and changing soil microbial community structure and biodiversity, biochar can also increase crop yields. Many studies can prove this fact. When biochar is added to carrot soil, it significantly increases the fresh weight and height of seedlings.[98] When planting tomatoes, the use of different ratios of biochar increased the stem diameter, plant height and dry matter weight of tomato plants, the seedling strength index, root-shoot ratio and root activity, the number of leaves, the axial length of leaves at different leaf positions and the leaf area also increased.[99] When cultivating double-cropping rice, the addition of biochar increased the effective panicle number, grain number per panicle and seed setting rate.[100]

Some studies have also noted that biochar plays an incomplete role in promoting the growth of some crops. When cultivating soybean, the inhibitory effect on soybean growth and development in the early stage decreased gradually with time but the addition of biochar increased the dry matter weight of soybean, thus enhancing the inhibitory effect on soybean growth. The addition of biochar inhibited the early growth of maize, but the inhibitory effect was weakened slowly with the passage of growth time, and biochar was beneficial to the later development of maize.[101]

4.2.2. Effects of Biochar on Photosynthesis. Photosynthesis is essential for nutrient absorption and crop growth. Many studies indicate that the addition of biochar to soil is beneficial for the photosynthesis of crops. The increase of biochar increased the net photosynthetic rate, stomatal conductance, and transpiration rate of tomato, thus promoting the photosynthesis of tomato.[102] The increase of biochar increased the net photosynthetic rate, transpiration rate and stomatal conductance of eggplant, and increased the photosynthesis of eggplant.[100] The photosynthetic potential and maximum net photosynthetic rate of winter wheat at flowering and filling stages were improved by adding proper amount of biochar, but the photosynthetic performance of winter wheat at flowering and filling stages was decreased by adding excessive amount of biochar.[103] A research found that a biochar application rate of 24 tons per hectare increased soil available nitrogen, net photosynthetic rate of leaves, and relative chlorophyll values compared to the controlled trial. It also increased total root length, root surface area, root volume and root bleeding sap by

https://doi.org/10.1021/acsomega.4c10533
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8.5−29.9%, 13.5−18.5%, 0.8−12.1%, and 27.6−45.9% respectively.[104]

4.2.3. Effects of Biochar on Crop Quality. At present, it has been found that biochar based fertilizers can improve soil bioenzyme activity, which is conducive to the improvement of soil fertility and crop quality. When planting lettuce, adding biochar to the soil can reduce nitrate content, increase vitamin C and soluble sugar content, thereby improving the quality of endive plants.[105] When planting kiwifruit, biochar, and organic fertilizer mixed into soil can significantly increase the contents of soluble solid, soluble sugar, soluble protein, vitamin C, and sugar-acid ratio of fruit and significantly reduce the titrable acid content, so as to improve the quality of kiwifruit.[106] When planting rapeseed, biochar and reduced fertilizer mixed into soil can significantly inhibit erucic acid, glucoside and linolenic acid, promote the increase of oleic acid content and yellow seed degree, and thus improve the quality of rapeseed.[107]

4.2.4. Effects of Biochar on Crop Yield. Several studies have reported a positive correlation between the biochar application and crop yield. Biochar could significantly increase maize yield, which increased with the increase in the amount of biochar added.[108] In the greenhouse, adding 5% biochar to the soil where cucumbers were planted for 6 years and 10 years could increase fruit yield and reduce the growth barrier of cucumbers caused by continuous cropping.[109] Under the condition of reasonable reduction of nitrogen fertilizer and reasonable addition of biochar, rice yield was significantly increased compared with that under the condition of no treatment.[110] A research used sunflower stalk biochar to carry out field experiment, and found that soil nutrient availability and redox enzyme activity were both improved, and crop yields were increased by 300%.[111] A research used cotton hull to carry out houseplant experiment, and found that the yield of quinoa and seeds increased by 51%.[112] A research found that the crop yield increased by 50.09% after adding corn stover biochar to the soil.[113]

4.2.5. Other Applications of Biochar in Agriculture. Biochar offers following additional benefits in agriculture. First, biochar is beneficial for reducing straw burning. At present, some studies have found that the way of heat treatment of straw into biochar in the field before returning it to the field can not only reduce the phenomenon of straw burning but also effectively improve the quality of cultivated land and soil fertility, thus promoting the growth of crops.[114]

Second, biochar is beneficial for reducing the use of chemical fertilizers. Biochar can effectively improve the water retention of soil and delay the release of water-soluble fertilizers in soil, thus prolonging the validity period of nutrients, enabling crops to fully absorb nutrients and improving the utilization rate of fertilizers.[115]

Third, biochar is beneficial for reducing carbon emissions from production. Some research data show that carbon emissions caused by excessive fertilizer application in China account for a large proportion of agricultural carbon emissions. Adding biochar to soil can inhibit the decomposition and mineralization of soil organic matter, thus reducing the carbon dioxide emission in soil.[116] In addition, biochar can reduce greenhouse gas emissions, such as methane and nitrous oxide, in soil.

5. CONCLUSION AND PROSPECTS

Given the limitations of traditional techniques for treating soil pollution, such as secondary pollution, soil structure damage, high costs, and poor efficacy, this study opted to use biochar for soil treatment. The development of biochar preparation methods has progressed from early gasification and pyrolysis to modern hydrothermal carbonization. To improve biochar's efficiency in soil remediation, activation and modification techniques have been developed. The modification methods of biochar mainly include metal modification, organic modification, acid−base modification, microwave modification, high temperature heat treatment modification, and hydrothermal modification.

Due to the large specific surface area and developed pore structure of biochar, the addition of biochar to soil can effectively reduce the bulk density and density of soil and improve the porosity and specific surface area of soil, which enhances the air permeability and water retention of soil. Biochar also contains rich functional groups and soluble cations, so adding biochar to soil can enhance soil pH value, increase soil cation exchange capacity, and reduce soil conductivity. At the same time, it enriches organic matter and carbon content, thus providing nutrients for the growth of microorganisms. In addition, the addition of biochar in soil increases enzyme activity and improves soil community structure and biodiversity. Therefore, it is beneficial to the metabolic activities of soil microorganisms.

Biochar is widely used in agriculture. Combined with other soil amendments, biochar can improve the physical and chemical properties of saline-alkali soils and enhance soil activity, contributing to the reclamation of degraded lands. Its ability to adsorb heavy metal ions and reduce their bioavailability makes biochar an effective tool for heavy metal remediation. Biochar's synergistic effect with other materials helps eliminate organic pesticide pollution in soils. The addition of appropriate amounts of biochar is conducive to the photosynthesis of crops, thus improving crop quality and yield. It is also conducive to reducing straw burning, fertilizer use, and carbon emissions in agricultural production.

Despite the promising potential of biochar in soil improvement and crop production, several issues remain unresolved:

- First, a unified standard for biochar production is needed to clarify the characteristics of biochar produced by different raw materials under different pyrolysis conditions, so as to accurately predict the role and effect of biochar in the soil environment.
- Second, current biochar research is mainly conducted in laboratories. Field trials are required to determine its effectiveness in real-world agricultural and soil remediation applications.
- Third, biochar can exist in soil for a long time, so it is necessary to further study the ecotoxicological mechanism of biochar in order to avoid the potential ecological risks caused by the addition of biochar, such as ammonia volatilization, soil carbon to nitrogen ratio imbalance, and the release of toxic substances in biochar.
- Fourth, further research should focus on enhancing the interaction between biochar and various biological resources.
- Fifth, it is necessary to develop new biochar products. Not only is it beneficial to the ecological network composed of soil, plants and microorganisms, but also it can stimulate the positive effect of microorganisms, so that the cultivated soil and agricultural ecology can develop sustainably.

https://doi.org/10.1021/acsomega.4c10533
ACS Omega 2025, 10, 9854−9868

- Sixth, future studies should address biochar postusage treatment and recycling methods to recover used biochar efficiently.
- Seventh, it is necessary to optimize the temperature and time during biochar production, modification, and regeneration process to reduce energy consumption. Additionally, it is necessary to develop technologies for harvesting the resulting bio-oil and syngas, and to develop new methods for regenerating biochar to save costs, energy and ensure the regeneration performance and stability of biochar.
- Eighth, when adopting the method of chemical modification of biochar, it is essential to identify economic and environmentally friendly agents to control costs and minimize pollution risks. The research of biochar modified by green economic reagents should be strengthened.

In addition, future research should prioritize the functional modification and application optimization of biochar to fully realize its potential in soil remediation and sustainable agricultural development. At the same time, the long-term environmental impact and ecological safety of biochar should be evaluated.

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Funding

The authors are grateful for the support from Linking increase and decrease and Monitoring and Evaluation of planning Permission (Research on Updating the Policy of Linking increase and Decrease of Urban and rural Construction Land in Shandong Province and Tracking Guarantee), Natural Science Foundation of Shandong Province (ZR2024QD059), Key Research and Development Project of Shandong (2020CXGCO11404), Innovation found for Jinan high-education's 20 policies (202228056), Taishan Scholars Project.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors would like to thank all the anonymous referees for their constructive comments and suggestions.

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https://doi.org/10.1021/acsomega.4c10533
ACS Omega 2025, 10, 9854−9868