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Biochar-Based Fertilizers: Advancements, Applications, and Future Directions in Sustainable Agriculture—A Review

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Abstract: Amid escalating global demands for both enhanced agricultural productivity and environmental sustainability, biochar-based fertilizers have emerged as a promising solution in modern agriculture. These fertilizers, made from biochar derived from agricultural residues, have shown considerable potential in improving soil quality, enhancing nutrient release dynamics, and reducing greenhouse gas emissions. This review systematically examines the production technologies, application strategies, and potential environmental and agronomic benefits of biochar-based fertilizers. Studies highlight their ability to improve soil structure, increase soil organic matter, and boost nutrient utilization efficiency, which contribute to higher crop yields and better crop quality. Moreover, biochar-based fertilizers have demonstrated notable environmental advantages, such as reducing the emissions of methane (CH_4) and nitrous oxide (N_2O), while promoting sustainable resource recycling. However, challenges such as production costs, variability in efficacy across different soil types, and the need for further optimization in formulation and application remain. Future research should focus on improving production efficiency, optimizing biochar-based fertilizer formulations, and conducting long-term field trials to validate their ecological and agronomic performance. This review provides valuable insights for researchers, policymakers, and practitioners, offering a comprehensive theoretical framework for the integration of biochar-based fertilizers into sustainable agricultural practices.

Keywords: biochar-based fertilizer; sustainable agriculture; greenhouse gas emissions; soil improvement; nutrient release

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1. Introduction

With the persistent growth of the global population, food production faces unprecedented challenges. Aligned with the sustainable development goals targeting hunger eradication, food security, and nutritional improvement [1], agriculture and agri-food systems have become focal points of concern. Modern agriculture heavily relies on chemical fertilizers to enhance crop productivity and ensure food security. However, improper fertilization practices and a lack of scientific guidance have exacerbated soil degradation issues, including soil fertility decline [2], acidification [3,4], nutrient imbalance [5], agricultural product quality decline [6,7], and microbial community dysbiosis [8]. Concurrently, the low efficiency of fertilizer utilization has resulted in resource waste and environmental pollution, necessitating the urgent development of efficient and eco-friendly alternatives.

Biochar, as a soil amendment and fertilizer additive with sustainable development potential [9–11], has attracted widespread attention due to its unique physical and chemical properties. Its application can effectively improve soil quality [12,13], enhance water and nutrient retention [14], promote soil carbon sequestration [15–17], reduce greenhouse gas emissions [18], stimulate plant growth, improve both crop yield and quality [19,20], and reduce soil heavy metal toxicity [21]. However, the effects of biochar are not always consistent, and different crops may respond differently [22,23]. This variability primarily arises from the diverse feedstocks used for biochar production, which lead to significant differences in the physical structure and nutrient composition of the resulting biochar, potentially failing to meet the specific needs of various crops. In addition, biochar's high nutrient adsorption capacity can sometimes limit nutrient availability [24–26]. Moreover, biochar may carry heavy metals that adversely affect plant growth [27]. Therefore, the production and application of biochar may need to meet certain criteria, such as a high mechanical strength [28], a large surface area [29], a well-developed pore structure [30], and a high nutrient content [31], to ensure its effectiveness as a soil amendment.

Despite these demonstrated benefits, the actual adoption of biochar in modern agriculture remains minimal. In large-scale farming systems, biochar use is close to zero. Several critical barriers hinder its widespread application. These include high production and transportation costs, the lack of uniform standards in biochar quality and application rates, and insufficient long-term field validation. In addition, low farmer awareness and inadequate government incentives further limit its practical utility. In recent years, many studies have focused on the development of biochar to overcome its limitations in agricultural applications. To address these challenges, various techniques have emerged, notably the production of biochar-based fertilizer, which offers a novel approach to optimize biochar properties and enhance its nutritional benefits. Biochar-based fertilizer can be produced either by the direct pyrolysis of nutrient-rich feedstocks or by nutrient enrichment before or after pyrolysis. As a novel fertilizer, biochar-based fertilizer has proven effective in overcoming the limitations of conventional biochar, such as its low mineral nutrient content [32], unstable performance [33], unclear long-term effects, and potential for the presence of harmful substances [34]. Compared to biochar, biochar-based fertilizer possesses superior physicochemical properties. Its application not only improves soil texture and enhances the soil's water and nutrient retention capacity, but also promotes crop growth [35–37] and reduces the use of chemical fertilizers. In addition, biochar-based fertilizer can neutralize soil acidity by releasing alkaline elements [38].

In summary, biochar-based fertilizers hold promise in addressing soil quality degradation and environmental pollution resulting from the overuse of chemical fertilizers. This review systematically summarizes the preparation methods, working mechanisms, and application effects of biochar-based fertilizers in agricultural ecosystems, with a focus on their compatibility with different soil types, nutrient release behavior, and environmental benefits. By combining the results from field experiments and mechanistic studies, this review aims to provide a theoretical basis for the targeted use of biochar-based fertilizers, and to highlight future research directions, including the development of cost-effective production techniques and multi-level environmental impact assessments. The central hypothesis of this review is that biochar-based fertilizers, when properly matched to soil and crop conditions, can be more effective than traditional fertilizers at improving nutrient use efficiency and lowering negative environmental impacts. The structure of this review is therefore designed to critically examine both the scientific foundation and practical challenges of biochar-based fertilizers in order to support further research and promote real-world applications.

2. The Concept, Classification, and Preparation Methods of Biochar-Based Fertilizers

2.1. Concept and Classification of Biochar-Based Fertilizers

Biochar-based fertilizer is a functional fertilizer in which biochar serves as the carrier to load nutrients such as nitrogen, phosphorus, and potassium through physical or chemical methods. According to the source and composition of the nutrients, biochar-based fertilizers can be mainly divided into three categories:

Biochar-based organic fertilizer: These are composed of biochar combined with organic materials from plants and animals (e.g., straw, rapeseed residue, kitchen waste, animal manure) [39,40].

Biochar-based inorganic fertilizer: These are prepared by integrating biochar with chemical fertilizers (e.g., urea, diammonium phosphate, potassium chloride) [41].

Biochar-based organic-inorganic compound fertilizer: These composite fertilizers incorporate both organic and inorganic components [42].

Furthermore, based on the nutrient type, biochar-based fertilizers can be further subdivided into the following:

Biochar-based nitrogen fertilizer: Composed of biochar mixed with chemical nitrogen fertilizers (e.g., ammonium nitrate, urea) [43].

Biochar-based phosphorus fertilizer: Prepared by combining biochar with chemical phosphorus fertilizers (e.g., monoammonium phosphate) [44].

Biochar-based potassium fertilizer: Produced by mixing biochar with chemical potassium fertilizers (e.g., potassium chloride, potassium sulfate) [45].

Biochar-based compound fertilizer: Composite fertilizers containing two or more nutrients [46].

In order to further enhance the functional properties of biochar-based fertilizers, researchers have employed various modification techniques to optimize their performance. For example, modification has been used to enhance the adsorption capacity [47], microbial inoculants have been added to increase the abundance of beneficial microorganisms in soil [48], and nanomaterials have been introduced to reduced nutrient loss [49] (Figure 1). These strategies not only significantly improve the slow-release efficiency of the fertilizers but also enhance crop resistance, providing important technical support for the development of precision agriculture.

2.2. Preparation Methods of Biochar-Based Fertilizer

The preparation method of biochar-based fertilizer is a key factor determining its performance and application efficiency. Typically, biochar-based fertilizer is produced by carbonizing biomass and then combining it with other fertilizer components (such as nitrogen, phosphorus, and potassium) using various processing techniques. Depending on the raw material source, preparation process, and fertilizer composition, the methods for producing biochar-based fertilizer exhibit significant diversity. The main preparation methods currently include co-pyrolysis [50], in situ pyrolysis [51], impregnation [52], granulation [53], and coating [54]. The specific preparation processes and characteristics of each method are described below (Figure 2).

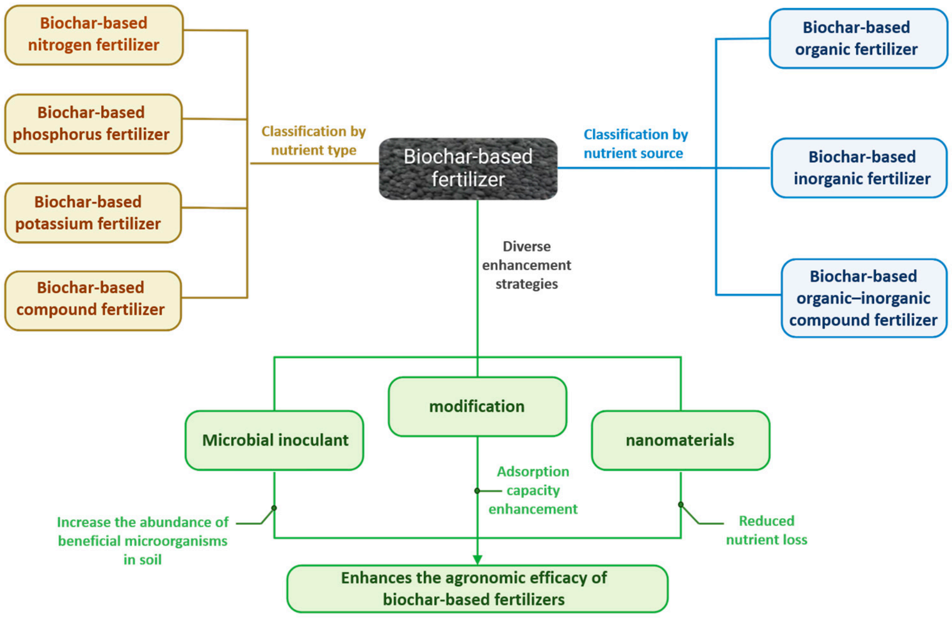

Figure 1. Classification of biochar-based fertilizers (Source: Authors' own work).

2.2.1. Co-Pyrolysis Method

The co-pyrolysis method synthesizes biochar [55,56] directly by the simultaneous pyrolysis of biomass and fertilizers or mineral additives. First, biomass materials (such as straw and animal manure) are mixed with fertilizers (such as urea and phosphate) in a specific ratio. The mixture is then subjected to pyrolysis under high-temperature and oxygen-limited conditions. After pyrolysis, the product is cooled, collected, and further processed through crushing, sieving, or granulation to form biochar-based fertilizer. This method enhances nutrient fixation during pyrolysis, significantly improving the stability and availability of fertilizer nutrients. The co-pyrolysis method is based on high-temperature carbonization technology, and its cost is primarily driven by factors such as investment in carbonization equipment (e.g., traditional carbonization kilns or pyrolysis furnaces), high energy consumption (requiring temperatures between 300 and 700 °C), fertilizer costs, equipment depreciation, and exhaust gas treatment expenses. Although the raw material costs are relatively low, the overall cost tends to be higher. The core advantage lies in the efficient synergy between biochar and fertilizer, leading to enhanced effects. Its application scenarios include the cultivation of degraded soils and economic crops [50,56,57].

2.2.2. In Situ Pyrolysis Method

The in situ pyrolysis method converts biomass into biochar directly in the soil or field environment while integrating fertilizer application. This process involves spreading biomass materials in the field, applying localized pyrolysis techniques to partially carbonize them, and simultaneously adding fertilizers. Subsequently, tillage is performed to ensure the uniform mixing of biochar with the soil. This method effectively reduces transportation and processing costs, making it particularly suitable for large-scale farmland improvement. The in situ pyrolysis method directly pyrolyzes biomass in the field, reducing transportation costs. Although its cost structure still needs to account for expenses such as equipment depreciation, energy consumption, environmental impact control, and fertilizer costs, the overall cost remains low. The core advantage is its ability to perform on-site conversion. Its application scenarios include soils that require straw return or those facing crop rotation barriers [51,58,59].

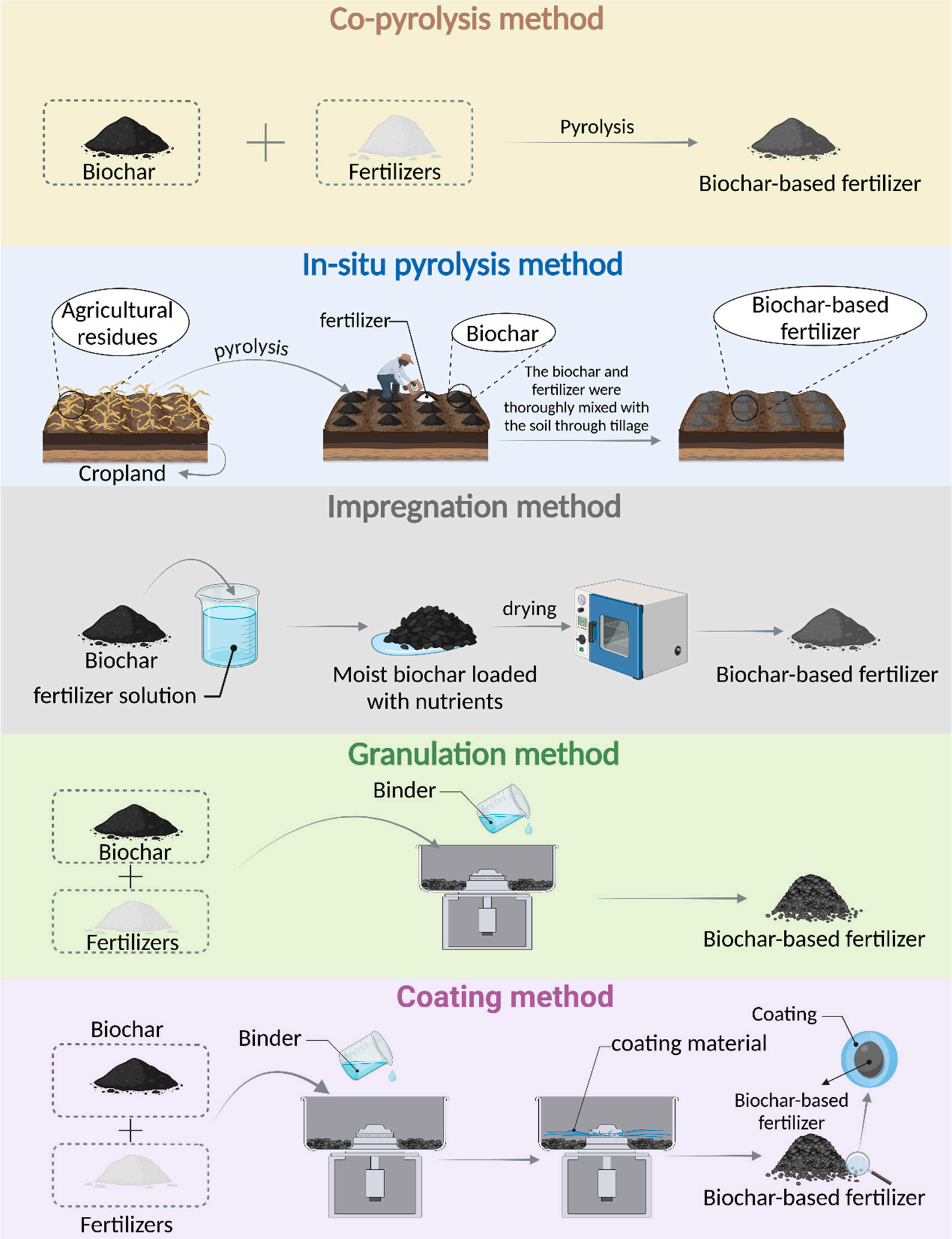

Figure 2. Preparation methods of biochar-based fertilizer (Source: Authors' own work).

2.2.3. Impregnation Method

The impregnation method utilizes the pore structure of biochar to load nutrients through adsorption or ion exchange into a solution. First, biochar is prepared and soaked in a pre-made fertilizer solution to allow it to adsorb nutrients. After a certain soaking period, the biochar is removed and dried, resulting in a biochar-based fertilizer with evenly distributed nutrients. This method allows for the flexible adjustment of nutrient composition according to different soil requirements, significantly improving fertilizer efficiency. The impregnation method requires chemical reagents (such as acid–base or salt solutions) and fertilizer solutions (e.g., nitrogen, phosphorus, and potassium solutions) for modification. Its cost is primarily derived from the procurement of reagents and fertilizers, solution recovery and treatment, energy consumption, and chemical storage management, with an overall low cost. The core advantage lies in the ability to easily and flexibly adjust the nutrient content of the fertilizer. Its application scenarios include leafy vegetables and situations requiring rapid nutrient supplementation [60–62].

2.2.4. Granulation Method

The granulation method improves the uniformity and flowability of biochar-based fertilizers through mechanical granulation processes. First, biochar powder is mixed with fertilizer raw materials, and an appropriate amount of binder (such as lignin or acetate) is added to enhance the particle stability. The granules are then prepared using drum granulation or extrusion granulation techniques. After granulation, the particles are dried, sieved, and packaged to produce a product suitable for mechanical fertilization. The granulation method involves additional mechanical processing steps. The main costs include investment in the granulation equipment (e.g., extrusion granulator or drum granulator), the equipment's energy consumption, the use of binders or additives (such as bentonite or sodium carboxymethyl cellulose), and fertilizer costs, resulting in a moderate overall cost. The core advantage lies in the more uniform and stable nutrient release. Its application scenarios include field crops and well-established orchards [41,53,63–65].

2.2.5. Coating Method

The coating method improves the sustained release of nutrients and fertilizer efficiency by applying a layer of controlled-release material on the surface of biochar-based fertilizer. First, biochar-based fertilizer granules are prepared and placed in a rotating coating device, where a coating material (such as sodium alginate or biopolymer) is sprayed onto the particles. The granules are then cured and dried to form a uniform coating layer. This method effectively controls the nutrient release rate, reduces nutrient loss, and significantly improves fertilizer efficiency. The coating method incurs costs for coating materials (such as polyvinyl alcohol, nano-iron oxide modifiers, etc.), precision coating equipment investment (e.g., drum coater), equipment energy consumption, and fertilizer costs. Although it offers excellent slow-release performance, the overall cost is high. The core advantage lies in its ability to meet the nutrient needs of different crops and improve nutrient utilization efficiency. Its application scenarios include high-value crops that require precise control over nutrient release [66–69].

Different biochar-based fertilizer preparation methods have significant differences in process flow and applicable scope, and the choice can be made based on the nutrient characteristics and application requirements of the target product. The core advantages and applicable scenarios of each method are shown in Table 1.

Table 1. Key characteristics and applicable scenarios of different biochar-based fertilizer preparation methods.

Method	Production Cost	Core Advantages	Applicable Scenarios
In situ pyrolysis method	low	on-site conversion	straw return to the field, continuous cropping obstacles
Impregnation method	low	flexible nutrient adjustment	fast-acting fertilization, applied to leafy vegetables
Granulation method	medium	uniform and stable nutrient distribution	field crops, orchards
Co-pyrolysis method	medium to high	synergistic retention of carbon and nutrients	degraded soils, economic crops
Coating method	high	high nutrient efficiency and nutrients released according to plant needs	high-value crops, precision agriculture

2.3. Life Cycle Assessment of Biochar-Based Fertilizer

The biochar required for the preparation of biochar-based fertilizers is typically produced from agricultural waste, such as straw and animal manure [70,71], through technologies like pyrolysis [72]. This not only achieves the resource utilization of waste but also reduces the environmental burden of waste disposal and is cost-effective.

During the production of biochar, biomass needs to be converted into biochar using high-temperature carbonization technology [73]. This pyrolysis process requires temperatures between 300 °C and 700 °C, which results in significant energy consumption and some greenhouse gas emissions (e.g., CO_2, CH_4). However, some of the flammable gases produced can be used as energy substitutes (e.g., for power generation and heating), indirectly reducing carbon emissions. If biomass is to decompose naturally or be directly burned, the carbon within will be rapidly released into the atmosphere in the form of CO_2 or CH_4. In contrast, when biomass is pyrolyzed into biochar, part of the carbon is stably fixed in the biochar, which has a high aromaticity and structural stability [74]. The process of combining biochar with mineral fertilizers (such as impregnation, coating, and granulation) requires certain economic investments (e.g., chemicals, equipment, and fertilizer costs).

After biochar-based fertilizers are applied to the soil, they can improve the soil's physical and chemical properties and microbial communities, reduce nitrogen leaching and greenhouse gas emissions, and thus enhance crop yield and quality [75]. Due to its excellent slow-release properties, biochar-based fertilizer can be applied once to the soil, reducing the cost of multiple fertilizer applications and labor, while also improving nutrient utilization efficiency [76].

Biochar-based fertilizers exhibit a low carbon footprint and pollution emissions throughout their life cycle and also have soil improvement effects, offering significant environmental benefits. The use of agricultural waste to produce biochar achieves the high-value utilization of waste, aligning with the principles of a circular economy.

However, there are limited LCA research data on biochar-based fertilizers, with a particular lack of systematic data on the environmental impacts of different raw materials and production processes. Although biochar-based fertilizer offers environmental benefits, its production is economically costly.

3. The Important Role of Biochar-Based Fertilizers in Agriculture

The effects of biochar-based fertilizers on soil's physicochemical properties and their application potential in agricultural ecosystems are gaining focus. As a functional fertilizer with biochar as the carrier, biochar-based fertilizers demonstrate significant potential in improving crop yield and quality [77,78], enhancing soil physical properties [79], optimizing soil chemical properties [75], and boosting soil biological activity [80,81]. A systematic analysis of the effects of biochar-based fertilizers on key physicochemical properties such as soil pH, soil structure, water retention capacity, and organic matter content can reveal the mechanisms behind their role in soil improvement. Additionally, exploring the application methods of biochar-based fertilizers and their potential environmental benefits can provide theoretical and technical support for promoting the sustainable development of agricultural production.

3.1. The Impact of Biochar-Based Fertilizers on Soil Chemical Properties

Biochar-based fertilizers significantly improve soil chemical properties through various mechanisms (Figure 3). First, biochar-based fertilizers are rich in plant nutrients such as nitrogen, phosphorus, and potassium [82]. After application, they can significantly increase the content of available nitrogen, phosphorus, and potassium in the soil [83], and effectively enhance soil fertility by balancing nutrient levels [58]. Additionally, biochar-based fertilizers have a notable effect on soil pH regulation [84]. On one hand, the alkaline biochar added during the production process can directly neutralize soil acidity [85]; on the other hand, the biochar in biochar-based fertilizers can alleviate soil acidification by adsorbing chloride ions and hydrogen ions through its abundant surface functional groups and porous structure, thereby reducing effective acidity [86]. For example, in wetland soils used for planting cabbage, biochar-based fertilizers made from three different raw materials significantly increased the soil pH [40]. In acidic red soils used for planting maize, biochar-based fertilizers increased the soil pH by up to 0.69 units [87]. However, in the calcareous soils of karst landscapes, biochar-based fertilizers did not significantly increase the soil pH [70]. These findings indicate that the pH-regulating function of biochar-based fertilizers has significant applicability based on soil type, and their use must carefully consider the physicochemical properties of the target soil and the characteristics of the raw materials.

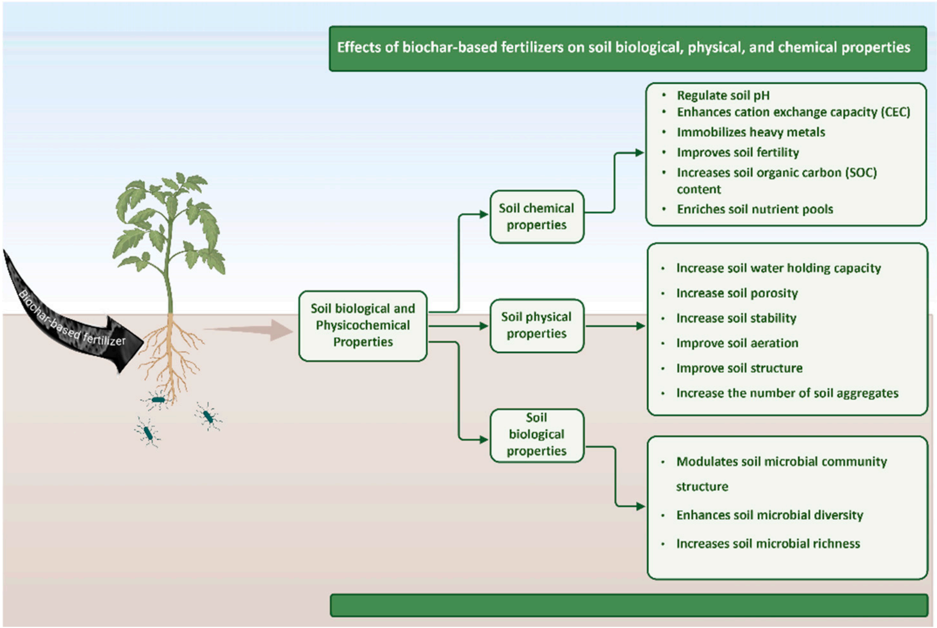

Figure 3. Effect of biochar-based fertilizers on soil's biological and physicochemical properties (Source: Authors' own work).

Soil heavy metal pollution not only damages soil fertility and microbial activity but also inhibits plant growth, thereby affecting crop yield and quality [88–90]. A higher cation exchange capacity (CEC) can enhance the soil's ability to retain heavy metals [91]. Biochars in biochar-based fertilizer, due to the oxygen-containing functional groups on their surfaces, carry abundant negative charges [12], giving them a high CEC [92]. When applied to soils with low cation exchange capacity, they can significantly increase the cation exchange capacity of the soil [93,94]. Studies have shown that biochar-based fertilizers can effectively reduce the bioavailability of heavy metals in rice through adsorption mechanisms [95,96]. For example, in Cd-contaminated paddy fields, biochar-based fertilizer reduced the concentration of available cadmium in the soil during the tillering and maturity stages of rice by 20.8–22.6% and 16.3–19.7%, respectively; simultaneously, the cadmium concentration in the plants decreased by 38.1–42.9% and 26.9–50%, respectively [96]. Meanwhile, in Cd-contaminated red soil used for maize cultivation, biochar-based fertilizer reduced the effective cadmium concentration in the soil by up to 32.84%, and the cadmium content in maize grains decreased by 26.27% [87]. Other research has found that, compared to single biochar, a new biochar-based fertilizer made from rice husk biochar combined with urea and hydrogen peroxide exhibited a 48.98% improvement in cadmium adsorption [63].

These findings indicate that biochar-based fertilizers have significant potential in the remediation of heavy metal-contaminated soils, providing a new strategy for soil pollution management [95].

Due to the slow-release characteristics of biochar-based fertilizers, they extend the residence time of nutrients in the soil and can also promote the accumulation of soil organic matter [97]. As a carbon-rich soil amendment, biochar-based fertilizers can increase the organic carbon content in the soil after application [98]. For example, in a karst area, the application of biochar-based fertilizers increased soil organic matter content by 45–64% [42]; in the yellow–brown soils of tobacco planting areas, biochar-based fertilizers increased the soil organic matter content by 22.37% compared to the original soil [97]; in sandy soils, the application of biochar-based fertilizers increased the soil organic carbon content by 34.34–40.34% [99]. These studies collectively confirm that biochar-based fertilizers can effectively increase soil organic matter and organic carbon content. However, whether they can still improve the organic matter content in clay soils with high organic matter or extremely barren sandy loam soils requires further experimental validation.

3.2. The Impact of Biochar-Based Fertilizers on Soil Physical Properties

After applying biochar-based fertilizer to the soil, it can significantly improve the soil's physical properties through various mechanisms (Figure 3). First, the porous structure of biochar in biochar-based fertilizers [100,101] can effectively increase soil porosity [102], promote the formation of soil aggregates [103], and enhance soil structural stability [104] and aeration [105]. Additionally, biochar-based fertilizers can significantly improve the soil's water retention capacity [106,107], likely due to the hydrophilic functional groups in biochar, which help retain moisture and reduce its loss through infiltration [108]. Furthermore, there is a significant positive correlation between microorganisms such as *Vicinamibacteraceae* and soil aggregate stability [55]. The application of biochar-based fertilizers can alter the abundance of these microorganisms [109], thereby enhancing the stability of soil aggregate stability. The improvement of the soil aggregate structure further enhances the soil's water retention and aeration properties, providing more space for water infiltration and root growth, which in turn optimizes water distribution and root development [110]. However, for certain clayey soils with a high moisture content, the water retention effect of biochar-based fertilizers is limited, and there may even be negative effects such as reduced permeability due to pore blockage. Additionally, improving total water-holding capacity does not necessarily equate to increasing plant-available water (PAW), which is the critical factor for crop productivity. Studies have shown that substantial quantities of biochar may be required to achieve meaningful changes in PAW. Moreover, materials such as clay minerals or organic amendments may provide similar or even superior effects at a lower cost. Therefore, the potential agronomic benefit must be weighed against the costs and compared with alternative water-retention strategies.

The impact of biochar-based fertilizers on soil bulk density remains inconsistent in the current research. Some studies suggest that the application of biochar-based fertilizers may reduce soil bulk density [111,112], while others report the opposite [113]. These discrepancies may be due to several factors, including crop type, soil type, biochar-based fertilizer composition, and nutrient content. Therefore, further systematic studies are needed in the future to clarify the specific mechanisms of biochar-based fertilizers on soil bulk density and the influencing factors.

3.3. The Impact of Biochar-Based Fertilizers on Soil Microorganisms

Soil microorganisms, as the core drivers of soil ecosystem functions, play a critical role in determining soil fertility maintenance and crop productivity. Research has shown that biochar-based fertilizers significantly influence the composition and function of soil microorganisms through multiple pathways (Figure 3). First, the high porosity and large surface area of the biochar in a biochar-based fertilizer provide abundant habitat space for microorganisms, and its surface microenvironment supports the colonization and interaction of various microorganisms [114,115]. Secondly, biochar-based fertilizers can regulate soil microbial activity and metabolite networks by altering the microbial community structure [42,116]. However, it is important to note that pure biochar may inhibit the activity of arbuscular mycorrhizal fungi (AMF) and reduce soil microbial abundance due to the presence of toxic compounds such as polycyclic aromatic hydrocarbons (PAHs). [34,117]. Therefore, combining biochar with fertilizers to form biochar-based fertilizers can mitigate the limitations of single materials and optimize microbial niches through nutrient synergistic effects [75].

Multiple studies have confirmed that biochar-based fertilizers significantly increase the abundance and diversity of soil microbial communities. In a tobacco planting system, the application of biochar-based fertilizers increased the Shannon index, ace index, and Chao index of the soil bacteria by 10.16%, 37.39%, and 38.76%, respectively [97]. In the oilseed rape cultivation system, biochar-based fertilizers enhanced microbial activity, promoting the succession of bacterial communities towards groups with efficient nutrient metabolism and recycling functions [118]. In acidified tea plantations, the application of biochar-based fertilizer was observed to increase the relative abundance of 10 key bacterial genera and 13 fungal genera [81]. Additionally, studies in karst regions have shown that biochar-based fertilizers significantly increased the number of bacterial OTUs as well as the Shannon index, Simpson index, ace index, and Chao index. The reason for these outcomes may be that the biochar in biochar-based fertilizers enhances the modularity of the microbial network in the soil. These pieces of evidence collectively indicate that biochar-based fertilizers can reconstruct the microbial community structure, providing significant support for the stability of the soil micro-ecosystem.

Biochar-based fertilizers not only alter the microbial community composition but also influence soil ecological processes by regulating the expression of functional genes. Metagenomic analyses have shown that in soils treated with biochar-based fertilizers, the abundance of functional genes related to energy metabolism (e.g., ATP synthase genes), nutrient cycling (e.g., ammonia monooxygenase gene, amoA), carbohydrate metabolism (e.g., cellulase gene, celA), and amino acid transport significantly increased [119]. This optimization of the functional gene profile suggests that biochar-based fertilizers can activate the microbial-mediated soil nutrient transformation network, thereby enhancing the ecosystem's service functions.

In summary, biochar-based fertilizers play a key role in soil microbial ecological regulation through multiple mechanisms, including improving microbial habitats, optimizing the community structure, and enhancing functional gene expression. However, although existing research has confirmed the multidimensional regulatory effects of biochar-based fertilizers on soil microbial communities, their long-term ecological impacts still present knowledge gaps. Current evidence mainly comes from short-term experiments, and the sustainability and functional stability of microbial community optimization under long-term applications remain unclear. Two ecological risks that urgently need systematic investigation should be particularly noted: first, the alkaline nature of some biochar-based fertilizers may cause drastic pH fluctuations in acidic agricultural systems, disrupting the microbial community balance; second, biochar-based fertilizers derived from industrial waste may contain heavy metals that could be toxic to microbial communities. Therefore, conducting long-term field trials to evaluate the dynamic effects of different types of biochar-based fertilizers on the microbial community structure and ecological function is crucial for ensuring their safe and efficient application.

3.4. Biochar-Based Fertilizers' Effects on the Growth, Development, Quality, and Yield of Different Crops

In recent years, research on biochar-based fertilizers has deepened, with numerous studies confirming their positive effects on improving soil's physical, chemical, and biological properties, as well as enhancing crop resistance to stress, increasing yields, and improving fruit quality [98,120,121]. Relevant studies show that the widespread use of biochar-based fertilizers in agricultural production brings significant benefits, not only increasing crop yields but also improving crop quality [81]. For example, compared to traditional chemical fertilizers, biochar-based fertilizers notably improved peanut yields [122]. Biochar-based fertilizers significantly enhanced the nitrogen content in maize stems and kernels, as well as the phosphorus content in maize axes and kernels, with a yield increase of 9.2% and the nutrient use efficiency improving by 31.57–54.57% [76]. In a maize–soybean rotation planting system, although biochar-based fertilizer showed a year-on-year increase in soybean yield, it had no impact on maize yield [123]. Whether this difference in results was related to the cropping system requires further experimental validation.

Soil contamination with cadmium severely affects rice growth and quality, and may pose potential health risks. However, research has shown that when the biochar content in biochar-based fertilizers reached a certain level, soil quality improved significantly. Rice growth indicators partially increased, and the bioavailability of cadmium in the soil was effectively reduced, leading to lower cadmium absorption by rice and an improvement in both yield and quality [95]. Compared to chemical compound fertilizers, biochar-based fertilizers not only increased rice yield by 9.2%, but also reduced the cadmium content in rice grains by 79% [124].

In addition to their positive impact on yield and quality in field crop production, biochar-based fertilizers have also shown significant effects in vegetable cultivation. In sugar beet cultivation, biochar-based organic fertilizer not only enhanced crop yield but also significantly improved photosynthetic capacity and increased sugar content in beets [125]. Compared to chemical fertilizers, biochar-based fertilizers not only significantly increased eggplant yield but also effectively reduced nitrate content in the fruit, while increasing vitamin C (VC), soluble sugars, and nitrogen, phosphorus, and potassium accumulation [126]. Moreover, biochar-based fertilizers made from biogas and lignocellulosic agricultural residues significantly increased nitrogen, phosphorus, and potassium concentrations in cucumbers [61]. Compared to chemical fertilizers, biochar-based fertilizers increased the fresh weight of cabbage by approximately 14.02% [127], and also significantly improved cabbage growth traits such as chlorophyll content, plant height, maximum leaf length, and maximum leaf width.

Biochar-based fertilizers influence the physical, chemical, and biological properties of soil, working synergistically to enhance crop productivity and quality. The mechanisms of their action can be explained as follows: firstly, at the physical level, biochar-based fertilizers optimize the soil pore structure, improving water retention and aeration, which, in turn, promotes the morphological development of crop roots [51]. At the chemical level, biochar-based fertilizers can increase the soil's redox potential (Eh), thereby enhancing the root membrane potential, reducing the free energy demand required for nutrient accumulation in the roots, and promoting the absorption of nitrogen nutrients [128]. At the biological level, biochar-based fertilizers improve crop yield and quality through modulating rhizosphere microbial community composition and enhancing soil microbial activity [128,129]. These interactions enhance the crop's photosynthetic efficiency, nutrient absorption capacity, and resistance to stress, significantly improving crop yield and quality, such as increasing sugar accumulation [126], optimizing protein content, and inhibiting heavy metal translocation [63]. This process reflects the cascading response characteristics in the soil–plant system.

Although there are currently various slow-release fertilizers on the market which are lower in cost than biochar-based fertilizers and can promote crop yield to some extent while providing slow-release effects, their environmental risks and functional limitations should not be ignored. Traditional slow-release fertilizers typically use synthetic coating materials (such as resins or plastics) or chemical chelation techniques, which can lead to microplastic pollution and persistent chemical residues. Moreover, the functional design of these fertilizers is relatively simple, primarily focusing on nutrient release control, and they lack synergistic effects on improving soil's physical and chemical properties as well as biological communities. In contrast, biochar-based fertilizers not only affect soil's physical, chemical, and biological properties but also exhibit synergistic effects. They enhance crop yield and quality while boosting environmental benefits, offering superior environmental outcomes compared to traditional fertilizers. However, their cost increase far exceeds the market premium, which results in a low willingness among farmers to purchase them. Therefore, long-term research on the application of biochar-based fertilizers should be conducted to monitor whether the long-term benefits of improving soil properties are significant. Additionally, focus should be placed on developing new technologies to reduce production costs, achieving a synergy between environmental benefits and economic returns.

3.5. Advantages of Biochar-Based Fertilizers in Nutrient Release

The significant difference between biochar-based fertilizers and conventional fertilizers lies in their more durable slow-release properties [58,130,131]. Biochar-based fertilizers can continuously provide nutrients throughout the entire crop growth cycle, thereby significantly improving the nutrient use efficiency of nitrogen (Figure 4) [132]. This feature allows biochar-based fertilizers to effectively meet the nutrient demands of crops at different growth stages. In contrast, although biochar itself has certain slow-release characteristics, its effect is less stable and its slow-release performance is not as effective as that of biochar-based fertilizers. Comprehensive analyses using techniques such as X-ray diffraction, Fourier-transform infrared spectroscopy, and X-ray photoelectron spectroscopy have shown that biochar-based controlled-release fertilizers perform better in the control of nutrient release than mixtures of biochar and NPK fertilizers, with biochar-based fertilizers more effectively regulating the release of nutrients from biochar [133]. Various slow-release fertilizers based on biochar have been proven to effectively control the slow release of nutrients required by plants [65,67,134–136]. Comparative studies on the nutrient release rates of modified biochar-based slow-release fertilizers, modified biochar, and chemical fertilizers showed that in the early stages of the experiment, modified biochar and chemical fertilizers released nutrients quickly, after which the release rate stabilized. In contrast, modified biochar-based slow-release fertilizers exhibited a lower nutrient release efficiency, with a slower and more sustained release characteristic [137]. Additionally, studies have found that biochar-based controlled-release nitrogen fertilizers, made by mixing biochar with ammonium sulfate and granulating it then coating it with polylactic acid, significantly extended the nitrogen release period, thereby improving nitrogen use efficiency [138]. When a nitrogen–phosphorus–potassium mixed fertilizer solution was combined with humic acid and seaweed extract to form biochar-based fertilizers, they exhibited a similar NO_3^--N release rate to conventional fertilizers in rice cultivation, but with a significantly slower release rate for NH_4^+-N, phosphorus, and potassium [139]. Furthermore, this biochar-based fertilizer also significantly improved the apparent utilization rates of nitrogen, phosphorus, and potassium, further demonstrating its advantages in nutrient retention and enhancing fertilizer use efficiency.

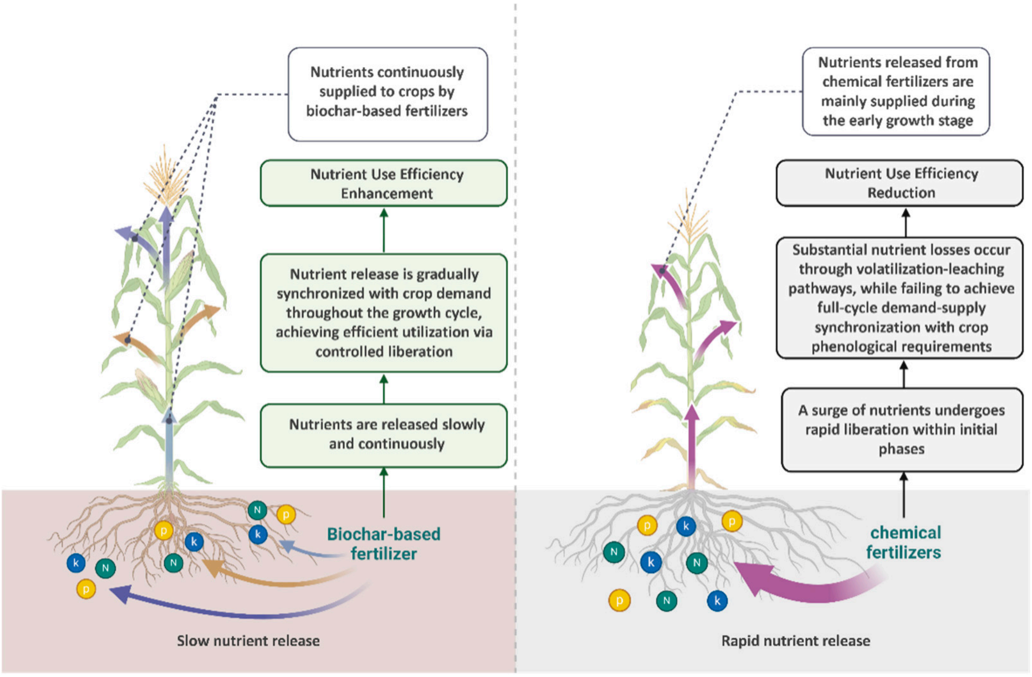

Figure 4. The slow-release effect of biochar-based fertilizers on the nutrients required by crops. (Source: Authors' own work).

Therefore, biochar-based fertilizers demonstrate significant advantages in agricultural applications, particularly in nutrient release control [63] and nutrient use efficiency [77]. By effectively combining with organic matter, biochar-based fertilizers can release nutrients more precisely, meeting the needs of crops at different growth stages.

3.6. The Relationship Between Biochar-Based Fertilizers and Sustainable Agriculture

Chemical fertilizers are often derived from fossil fuels (such as coal, oil, and natural gas) or mineral resources (such as ores). The extraction and processing of these materials not only depletes non-renewable resources but can also lead to environmental pollution. Additionally, the application of chemical fertilizers often results in the emission of greenhouse gases, such as nitrous oxide (N_2O) [140–142]. Some chemical fertilizers also contain heavy metals and other harmful substances that accumulate in the soil, potentially threatening the health of plants, animals, and humans [143–145]. In contrast, biochar-based fertilizers are typically made from natural renewable organic materials (such as plant straw, wood chips, and agricultural residues) through high-temperature pyrolysis. Compared to chemical fertilizers, biochar-based fertilizers reduce dependence on natural resources and mitigate environmental damage. Furthermore, biochar-based fertilizers have shown significant potential in soil improvement [135], enhancing soil fertility [146], reducing chemical fertilizer usage [110], and increasing crop yields [129]. The main raw materials for biochar-based fertilizers include crop residues such as straw and livestock manure [56,71]. Utilizing straw and livestock manure as biochar feedstocks not only effectively recycles waste resources but also helps reduce environmental issues caused by livestock manure pollution and straw burning [147–149]. This reflects the concept of resource recycling and aligns with the principles of environmental protection and sustainable development.

Methane, as a greenhouse gas, exacerbates global warming when its emissions increase [150,151], leading to frequent extreme climate events that affect crop growth and yield stability. Methane emissions, particularly from rice paddies and wetlands, further aggravate this issue [152,153], threatening agricultural sustainability and food security. Therefore, reducing methane emissions has become an urgent task in protecting agricultural ecosystems and combating climate change. Studies have shown that the application of biochar-based fertilizers can effectively reduce methane emissions. Specifically, biochar-based fertilizers significantly lower methane and ammonia emissions in rice paddies throughout the entire growing season [154]. This effect may be related to the slow-release characteristics of biochar-based fertilizers, which can more effectively reduce the relative abundance of methane-producing microbial communities while increasing the relative abundance of *Rice Cluster I*. Additionally, replacing conventional urea with biochar-based urea in China's Moso bamboo forest ecosystems alone could increase the annual soil CH_4 uptake by an estimated 4450 tons. Biochar-based urea not only stimulates methanotroph activity but also significantly enhances soil *pmoA* gene abundance and the p*moA/mcrA* ratio, thereby accelerating CH_4 oxidation [155].

Biochar-based fertilizers not only effectively inhibit methane emissions but also reduce N_2O emissions in the short term (Figure 5). For example, in the case of bamboo planting, biochar-based fertilizers can reduce the concentration of water-soluble organic nitrogen and the activity of nitrogen cycle-related enzymes, which is expected to reduce N_2O emissions by 383 tons annually [156]. Other studies have found that low doses of biochar-based fertilizers significantly promote N_2O emissions, but when the application rate exceeds a certain threshold, N_2O emissions are significantly suppressed [157]. Furthermore, when the pH is less than 7, the activity of N_2O reductase decreases as the pH drops, while the activity of other denitrifying enzymes increases, promoting soil denitrification and leading to higher N_2O emissions [158]. Biochar-based fertilizers, however, raise soil pH, thereby suppressing N_2O emissions. In canola cultivation, the application of biochar-based fertilizers in split doses to partially replace chemical fertilizers not only improves nitrogen use efficiency but also effectively reduces NO_3^- losses by limiting the abundance of *nirS* and *nirK* [118].

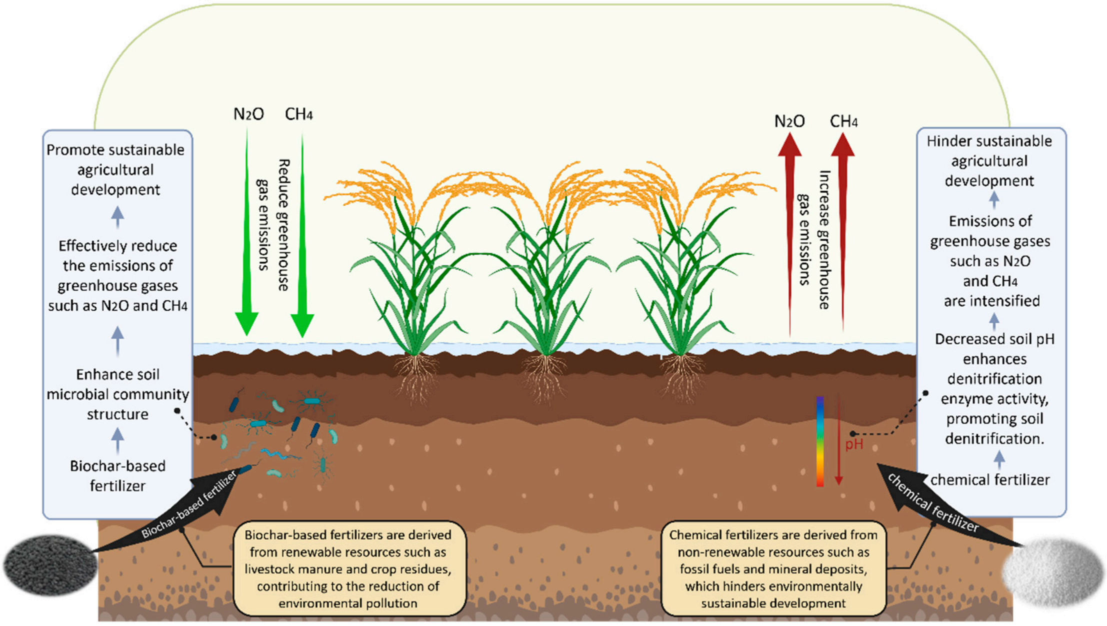

Figure 5. The relationship between biochar-based fertilizers and sustainable agriculture. (Source: Authors' own work).

Although existing studies have confirmed that the long-term application of biochar reduces N_2O emissions [159], current research on the impact of biochar-based fertilizers on N_2O emissions is mostly limited to short-term field trials. Given that biochar-based fertilizers may induce temporal changes in soil physical properties and microbial communities, the stability and sustainability of N_2O reduction during long-term application still require systematic, long-term observational studies. In particular, it is necessary to clarify the long-term effects of biochar-based fertilizers on the activity and regulation of the expression of key nitrogen cycle-related functional genes under different climatic regions, farming systems, and soil types. Such foundational research is not only of significant scientific value in improving agricultural greenhouse gas emission models but also provides crucial theoretical support for optimizing the application of biochar-based fertilizers and formulating agricultural carbon neutrality policies.

4. Conclusions and Future Perspectives

Biochar-based fertilizers show great potential in enhancing soil fertility, increasing crop yields, and alleviating non-point source pollution in agriculture. A deep understanding of the preparation methods, classification, and properties of biochar-based fertilizers reveals that, as a novel fertilizer, biochar-based fertilizers not only effectively increase soil nutrient availability and crop nutrient uptake but also improve soil structure, enhance soil water and nutrient retention capacity, and reduce greenhouse gas emissions.

However, there are still several issues that hinder the large-scale application of biochar-based fertilizers. Firstly, current research on biochar-based fertilizers is primarily based on short-term experiments, with a lack of long-term, cross-season, and field-based empirical studies under different cropping systems. Secondly, the interaction mechanisms between different types of biochar-based fertilizers, soil, nutrients, and microorganisms are not fully understood, particularly the regulation mechanisms of nitrogen transformation processes under dynamic environmental conditions, which require further exploration. Thirdly, there is a lack of standardized preparation techniques for biochar-based fertilizers, with inconsistencies in raw material selection, pyrolysis processes, modification technologies, and post-treatment methods, which restrict the industrialization of biochar-based fertilizers.

Additionally, the production of biochar and its modification processes often involve relatively high energy consumption and material costs. This, especially under the conditions of large-scale production or composite functional modifications, leads to higher product market prices. This, to some extent, limits the widespread adoption of biochar-based fertilizers in agricultural production, particularly weakening the willingness of farmers from small- and medium-sized farms or those in economically limited regions to purchase, thus hindering its expansion in green agriculture and ecological agriculture.

Despite certain economic challenges, biochar-based fertilizers still offer significant environmental advantages. They show great potential in reducing nitrogen and phosphorus nutrient loss, mitigating soil acidification risks, providing slow-release nutrients, controlling heavy metal pollution, and promoting carbon sequestration. With the promotion of the "dual carbon" goals and the urgent need for sustainable agricultural development, biochar-based fertilizers are expected to become a bridging technology between agricultural productivity and ecological protection.

Future research should focus on the following areas:

(1) Strengthening long-term, multi-region, and multi-crop system field trials to verify their adaptability and stability under different soil types and climatic conditions.
(2) Using molecular biology, soil ecology, and material science to deeply analyze the regulatory mechanisms of biochar-based fertilizers on the soil microbial community structure, enzyme activity, and nutrient transformation pathways.
(3) Exploring green, low-cost, and high-efficiency preparation processes to develop scalable and functional biochar-based fertilizer products.

(4) Establishing comprehensive product quality standards and field application guidelines to promote their practical use in green agriculture and precision nutrient management systems.

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