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EDITED BY
Xuezhi Liu,
Ningxia University, China

REVIEWED BY
Marco E. Mng'ong'o,
Mbeya University of Science and Technology, Tanzania
Bi Ruiyu,
Nanjing Agricultural University, China

*CORRESPONDENCE
Hui Liu
✉ hui.liu@ecoprobio.cn
Xiaokai Zhang
✉ xiaokai.zhang@jiangnan.edu.cn

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Enhancing vegetable yield and quality with biochar: prospects and challenges

Xiaoli Xu[1], Haiyan Wang[2], Ishioma Laurene Egun[3,4], Tao Gan[2], Zefeng Huang[2], Hui Liu[5]*, Williamson Gustave[6] and Xiaokai Zhang[2]*

[1]Zhejiang Ecopro Agro Technology Co., Ltd., Jiaxing, Zhejiang, China, [2]Institute of Environmental Processes and Pollution Control, School of Environment and Ecology, Jiangnan University, Wuxi, China, [3]School of Biological and Chemical Engineering, NingboTech University, Ningbo, China, [4]College of Chemical and Biological Engineering, Zhejiang University, Hangzhou, Zhejiang, China, [5]Zhejiang Ecopro Biotechnology Co., Ltd., Jiaxing, Zhejiang, China, [6]School of Chemistry, Environmental and Life Sciences, University of the Bahamas, Nassau, Bahamas

In the context of global climate change, biochar has been recognized as a multifunctional soil amendment that supports sustainable agricultural development and increases vegetable yields. However, there is a lack of comprehensive review of how biochar affects vegetable yields and the potential risks associated with its application. Thus, in this paper, we systematically review the physical, chemical, and biological properties of biochar, as well as its effects on vegetable growth, by optimizing soil structure, enhancing nutrient adsorption, regulating microbial communities, and improving vegetable stress tolerance (e.g., drought and salt resistance). The properties and performance of biochar are dependent on the type of raw material feedstock, pyrolysis temperature, and soil environmental conditions. Although studies have shown that biochar can significantly increase vegetable yield and improve vegetable quality, the high nitrogen content in environments or over-application may cause adverse effects, including the potential release of pollutants, posing environmental risks, and requiring strict quality control during application. Thus, future research is necessary to thoroughly explore the synergistic mode of biochar and organic fertilizer, the development of modified composite materials, and precise application technology to balance the ecological and economic benefits. This review provides the theoretical basis and technical reference for the scientific application of biochar in vegetable production, which is of great significance in achieving sustainable agricultural development.

KEYWORDS
biochar, vegetable growth, soil amendment, risk assessment, synergistic effects

1 Introduction

Vegetables play a crucial role in the daily diet of humans and animals, with a per capita intake of at least 240 g per day, as recommended by the World Health Organization (Kalmpourtzidou et al., 2020). To meet the growing demand for vegetables, large amounts of chemical fertilizers have been applied to soils to boost yields (Timsina, 2018), and their use is 3.3 times higher than that of other grain crops (Qi et al., 2021). On average, the total amount of N, P_2O_5, and K_2O applied to major vegetable crops was 1.9, 5.4, and 1.6 times the respective recommended levels (Shao et al., 2017). However, long-term over-reliance on chemical fertilizers in agricultural production can lead to environmental issues such as soil structure degradation, soil acidification, and eutrophication of water bodies caused by surface runoff (Khan and Mohammad, 2014). Therefore, the current challenge is to find alternative fertilizers or soil amendments that are both sustainable and environmentally friendly, thereby improving soil quality while reducing the application rate of chemical fertilizers.

Biochar is a material with high carbon content formed from the pyrolysis of biomass under oxygen-limited conditions at low and medium temperatures. It is composed mainly of carbon (up to 65%), hydrogen, and oxygen, with a lower extent of potassium, calcium, sodium, magnesium, and other elements (Wang et al., 2025). Common raw materials for biochar preparation include agricultural wastes (such as rice husk, straw, and fruit shells), forestry wastes (including branches, leaves, sawdust, and bark), and municipal wastes (including domestic garbage and sludge) (Dong et al., 2025). Biochar is alkaline, has a complex pore structure, high specific surface area, and various types of functional groups, and is regarded as a new type of organic multifunctional material (He et al., 2025). Numerous studies have demonstrated that the incorporation of biochar into the soil can substantially improve the soil environment, stimulate microbial activity, foster the growth of beneficial microorganisms, increase crop yields, and enhance crop quality (He et al., 2025; Luan et al., 2025). In a pot experiment conducted by Akhtar et al., the application of rice husk biochar and cottonseed husk biochar at a rate of 67.5 t ha^{-1} increased the yield of tomatoes by 20% compared to the control without biochar (Akhtar et al., 2014). Some studies have shown the positive effects of biochar application on soil nutrient supply, vegetable growth, and yields are sustainable and long-term. He et al. investigated the sustained impact of biochar on improving soil quality and providing nutrients to vegetables through a two-year potting experiment (He et al., 2025). They observed a decline in Chinese cabbage yield in the second year, while biochar and wood vinegar continued to show long-term efficacy in improving soil properties compared to chemical fertilizers (He et al., 2025). The reduction in yield is not due to any adverse effects of biochar on vegetables but rather because biochar alone does not supply sufficient nutrients for optimal vegetable growth (Dong et al., 2025; Wang et al., 2020). Instead, it primarily improves nutrient uptake efficiency by altering the soil's physical and chemical properties. In He's study, no fertilizers were applied during the long-term experiment, resulting in inadequate nutrient availability and, subsequently, lower yields. However, yields were still higher than those of the control group that did not receive biochar, providing further evidence of biochar's long-term benefits in improving soil properties.

Vegetable crops encompass over 200 species of herbaceous plants consumed by humans in various forms, including leaves, roots, fruits, seeds, flowers, inflorescences, and stems (Duan and Lin, 2024). A search on Web of Science with biochar, yield, and 13 typical vegetables (tomato, spinach, carrot, lettuce, rapeseed, cucumber, pepper, eggplant, potato, radish, beet, green bean, and cowpea) as keywords revealed an increasing trend of published papers in recent years on the effects of biochar on vegetable growth. Figure 1 illustrates that existing research on biochar applications in vegetable systems primarily focuses on aspects such as yield, quality, mechanisms, pest and disease management, economic benefits, and drought mitigation. In contrast, there is comparatively limited investigation into the potential adverse environmental effects or negative impacts on vegetables resulting from the use of biochar. Given its role as a soil additive, it is essential to evaluate and emphasize both the positive and negative environmental implications associated with biochar application. However, the effects of biochar on vegetable growth mechanisms and associated ecological risks can vary depending on the cultivation method (e.g., open-field vs. greenhouse). In this review, we did not differentiate between cultivation methods; however, most of the data analyzed were derived from pot experiments and greenhouse cultivation.

Given the differences in the raw materials for biochar preparation, pyrolysis temperatures, as well as the diversity of soil properties and types of cultivated crops, there is bound to be significant variability in the specific effects of biochar application to soil on different vegetables (Luan et al., 2025; Itoh et al., 2020; Sharma et al., 2025). However, the existence of patterns of such differences has not been reported in detail. Additionally, the current research, which focuses on the application of biochar in vegetable production and its single effects (yield), lacks a systematic analysis. In addition, the instability of biochar effects, such as the negative effect under high nitrogen conditions, needs urgent research attention. Thus, this review paper aims to fill these research gaps by conducting a systematic review of the mechanism of biochar's effect on vegetable growth, discussing the negative environmental effects of biochar application, and analyzing the economic benefits of biochar application. This review provides a theoretical and practical guide for improving the precise application of biochar in vegetable production, which is of great significance in promoting the sustainability of agricultural development.

2 Mechanism of biochar on regulating vegetable growth

The mechanism of vegetable growth with biochar involves various approaches, including improving soil structure, enhancing the nutrient absorption efficiency of vegetables, addressing potential risks associated with biochar, and improving salt and drought stress tolerance in vegetables. In this section, these various mechanisms are discussed in detail.

2.1 Improving soil structure

Soil structure is defined as the three-dimensional arrangement of soil particles, aggregates, and pores. It is a critical factor influencing soil fertility, water movement, and gas exchange processes that significantly affect vegetable growth (Amoakwah et al., 2017). Proper soil structure facilitates soil and water conservation, as well as the growth of vegetables (Thakur et al., 2024). As a soil amendment, biochar can promote the formation of soil aggregates through its porous structure, increase soil porosity and reduce bulk density (Sun et al., 2021; An et al., 2022), and improve water-holding capacity and permeability (Xue et al., 2022), thereby enhancing vegetable growth and yield. Table 1 presents a

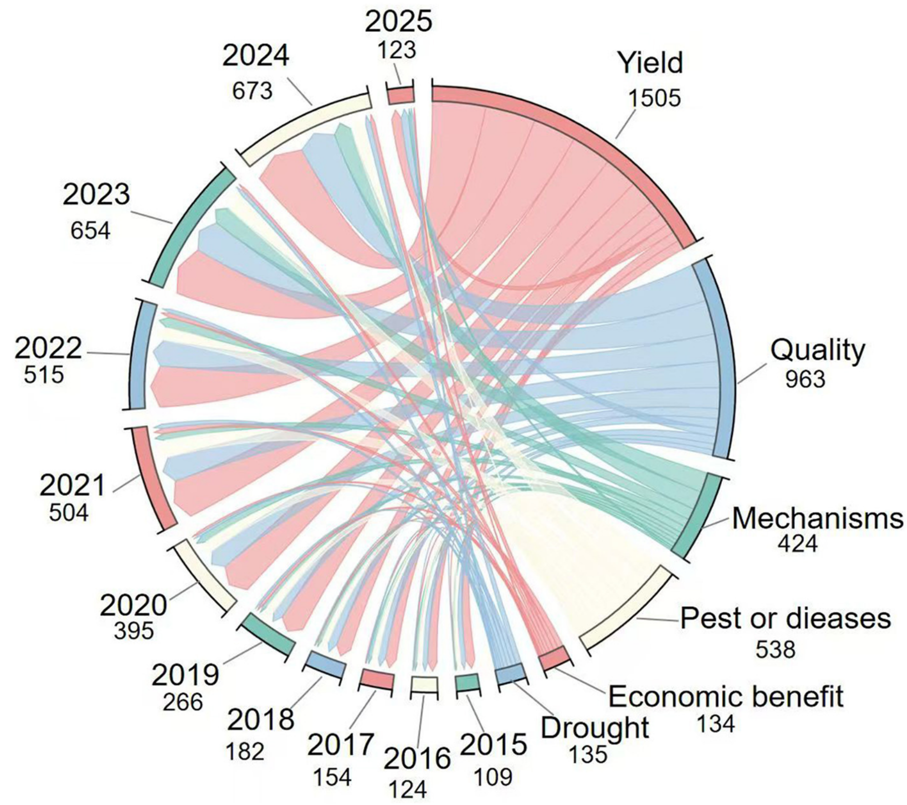

FIGURE 1
Number of publications and the distribution of research directions of biochar in the field of vegetable cultivation.

comparison of soil structure improvement using biochar derived from different feedstocks.

Soil aggregates primarily affect soil structure and help to maintain and stabilize the porous mature soil layer, which is the basis of soil function and agricultural productivity (Wang D. et al., 2017). The use of biochar enhances the stability of soil aggregates and is crucial for seed germination, root growth, and overall crop growth mechanisms (Cen et al., 2021). In most cases, biochar can increase the flocculation of clay particles and soil pH, thereby promoting the formation of aggregates (Islam et al., 2021). Additionally, functional groups on the surface of biochar, such as carboxyl groups and phenolic hydroxyl groups, can adsorb clay-grained minerals in the soil, promoting agglomerate formation and thereby improving soil structural stability (Hartley et al., 2016). It was found that soil aggregate stability increased by 6% to 217% with the addition of biochar (Ali et al., 2024). Wang D. et al. (2017) found that commercially available softwood-based biochar and walnut shell biochar treatments increased the mean weight diameter of soil aggregates by 217% and 126%, respectively.

The particle size of biochar falls between that of sand and clay particles, which can fill the large pores of sandy soil and significantly increase the porosity after application to the soil (Wei et al., 2023). Due to its low bulk density, biochar reduces soil bulk density, thereby enhancing soil looseness, reducing resistance to root growth, and promoting root growth (Guo et al., 2020; Sun et al., 2020). For example, Liu et al. conducted a gradient experiment (0, 7.5, 15, and 22.5 t·ha^{-1} of corn stover biochar application). They found that soil bulk density decreased by 3.74%, 10.54%, and 11.27%, while soil porosity increased by 5.56%, 15.66%, and 16.73%, respectively, compared to the control (Liu et al., 2025). Both Toková et al. (2020) and Šimanský (2016) found that the application of biochar at a dose of 20 t ha^{-1} lowered the bulk density and increased the porosity (Toková et al., 2020) and the structural condition of the soil was significantly improved when compared to the blank control (Šimanský, 2016). The increase in soil porosity is typically accompanied by a decrease in bulk density, which synergistically enhances oxygen supply and water permeability in the root zone, promoting vegetable root development (Ruan et al., 2024; Wang et al., 2023).

For vegetable growth, a healthy soil structure is characterized by a combination of well-developed soil aggregates and pore systems that enhance soil water-holding capacity and improve soil permeability (Adhikari et al., 2022). According to Wei et al. (2023), the water availability of coarse-grained soils increased by 25.6% under the influence of biochar. This improvement was attributed to the optimization of soil pore structure, which reduced bound water and increased capillary water, thereby enhancing the efficient storage and availability of water for plant root uptake. In another study, it was also shown that biochar application increased soil water-holding capacity and soil permeability (Xue et al., 2022).

TABLE 1 Comparison of soil structure improvement by biochar derived from different feedstocks.

Feedstock	Pyrolysis temperature/°C	Improve soil structure	References
Corn stalk	400	The application of biochar increased water-holding capacity, porosity, soil liquid phase percentage and decreased soil bulk density, soil solid phase percentage.	Liu et al., 2025
Corn	500–600	The application of biochar significantly increased the proportion of aggregates, soil pore structure.	Xue et al., 2022
Straw	500–600	The application of biochar increased the content of water-stable aggregates and organic matter.	Cen et al., 2021
Walnut shells	900	The application of biochar increased pH and improved agglomerate stability.	Wang D. et al., 2017
Mesquite	400	The application of biochar increased reduced soil bulk weight and increased soil bulk density and porosity.	Liu et al., 2015
Mixture of paper fiber sludge and grain husks	550	The application of biochar increased reduced soil bulk weight, while increased soil bulk density, porosity, water content and water-holding capacity.	Toková et al., 2020
Picea abies wood	500	The application of biochar increased soil bulk density, improved water-holding capacity and increased soil porosity.	Zanutel et al., 2024
Rice straw	450	The application of biochar reduced soil bulk density and increased soil total porosity.	An et al., 2022
Maize straw	450–500	The application of biochar increased soil porosity and soil water-holding capacity.	Ruan et al., 2024

2.2 Improving the nutrient absorption efficiency of vegetables

Numerous studies have demonstrated that biochar has a positive influence on the physicochemical properties of soil, significantly impacting soil nutrient content, nutrient retention, and crop nutrient uptake (Hossain et al., 2020; Hou et al., 2022; Liu et al., 2018) (Figure 2). Biochar contains essential nutrients such as nitrogen, phosphorus, and potassium, as well as secondary and trace elements like sulfur, calcium, magnesium, iron, and copper, which can directly support vegetable growth. Nitrogen is an essential nutrient for plant growth, but it is easily volatilized and leached out of the soil. Biochar contains a variety of inorganic (NH_4^+, NO_3^-, N_2O^-) and organic forms of nitrogen (hydrolyzable, non-hydrolyzable, and water-soluble nitrogen), making it an effective source of nitrogen (Liu et al., 2018). Phosphorus is an essential element for plant growth and is crucial for various physiological processes, including energy transfer and photosynthesis. The phosphorus content of biochar prepared under different pyrolysis conditions fluctuated from 0.05 to 5.9% (Ajmera et al., 2019). High-temperature pyrolysis increases the production of phosphorus-containing compounds from sewage sludge and poultry manure biomass (Li et al., 2020). The potassium content of different biochars ranged from 3.88% to 14.7%. In contrast, biochars such as poultry manure and chicken manure are rich in potassium, and biochars from rice hulls and corn stover are low in potassium content (Hossain et al., 2020). In addition, animal manure biochar contains a certain amount of calcium, magnesium, and other intermediate elements, as well as iron, zinc (Zn), copper (Cu), and other trace elements, and the sulfur content of different biochar products ranges from 0.2 to 1.36% (Adnan et al., 2020). These elements play important roles in photosynthesis, redox reactions, nutrient uptake, and disease resistance mechanisms in plants (Vatansever et al., 2017).

A study has shown that biochar can reduce nutrient loss when added to soil (Novak et al., 2009). In terms of nitrogen cycling, biochar is not only a source of released nitrogen but also prevents nitrogen leaching and stimulates nitrogen immobilization (El-Naggar et al., 2019). The excessive application of fertilizers often leads to nitrogen and phosphorus runoff into rivers and lakes through surface runoff, resulting in nutrient loss and eutrophication of water bodies (Glaser et al., 2003). Biochar has a large specific surface area and abundant oxygen-containing functional groups with high ion adsorption and exchange capacity. Thus, it can effectively adsorb nitrogen and phosphorus in the soil through physical adsorption and chemical adsorption, reducing nutrient loss (Yang et al., 2015). Lu et al. (2025) combined molecular dynamics simulations with experiments and found that biochar could adsorb and immobilize nutrient ions by surface chemisorption and internal physisorption. The results showed that biochar exhibited adsorption capacity for ammonium ions, nitrate nitrogen, effective phosphorus, and effective potassium, with effective potassium having the most adsorption sites. Zhao et al. (2024) investigated the effect of biochar on enhancing tomato water and fertilizer use, and the results showed that biochar could increase the quick-acting nitrogen content in the soil rhizosphere and reduce the risk of nitrogen fertilizer loss through leaching, thus promoting tomato growth. However, if the nutrients adsorbed by biochar are in forms that are not readily available to plants, or if adsorption is excessive, leading to low nutrient concentrations in the soil solution, it may temporarily inhibit the uptake of nutrients such as nitrogen and phosphorus by crops. For example, when high doses of biochar (e.g., >20 t/ha) are applied to phosphorus-deficient

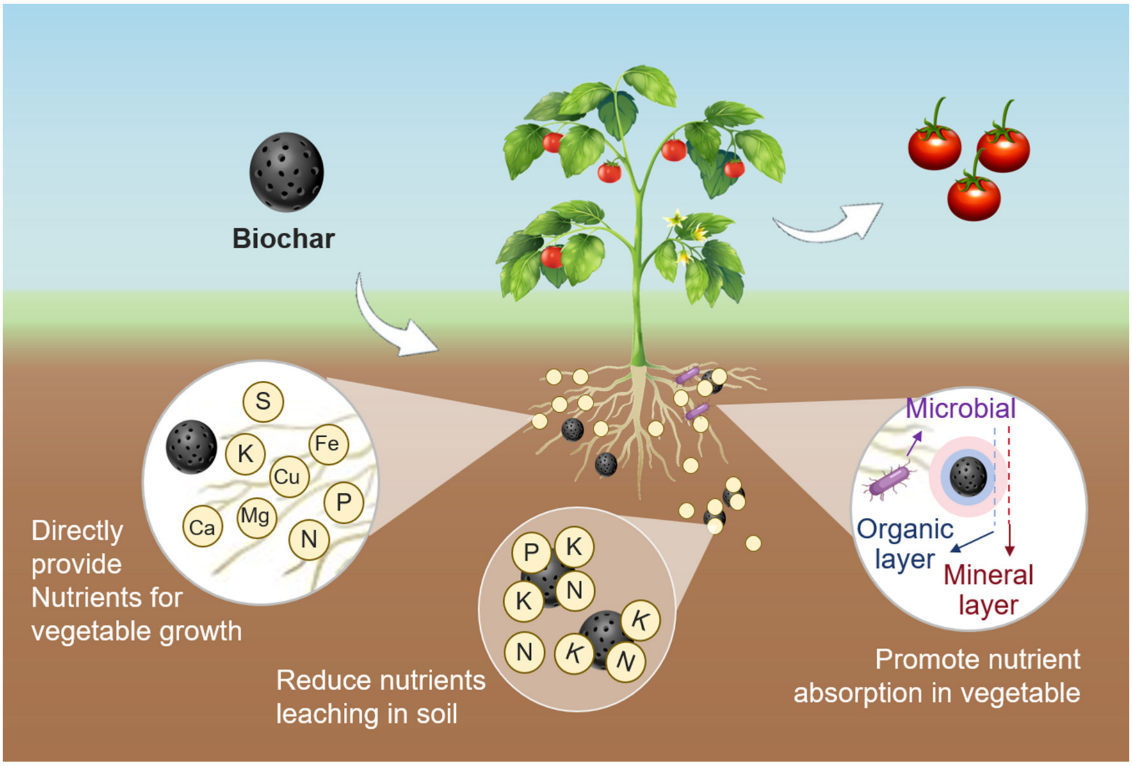

FIGURE 2
Mechanism of effect of biochar on nutrient uptake in vegetables.

soils, the strong adsorption of water-soluble phosphorus can temporarily reduce the soil's phosphorus availability, thereby limiting its uptake by plant roots (Glaser and Lehr, 2019). Therefore, both the application rate and the specific properties of the biochar should be carefully considered when using it to enhance vegetable yields.

Biochar applied to the soil not only increases the nutrient content of the soil or reduces nutrient loss but also promotes nutrient uptake by vegetables through a series of biotic and abiotic functions on the surface of pores (Figure 2, Joseph et al., 2010). An organic layer containing C-O and C-N functional groups will gradually form around the pores of the outer and inner layers of biochar, which can adsorb cations, anions, organic compounds, nano mineral particles, and heavy metals. The adsorption process primarily relies on key mechanisms, including cation exchange, anion exchange, ligand exchange, covalent bonding, complexation, chelation, precipitation, redox reactions, and acid-base reactions, which collectively form the organic-mineral layer (Hagemann et al., 2017). The nanopores of biochar are extremely tiny, making it easier for molecules to bind tightly compared to macropores (Pignatello et al., 2017). Therefore, when chemical fertilizers are used in combination with biochar, the essential nutrients released by the fertilizers can interact with the pore surfaces and the organic mineral layer of the biochar (Haider et al., 2022), thereby playing a key role in converting these nutrients for subsequent microbial communities. It has been found that biochar may have negative effects on the organic nitrogen mineralization in soil, potentially reducing the rate of nitrogen mineralization and decreasing the effectiveness of nitrogen for plants in the short term. However, in the long term, the benefits of biochar in improving soil structure can enhance microbial activity and nutrient cycling, thereby promoting crop nutrient absorption. This discrepancy reflects a difference between the short-term and long-term effects (Wu et al., 2018). In addition, Guo et al. (2021a) found that biochar enhanced soil microbial load and enzyme activities in the root zone, thereby increasing soil nutrient supply capacity and promoting nutrient retention in the rhizosphere soil. Consequently, tomato roots could better absorb and utilize nutrients and water. This trend further suggests that the application of biochar in vegetable cultivation has a promoting effect on nutrient uptake. As mentioned above, there are large differences in nutrient regulation in vegetable soils among different biochars due to differences in their properties. Therefore, when using biochar as a soil amendment, the physicochemical properties of the biochar and the properties of the target soil must be comprehensively considered to achieve the optimal amendment effect. By carefully selecting the type of biochar, controlling the application rate, and choosing appropriate application methods, the benefits of biochar on soil and crop performance can be maximized, potential negative effects minimized, and a synergistic improvement in both soil quality and vegetable growth can be achieved.

2.3 Inter-root microenvironment regulation

The rhizosphere serves as the direct interface between vegetable roots and soil, participating in nutrient acquisition and plant anchorage while forming a unique localized environment—the rhizosphere microenvironment (Hodge et al., 2009; Luo et al., 2024; Tripathi et al., 2024). Functioning as the plant's "second genome", this zone harbors distinct microbial communities that interact with root systems to establish a complex ecological system (Berendsen et al., 2012). Rhizosphere microorganisms process and exhibit inherent biological potential for enhancing crop nutrient use efficiency (Hassani et al., 2018; Ren et al., 2024). Studies have demonstrated that rhizosphere microorganisms enhance vegetable nutrient absorption by secreting polysaccharide-degrading enzymes (e.g., cellulase) and nitrogen-metabolizing enzymes, including urease, leucine aminopeptidase, and β-1,4-N-acetylglucosaminidase (Guang et al., 2017; Tao et al., 2015). Under stress conditions, arbuscular mycorrhizal fungi (AMF) enhance water use efficiency by forming symbiotic associations with roots and establishing hyphal networks for improved water absorption (Jia et al., 2021).

As a critical interface for plant-soil interactions, the rhizosphere microenvironment undergoes significant modifications through biochar application. As shown in Figure 3, the porous structure and surface characteristics of the biochar profoundly alter microbial community composition and functionality (Qi et al., 2022). Ren et al. (2024) reported that biochar application at 750 $kg \cdot ha^{-1}$ increased bacterial, actinomycete, and fungal populations in tomato rhizosphere soil by 82.51%, 63.75%, and 363.30%, respectively, compared to pre-planting conditions. This microbial enhancement results from biochar's multifaceted regulation of soil properties, including pH elevation (0.3–0.8 units in acidic soils) and the provision of carbon substrates for microbial growth (Palacios et al., 2014). Furthermore, its high porosity (specific surface area > 669 m^2 g^{1}) creates optimal microbial habitats (Sharma et al., 2025; Buss et al., 2018).

Biochar-mediated microbial restructuring regulates plant-microbe signaling by modifying root exudate synthesis and secretion (Figure 3). The enhanced abundance of beneficial fungi (e.g., *Penicillium* and *Talaromyces*) in biochar-amended soils activates plant terpenoid biosynthesis through volatile organic compound emission, thereby improving stress resistance (Cheng et al., 2024). Chen et al. (2024) observed up to 1.66% increase in microbial diversity under saline stress following biochar application. Notably, biochar suppresses specific taxa (Firmicutes, Thermoplasmatota, Streptomyces, and Arthrobacter), resulting in a 40.8% increased potential nitrification rate and 12.7% reduction in N_2O accumulation (Kerner et al., 2023). This bidirectional regulation occurs through metabolite-mediated chemical signaling, with biochar stimulating synthesis of vitamins (e.g., riboflavin), ubiquinone cofactors, and terpenoid quinones that interact with plant growth-promoting bacteria (Palacios et al., 2014).

Biochar enhances plant resistance against phytopathogens through multiple mechanisms. Jin et al. (2023) demonstrated that application of 1–2% biochar significantly reduced *Fusarium oxysporum* populations ($p < 0.05$) and suppressed tomato wilt incidence. Yang et al. (2025) revealed that biochar induces modulation of root metabolomes, particularly flavonoid compounds that attract specific plant growth-promoting bacteria (e.g., *Burkholderiales*), thereby enhancing pathogen resistance. The combined application of biochar with beneficial rhizobacteria resulted in an 89.34% improvement in bacterial wilt control through resource competition with pathogens (Wang et al., 2022). By modulating rhizosphere microbial communities and microenvironment dynamics, biochar can effectively enhance the acquisition of nutrients by vegetables and their resistance to pathogens, ultimately promoting plant growth and productivity.

2.4 Improving the tolerance of vegetables to salt and drought stress

Studies have shown that the application of biochar to vegetable garden soil can enhance the stress resistance of vegetables, including tolerance to salinity and drought (Akhtar et al., 2014; Usman et al., 2016). Salt stress primarily disrupts the ionic balance in vegetables by causing excessive accumulation of sodium ions (Na^+), which inhibits root uptake of water and essential mineral nutrients. Due to its high porosity, large specific surface area, and strong cation exchange capacity, biochar can effectively adsorb Na^+ in the soil, thereby reducing ion toxicity (Jing et al., 2022; Ren et al., 2025) (Figure 4). Additionally, biochar, rich in mineral elements, gradually releases beneficial ions such as potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) into the soil. These elements are not only essential nutrients for vegetable growth but also compete with Na^+ for adsorption sites, indirectly mitigating the negative effects of Na^+. Moreover, these mineral nutrients also help to maintain osmotic balance in vegetable cells, thereby enhancing vegetable tolerance to salt stress (Ren et al., 2025).

Under drought conditions, vegetable growth is significantly inhibited. The application of biochar can effectively alleviate this limitation, primarily because biochar improves soil structure, particularly by enhancing soil water-holding capacity (Figure 4). Coarse-textured soils, such as sandy soils, are more responsive to biochar amendments due to their larger pores and rapid water loss, which results in poor inherent water retention. The addition of fine-grained biochar can fill large soil pores and reduce saturated hydraulic conductivity, thereby increasing water retention and the availability of plant-accessible water (Edeh et al., 2020). On the contrary, in fine-textured soils, especially those that are heavily compacted, the addition of biochar improves aggregate structure by converting ultra micropores into larger pores, which enhances saturated hydraulic conductivity and facilitates water infiltration (Zaffar and Sheng, 2015). This dual regulatory effect of biochar promotes water uptake by vegetables under drought or saline conditions, contributing positively to soil and water conservation in arid and semi-arid regions (Murtaza et al., 2024).

Numerous studies have shown that proline accumulation in vegetables increases under drought and salt stress conditions (Chaudhary et al., 2024; Toyoshima et al., 2011). Murtaza et al. (2024) reported that deficit irrigation significantly elevated proline levels in tomatoes. However, tomato plants treated with 3% biochar exhibited the highest relative leaf water content and

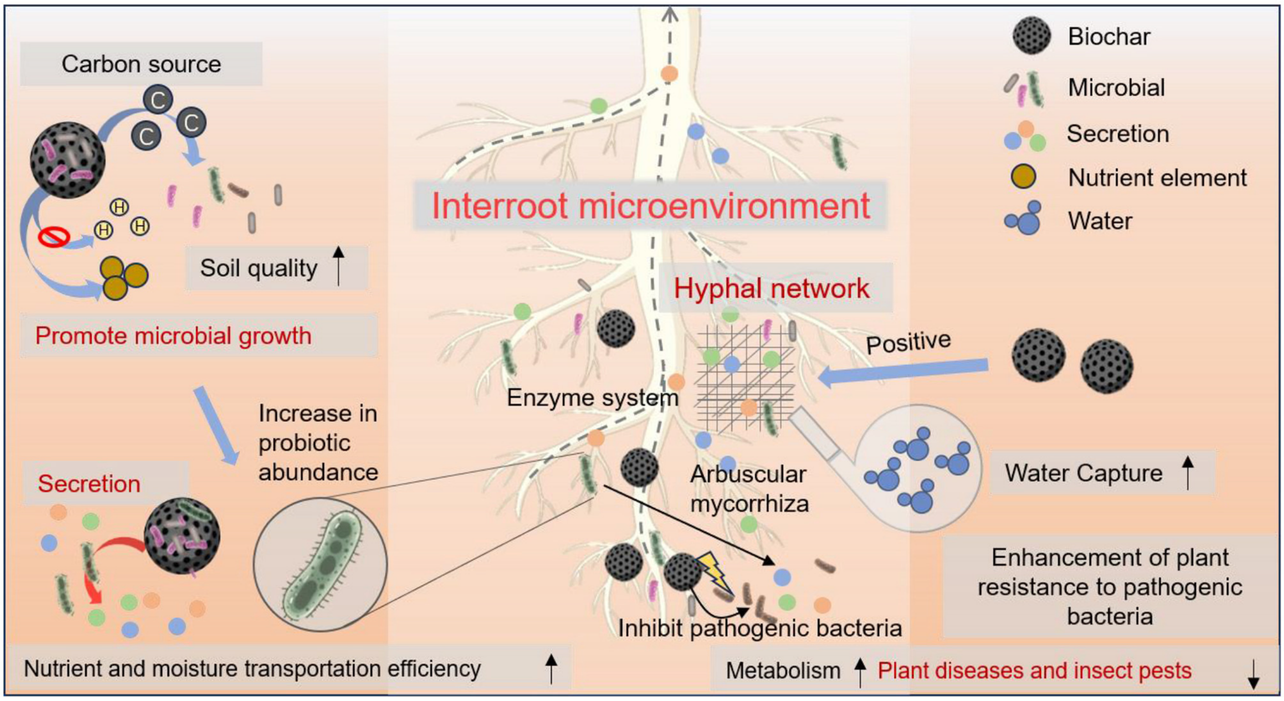

FIGURE 3
Schematic diagram of biochar promoting vegetable growth by influencing soil microorganisms.

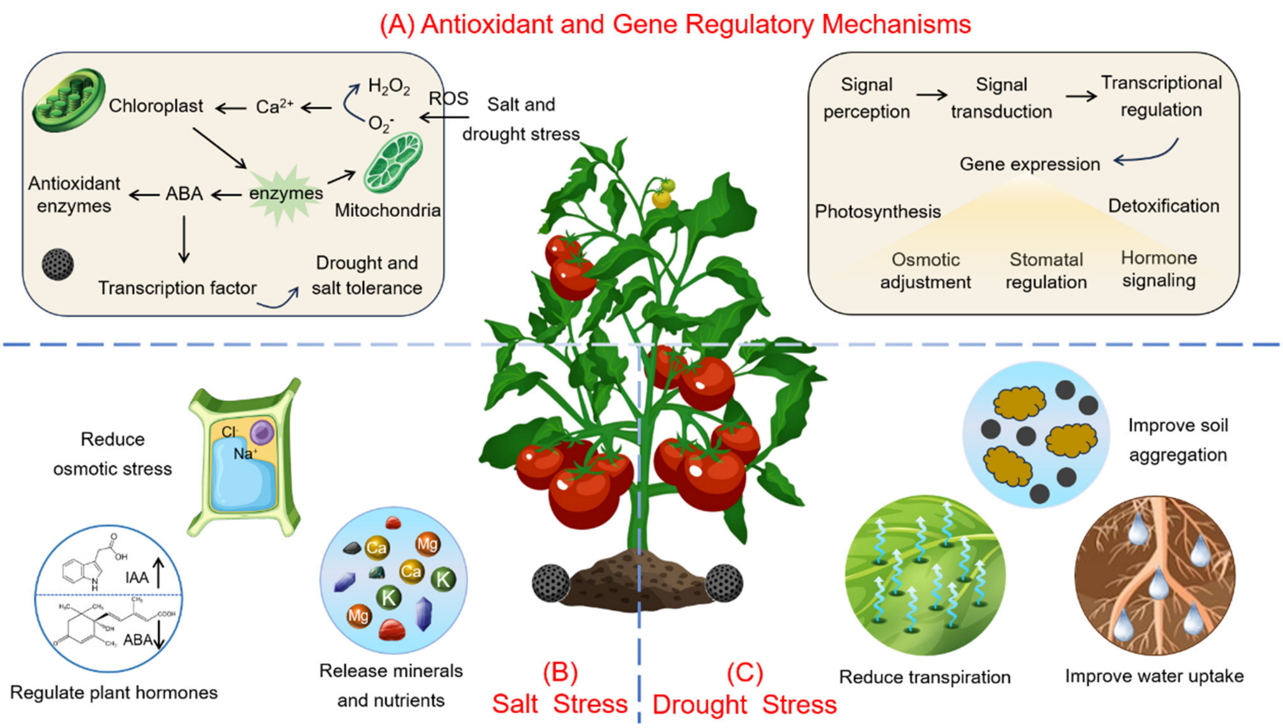

FIGURE 4
Mechanisms of adding biochar to enhance salt and drought resistance in vegetables.

the lowest proline levels. This trend was primarily attributed to the enhanced gas exchange capacity and improved soil water availability resulting from biochar application, which facilitated the leaching of salts from the rhizosphere and alleviated osmotic stress, thereby promoting water uptake by plants. Drought and soil stress also lead to ionic imbalance and osmotic stress in plant cells, triggering a cascade of cellular stress responses. These adverse conditions disrupt intracellular homeostasis, resulting in the excessive accumulation of reactive oxygen species (ROS). To minimize water loss, plants respond by closing stomata and reducing transpiration, which subsequently decreases photosynthetic efficiency and CO_2 assimilation.

Furthermore, such stress often results in abnormal root cell development, inhibits normal plant growth and development, and may ultimately lead to cell death (Toyoshima et al., 2011). Studies have shown that the application of biochar can effectively alleviate osmotic stress and oxidative stress induced by drought and soil salinization, thereby promoting the growth of vegetables (Chaudhary et al., 2024). Under drought and salt stress conditions, the level of abscisic acid (ABA) in plants increases significantly. As a key plant hormone, ABA plays a crucial role in regulating plant responses to environmental stress and helps maintain cellular redox homeostasis by modulating the production of reactive oxygen species (ROS), thereby mitigating stress-induced damage (Lupo and Moshelion, 2024). This study is supported by the findings of Zhang et al. (2023), who reported that the application of livestock-derived biochar reduced ABA concentrations from 653 pmol·mL^{-1} to 451 pmol·mL^{-1} under deficit irrigation and no NaCl conditions. Under 200 mmol·L^{-1} NaCl treatment, ABA concentrations were reduced from 1181 pmol·mL^{-1} to 695 pmol·mL^{-1}. These results indicate that biochar application effectively lowers ABA levels in plants, helping to alleviate stress-induced stomatal closure and transpiration inhibition and ultimately enhancing plant physiological activity.

Additionally, drought and salt stress have detrimental effects on the photosynthetic performance of vegetables. Roşca et al. (2023) reported that increased soil salinity resulted in a 10.2%-12.4% reduction in the photosynthetic rate of tomato plants, accompanied by decreases in transpiration rate of 24.6%-26.9% and stomatal conductance of 23.4%-24.1%, thereby impairing leaf gas exchange and photosynthetic efficiency. However, Zhang et al. (2023) demonstrated that under salinity and drought stress, biochar application significantly improved the root water potential and osmotic potential of tomato seedlings, resulting in a 24.37% increase in leaf relative water content. This alleviated salt-induced dehydration and enhanced the plant's ability to absorb and retain water. Similarly, Guo et al. (2021a) confirmed that the application of biochar significantly improved the photosynthetic performance of tomato plants. Compared with untreated controls, the application of 50 t ha^{-1} biochar resulted in increased net photosynthetic rate, stomatal conductance, transpiration rate, and chlorophyll content, with increases ranging from 2% to 60%, ultimately doubling the tomato yield. Moreover, the reduction in chlorophyll content is another key factor contributing to the decline in photosynthetic rate under drought and salt stress. This decrease is primarily due to the excessive accumulation of reactive oxygen species (ROS), which damages the thylakoid membranes in chloroplasts, increases membrane permeability, and leads to chlorophyll leakage or degradation, thereby impairing photosynthetic efficiency (Abbas et al., 2024; Ma et al., 2022). However, Murtaza et al. reported that biochar application significantly increased the SPAD value, chlorophyll a, chlorophyll b, total chlorophyll, and carotenoid contents in tomato plants compared to the untreated control (Murtaza et al., 2024). These findings are consistent with those of Guo et al. (2021b), who reported that under drought and salinity stress, the enhancement of chlorophyll and carotenoid content by biochar was closely associated with increased antioxidant enzyme activity and improved antioxidant capacity in plants. These studies suggest that biochar application significantly improves plant physiological activity and crop yield under saline and drought conditions, offering a promising strategy for stress-resilient agriculture.

3 Potential risks of biochar addition to vegetable growth

Although the majority of studies have demonstrated that biochar can be effectively utilized for soil amelioration and enhancing vegetable yields, emerging evidence suggests that biochar may introduce contaminants into soil systems (Figure 5). Notably, the U.S. Environmental Protection Agency (EPA) reports that contaminants in soil–crop systems at concentrations of 0.01–0.5 μg kg^{-1} (wet weight) may pose risks to crop growth (Paris et al., 2018). This guideline serves as a critical benchmark for evaluating the potential hazards associated with contaminants in biochar applications. As shown in Figure 5, biochar also poses a potential risk to vegetable growth when added to the soil. The compositional characteristics of pollutants in biochar, including their types and concentrations, are predominantly influenced by feedstock sources and pyrolysis temperatures. Biochar has been demonstrated to contain polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds, and phenolic compounds, which exhibit growth-inhibitory effects on vegetables when introduced into soil environments (Ghidotti et al., 2017; Wang et al., 2018). Additionally, aged biochar may release previously adsorbed pollutants, thereby diminishing its efficacy as a soil amendment (Wang H. et al., 2017; Xiang et al., 2021). These adverse effects demonstrate significant amplification in intensive vegetable cultivation systems.

Research has shown that biochar produced at low pyrolysis temperatures (300–400°C) is more susceptible to retaining hydrophobic organic contaminants, such as polycyclic aromatic hydrocarbons (PAHs) and dioxins. These persistent compounds remain sequestered within the porous structure of biochar, posing potential threats to ecosystem integrity and vegetable safety (Xiang et al., 2021; Ramanayaka et al., 2020). Organic pollutants, such as PAHs, can disrupt plant physiological functions through mechanisms including oxidative stress induction and photosynthetic inhibition (Hu et al., 2023; Kreslavski et al., 2014; Liu et al., 2009). Furthermore, biochar derived from industrial sludge, livestock manure, or heavy metal-contaminated biomass often exhibits enrichment of heavy metals, including cadmium (Cd), copper (Cu), lead (Pb), zinc (Zn), and nickel (Ni) (Xiang et al., 2021). Lu et al. (2016) reported that sewage sludge-derived biochar contained heavy metal concentrations (excluding arsenic) that were enriched 2.5–3.5 times compared to the raw materials. Zeng et al. (2018) identified elevated environmental risks associated

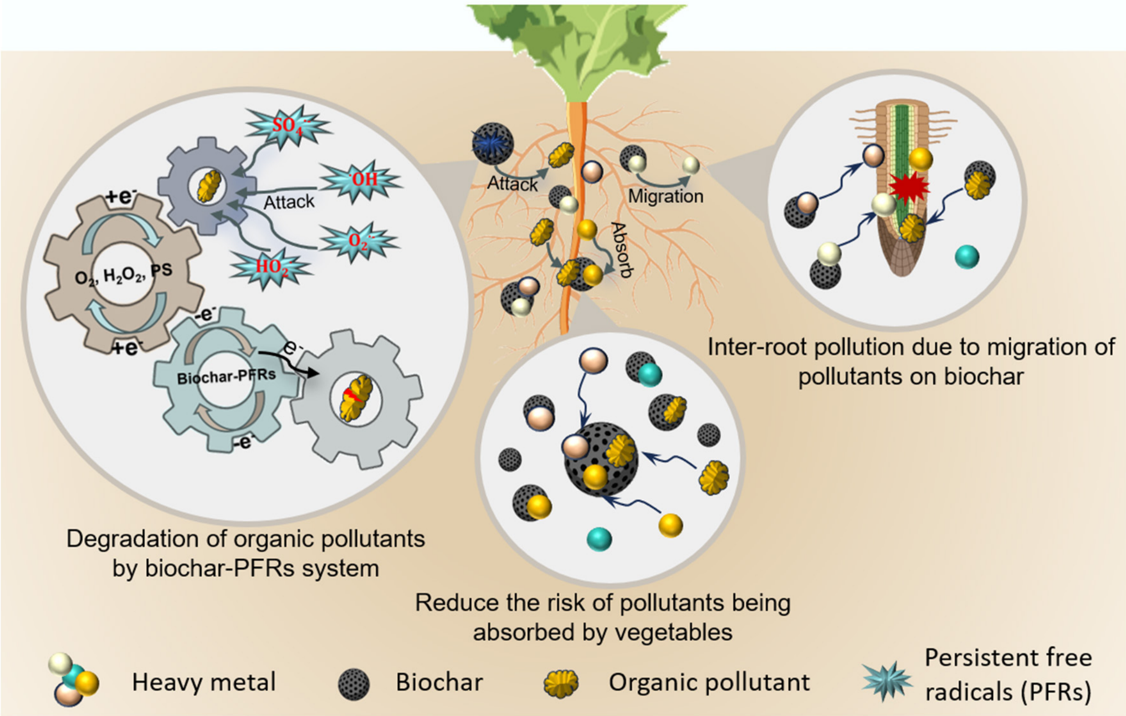

FIGURE 5
Mechanisms of potential risk to vegetable growth by the addition of biochar.

with Cd and Ni in swine manure (SM)- and goat manure (GM)-derived biochar. Following soil incorporation, these metal contaminants demonstrate high mobility within the soil-plant continuum, undergoing root uptake and subsequent accumulation to toxic levels in edible vegetable tissues, ultimately impairing vegetable growth (Nzediegwu et al., 2019; Xie et al., 2020).

Although biochar may carry toxic pollutants, its high specific surface area, abundant surface functional groups, such as carboxyl and hydroxyl, and alkaline properties endow it with a remarkable capacity for pollutant immobilization (Figure 5). For example, Munir et al. (2024) found that walnut shell biochar, with its high porosity and large surface area, demonstrated excellent pollutant removal efficiency—achieving maximum removal rates of 92%, 90%, and 87% at adsorbent concentrations of 1, 2, and 3 mg·L^{-1}, respectively. In another study, Wang et al. demonstrated that peanut shell biochar (applied at 5% dosage) reduced PAHs accumulation in radish by 84% (Wang et al., 2018). Furthermore, persistent free radicals (PFRs) in biochar not only efficiently degrade organic pollutants through redox pathways but also synergize with the biochar matrix (biochar-PFRs system) to catalyze the generation of ROS from hydrogen peroxide (H_2O_2), persulfate (PS), and oxygen (O_2), thereby enhancing pollutant removal efficiency via free radical chain reactions (Xie et al., 2024). Elsafi et al. (2025) further confirmed that the biochar-PFR system achieved over 80% degradation efficiency for organic contaminants. However, the immobilization efficiency is constrained by the properties of biochar and environmental conditions. For example, excessive application may lead to saturation of biochar adsorption sites, potentially triggering pollutant re-mobilization under fluctuations in pH or redox conditions (Lal et al., 2020).

Based on the discussion above, current research should focus on source pollution control through feedstock selection and optimization of the pyrolysis process. High-temperature slow pyrolysis significantly reduces the generation of PAHs and enhances the chemical stability of heavy metals (Hou et al., 2024). Post-treatment technologies, such as acid washing and mineral modification, can further decrease the bioavailability of contaminants. Alumina-modified biochar has been shown to demonstrate a 1.5-fold increase in pollutant adsorption capacity (Liu et al., 2022). To mitigate the potential adverse effects of toxic pollutants in biochar on vegetable growth, it is essential to establish threshold standards for contaminants in biochar-based fertilizers and to assess their cumulative ecological effects through long-term field monitoring. Existing studies still exhibit significant knowledge gaps regarding the long-term fate of biochar-borne pollutants and their interactions with environmental contaminants, as well as a lack of long-term research on the role of soil microorganisms in pollutant transformation. Future research should prioritize investigations into the potential negative impacts of biochar on soil environments and the growth of vegetables. This includes screening high-quality biochar, optimizing application protocols, and ensuring the safe use of biochar for enhanced vegetable yield and quality.

4 Analysis of economic and environmental benefits of biochar

For practical agricultural applications, research attention needs to be extended beyond the role of biochar in vegetable yield and quality improvement, but should accurately account for the cost of biochar input. This way, we can effectively analyze the economic benefits of biochar in agriculture and provide qualitative and quantitative data to support and make decisions for its rational application. According to a survey, the market price of biochar is approximately USD 246 t^{-1}, but it fluctuates depending on the type of feedstock, year, and region (Premarathna et al., 2019). For example, Patel and Panwar (2024) found that the total cost of producing biochar is USD 232.87 $t^{-1,}$ using economic parameters such as yearly instrument operating expenses of USD 2,339.40, feedstock cost of USD 2,420.25, and transportation cost of USD 293.71 during the biochar preparation process. The cost of biochar has mainly focused on raw materials, process preparation, and transportation (Liang et al., 2024). A study by Homagain et al. (2016) showed that during biochar preparation, the pyrolysis process accounted for about 36% of the total production cost, while land use, feedstock collection, and transportation accounted for 14%, 12%, and 9%, respectively. Therefore, rational optimization of the pyrolysis process for biochar and the use of diversified raw materials for production are of great significance in reducing preparation costs and improving the economic benefits of practical applications.

Currently, a range of biochar types, including peanut shell biochar, straw biochar, and corn cob biochar, are utilized for agricultural applications. Variations in their production methodologies and application procedures significantly influence their impact on crop performance (Wang H. et al., 2017; Chen L. et al., 2022; Chen X. et al., 2022). The specific preparation processes, production costs, and application effects on vegetables for some common biochars are presented in Table 2. According to the table, selecting the appropriate biochar for different vegetable species is crucial to enhancing the profitability of the vegetable growing industry. For example, González-Pernas et al. (2022) found that applying 1 $kg{\cdot}m^{-2}$ of biochar from coast pine wood chips increased the total weight of tomato fruits by 63.3%. When the addition was increased to 2 $kg{\cdot}m^{-2}$, the total yield of bell peppers increased by 92.6%. In this study, four vegetables—tomato, radish, lettuce, and bell pepper—yielded 3,500–32,000 EUR·ha-1 when the cost of biochar was calculated at 800 $EUR{\cdot}t^{-1}$ (González-Pernas et al., 2022). Bi et al. (2022) also demonstrated that vegetable yield could be increased by 28.4% of the original yield using 20 t ha^{-1} of biochar in combination with chemical fertilizer. Therefore, the application of biochar to the soil can effectively improve soil fertility and has a slow-release effect when combined with chemical fertilizers, thereby avoiding nutrient loss and saving on fertilizer costs (Premalatha et al., 2023). Additionally, selecting the optimal amount of biochar to apply is a crucial factor in achieving increased crop yields. Research has also shown that the maximum annual income from crop production, such as peas, reaches USD 525.88 ha^{-1} at a biochar application rate of 12 $t{\cdot}ha^{-1}$. The income from carbon sequestration was USD 186.6 t^{-1} of biochar. Economic indicators showed that the highest benefit-cost ratio was achieved when biochar was applied at a rate of 8 $t{\cdot}ha^{-1}$, and the Net Present Value and the rate of return also reached their maximum values at this application rate, which were USD 932.85 and 85.71%, respectively (Patel and Panwar, 2024).

Furthermore, biochar, as an environmentally friendly material applied to soil, can bring significant environmental benefits. Biochar enhances the soil's carbon sequestration capacity by fixing atmospheric carbon dioxide in a stabilized form, thereby reducing greenhouse gas emissions and contributing to the mitigation of global warming (Campion et al., 2023). Some studies have shown that for every 1 t of biochar applied, greenhouse gas emissions emission reductions range from −0.124 to 16 t CO_2e, which, according to the algorithms, is worth between USD 15 and USD 80 per t CO_2e^{-1}, which can be effective in improving the economic efficiency of the crop (Dickinson et al., 2015). This is primarily because biochar is highly aromatic, structurally stable, and difficult for microorganisms to decompose, retaining soil-fixed carbon for an extended period (Gross et al., 2024). Moreover, biochar can combine with soil minerals to form an organic-mineral complex, which regulates the mineralization of soil organic carbon, reduces the risk of microbial decomposition, and reduces carbon emissions (Shi et al., 2024). Additionally, the abundant pores and surface functional groups of biochar can adsorb ammonium nitrogen, reducing nitrogen leaching and volatilization and regulating soil microorganisms to promote the growth and reproduction of nitrogen-fixing bacteria, thereby enhancing nitrogen fixation and reducing the emission of the N_2O greenhouse gas (Ming et al., 2019). As the work of Bi et al. showed that while biochar treatment increased vegetable yields by an average of 28.4% and net ecosystem economic benefits by 7.1% compared to traditional fertilizer treatments, it also reduced N_2O emissions by 45.4%, reducing the cost of environmental damage and effectively improved the environmental benefits of biochar (Bi et al., 2022).

5 Conclusions

This review systematically analyzes the potential application of biochar in vegetable production and its underlying mechanisms. The findings suggest that biochar is particularly effective in regulating sandy loam and infertile soils with low organic matter and nutrient content, poor aggregate stability, and weak water-holding capacity. It significantly improves the rhizosphere microenvironment by optimizing soil pore structure, enhancing water retention, and promoting aggregate formation, thereby supporting the growth of vegetables. Additionally, the rich surface functional groups of biochar can effectively adsorb nutrient ions, reduce nitrogen and phosphorus losses, and enhance nutrient use efficiency by influencing the soil microbial community. Under adverse conditions, biochar enhances vegetable resistance by regulating ion balance, alleviating oxidative stress, and improving photosynthetic performance. It is worth noting that the effects of biochar prepared from different feedstocks and pyrolysis temperatures vary, with biochar from high-temperature pyrolysis ($>$ 500°C) being more advantageous in controlling pollutants. Current research needs to address key issues, such as the cumulative effects of pollutants and microbial response mechanisms of long-term biochar application. In the future, research on biochar-microbial interactions should be strengthened,

TABLE 2 Preparation methods, costs, and effects on vegetable growth of commonly used biochar.

Types of biochar	Preparation process	Costs	Effects	References
Peanut shell biochar	Pyrolysis in a pyrolysis reactor at 350°C for 3 h	Approximately USD 246 t^{-1}	Vegetable biomass was increased to 186% of the original, and soil SOM content was effectively increased.	Premarathna et al., 2019; Wang et al., 2018
Corncob biochar	Corn cobs were pyrolyzed in vertical kilns at temperatures of 360-420°C	Approximately USD 307.7 t^{-1}	Application of appropriate levels of biochar increased cauliflower yield by 43.5% over the organic fertilizer treatment.	Wang et al., 2019
Biomass (e.g., crop residues, livestock manure and solid waste) biochar	Produced by pyrolysis under anoxic or anaerobic conditions through thermochemical conversion	Approximately USD 126.87∼253.73 t^{-1}	The application of biochar significantly increased vegetable yield by 28.4% compared to traditional fertilizer application.	Bi et al., 2022
Beechwood biochar	Prepared by slow pyrolysis of beech wood at 550°C	Approximately USD 110∼550 t^{-1}	The application of biochar increased eggplant yield by 37%.	Dickinson et al., 2015; Iacomino et al., 2022
Palm tree branches biochar	Produced by a pyrolysis process at 500–600°C under anaerobic conditions	Approximately USD 1,500 t^{-1}	The application of appropriate amount of biochar significantly increased the yield of sugar beet by 30–40%.	Li et al., 2022
Fruit tree branches biochar	Prepared by pyrolysis at a temperature of 450°C	Approximately USD 307.69 t^{-1}	The application of biochar significantly increased the yield of tomato by 54.79% as compared to the treatment without biochar.	Guo et al., 2021b

and environmentally friendly composite amendments should be developed to enhance the sustainability of these interactions. The establishment of a soil-crop system based on the precise application of biochar will provide new insights into achieving the sustainable development of the vegetable industry.

Author contributions

XX: Conceptualization, Methodology, Project administration, Visualization, Writing – original draft. HW: Visualization, Writing – review & editing. IE: Writing – review & editing, Conceptualization, Methodology, Project administration. TG: Visualization, Writing – review & editing. ZH: Visualization, Writing – review & editing. HL: Conceptualization, Funding acquisition, Writing – review & editing, Supervision. WG: Writing – review & editing. XZ: Conceptualization, Supervision, Writing – review & editing.

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Conflict of interest

XX was employed by Zhejiang Ecopro Agro Technology Co., Ltd. HL was employed by Zhejiang Ecopro Biotechnology Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

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