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Biochar

REVIEW **Open Access**

Stress resistance enhancing with biochar application and promotion on crop growth

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Abstract

Environmental stressors such as drought, salinity, and heavy metals pose significant obstacles to achieving sustainable food security, necessitating the development of universally applicable and cost-effective solutions to ameliorate soil under stress. Biochar, an eco-friendly material to increase crop yield, has been researched for almost two decades and has great potential for global use in enhancing stress resistance. However, there hasn't been comprehensive research on the impact of biochar application on soil properties, and root and crop growth. To optimize and promote biochar application in agriculture under stress, this study integrates over 100 peer-reviewed articles to explain how biochar promotes crop growth by enhancing soil resistance to stress. Biochar's distinctive properties, such as porous structure, alkaline nature, enriched surface functional groups, and nutrient content, are responsible for the following soil environment benefits: improved soil physiochemical properties, increased nutrient cycling, and boosted microbial growth. Moreover, the research emphasizes that the enhanced stress resistance of biochar optimizes nutrient absorption, alleviates soil pollutants, and thereby enhances overall crop productivity. The study discusses the roles and mechanisms of biochar on soil under stress, as well as the challenges linked to the sustainable and economical implementation of biochar in extreme soil conditions. This review aims to provide a theoretical basis for the widespread and cost-effective use of biochar in improving soil under stresses, thereby enhancing soil health and food security.

Highlights

- Biochar's physicochemical properties help with stress resilience.
- Biochar's effect on multiple stresses mitigation promotes soil nutrients circulating.
- Biochar provides virtuous cycles for crop stress resistance and root growth.

Keywords Biochar, Crop, Soil aggregates, Nutrients, Stress resistance

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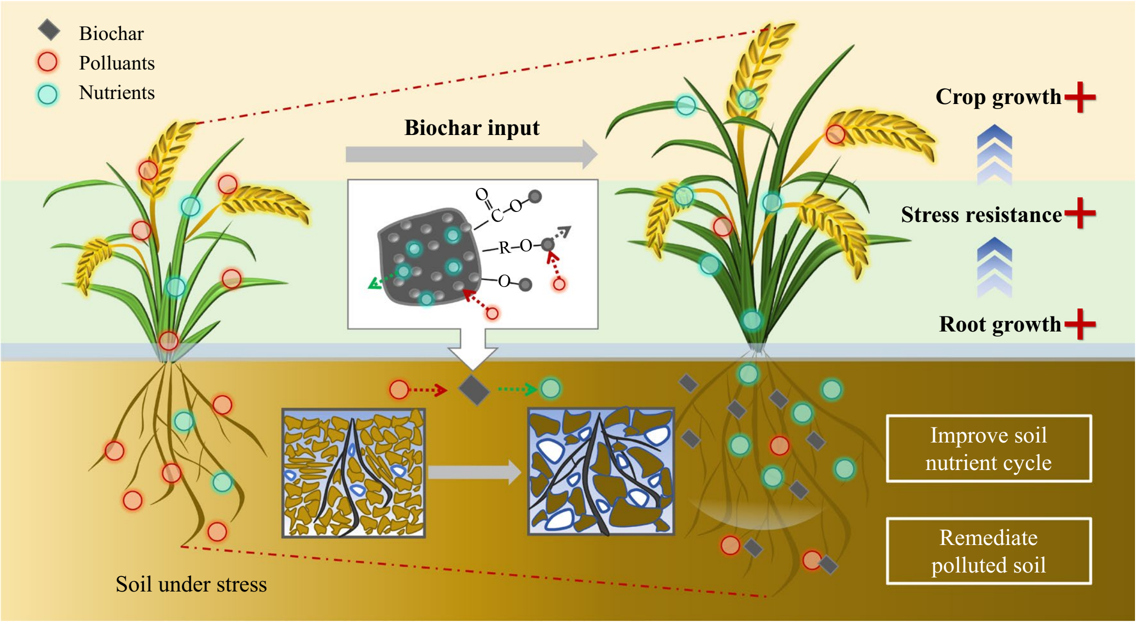
Graphical Abstract



1 Introduction

Ensuring food and nutrition security remains a significant challenge outlined in the United Nations' Sustainable Development Goals (SDGs). The global food demand is expected to surge by 35–56% between 2010 and 2050 due to the projected population growth to over 9.7 billion by 2050 (UNDESA 2024; van Dijk et al. 2021). However, urbanization, industrialization, climate change, and excessive use of fertilizers and pesticides have led to soil pollution and degradation, including heavy metal and pesticide contaminants, physical degradation, soil acidification, and salinization (Masmoudi et al. 2023; Pawlak and Kolodziejczak 2020). These factors have affected over 40% of agricultural land (Singh et al. 2022). Agricultural production has become even more challenging as crops exposed to abiotic stresses such as heat, waterlogging, drought, and nutritional deficiencies tend to grow poorly with low yield and quality (Ali et al. 2017; Hasnain et al. 2023; Radha et al. 2023). Therefore, the need for effective soil improvement is highly urgent.

Biochar is a soil amendment that is highly regarded for its potential to improve soil quality. Biochar is a highly porous and aromatic black substance derived from the pyrolysis of biomass under oxygen-deprived (anaerobic or oxygen-limited) conditions. After a news feature titled "Black is the new green" (Marris 2006) first revealed that the large amount of black char produced by primitive tribes is the key factor behind the soil fertility mystery of Terra Preta in 2006, the carbon storage capacity of biochar has been demonstrated through meticulous data analysis (Lehmann 2007). Additionally, considering the economic benefits of agricultural residue management (Sheer et al. 2024), pyrolyzed biomass amendment to farmland was encouraged, which could enhance crop yield in the meantime. Subsequently, scientists have conducted a series of studies to investigate how different biochar returning strategies can affect crop yields even under environmental stresses. Biochar possesses numerous excellent physicochemical properties, including a rich pore structure and high specific surface area, abundant ash content (as nutrients for crops), alkaline (most biochar is alkaline, but a small part of biochar is still acidic acidic), and highly stable nature (Sheer et al. 2024). Its stability, unique physical structure, and chemical composition make it a powerful tool for increasing stress tolerance and crop yield. The advanced surface functional groups and pore structure of biochar have the potential to mitigate the presence of heavy metals and organic pollutants in soil by adsorption or microbial degradation. Its physical properties also improve soil aggregates stability and water-holding capacity (WHC), which provides a buffer against drought (Zhang et al. 2024; Park et al. 2023; Raza et al. 2023) and overcomes the moisture defect of saline soil (Ran et al. 2020; Wang et al. 2023), thus protecting roots (Hazman et al. 2023). Additionally, biochar is rich in nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and other mineral nutrients (Okebalama and Marschner 2023). With its high cation exchange capacity (CEC) and alkaline character, biochar aids in nutrient retention and soil pH adjustment under stresses such as saline (Duan et al. 2023), drought (Park et al. 2023), or pollution (Sha et al. 2023). As a result, biochar amendment stimulates soil microbial activity and promotes nutrient cycling and uptake, thus improving soil quality, root development, crop productivity, and grain quality (Anwar et al. 2023; Zhang et al. 2024; Irfan et al. 2022). The wide optimal utilization of biochar into the soil can aid in developing a healthy and productive agricultural system and enhancing food security and sustainability.

Biochar has been shown to enhance soil physicochemical properties, consequently improving soil resistance to stresses and stimulating crop root development. This phenomenon creates a conducive environment for crop growth. To obtain a comprehensive overview of the present application of biochar in soil under stress, we collected 913 papers from the "Web of Science" and google scholar database related to biochar and soil stress resistance in the last 20 years since 2004. VOSviewer software (version 1.6.20) was used to analyze the co-occurrence of the keywords. Figure 1 shows a network consisting of 148 keywords categorized into 4 clusters, which demonstrates that (1) effects of biochar on crop growth under stresses such as saline and drought, as well as in contaminated soil have been widely studied, and (2) biochar affects crop

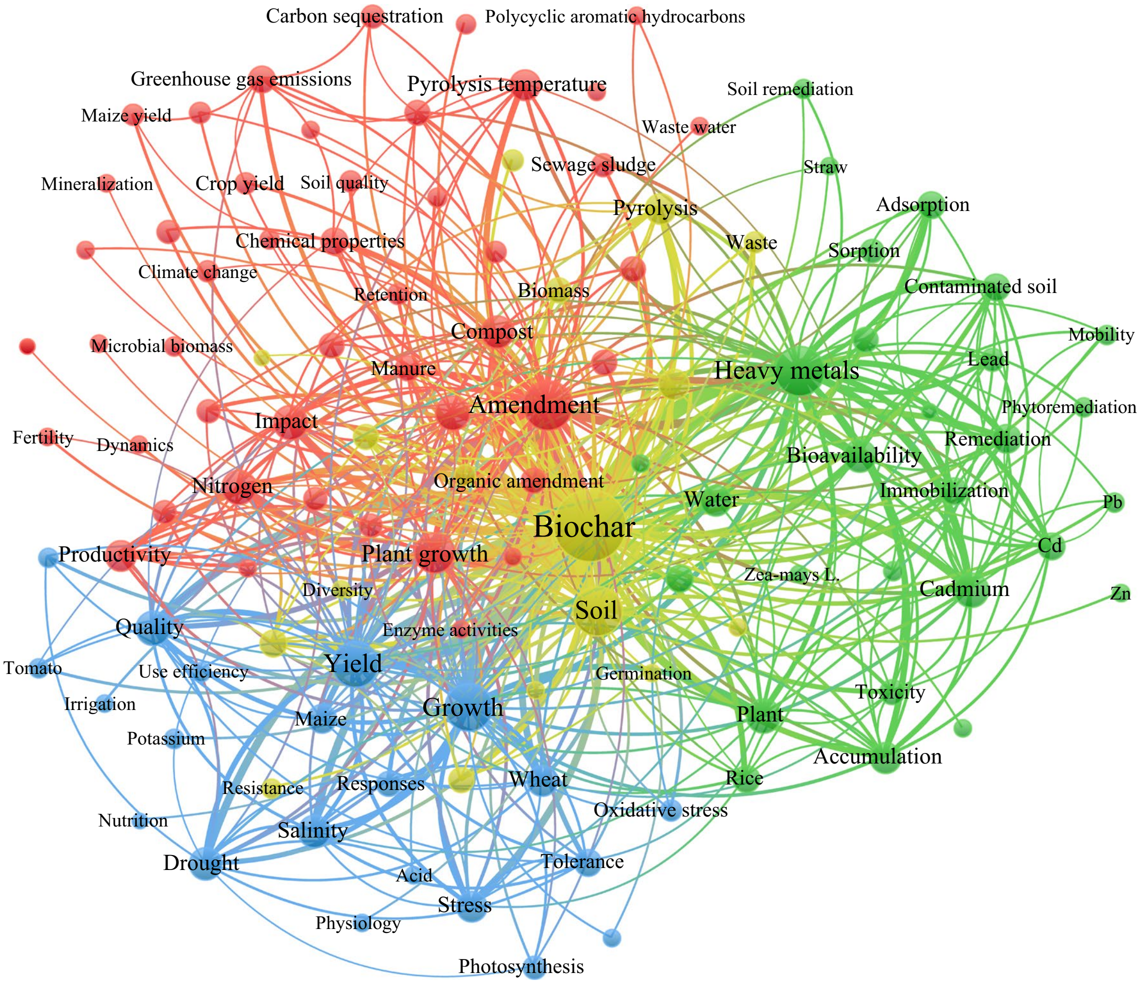


Fig. 1 Co-occurrence bibliometric map of 113 keywords of 913 publications from 1st February, 2004 to 1st February, 2024. The bibliographic data was retrieved from the "Web of Science Core Collection" with "TS = (biochar) AND TS = (soil) AND (TS = (crop yield) OR TS = (crop growth)) AND (TS = (stress) OR TS = (resistance) OR TS = (tolerance) OR TS = (salt) OR TS = (acidic) OR TS = (heat) OR TS = (pesticide) OR TS = (saline) OR TS = (waterlogging) OR TS = (compaction) OR TS = (crop lodging) OR TS = (drought) OR TS = (heavy metal))". The data was visualized using VOSviewer (version 1.6.20).

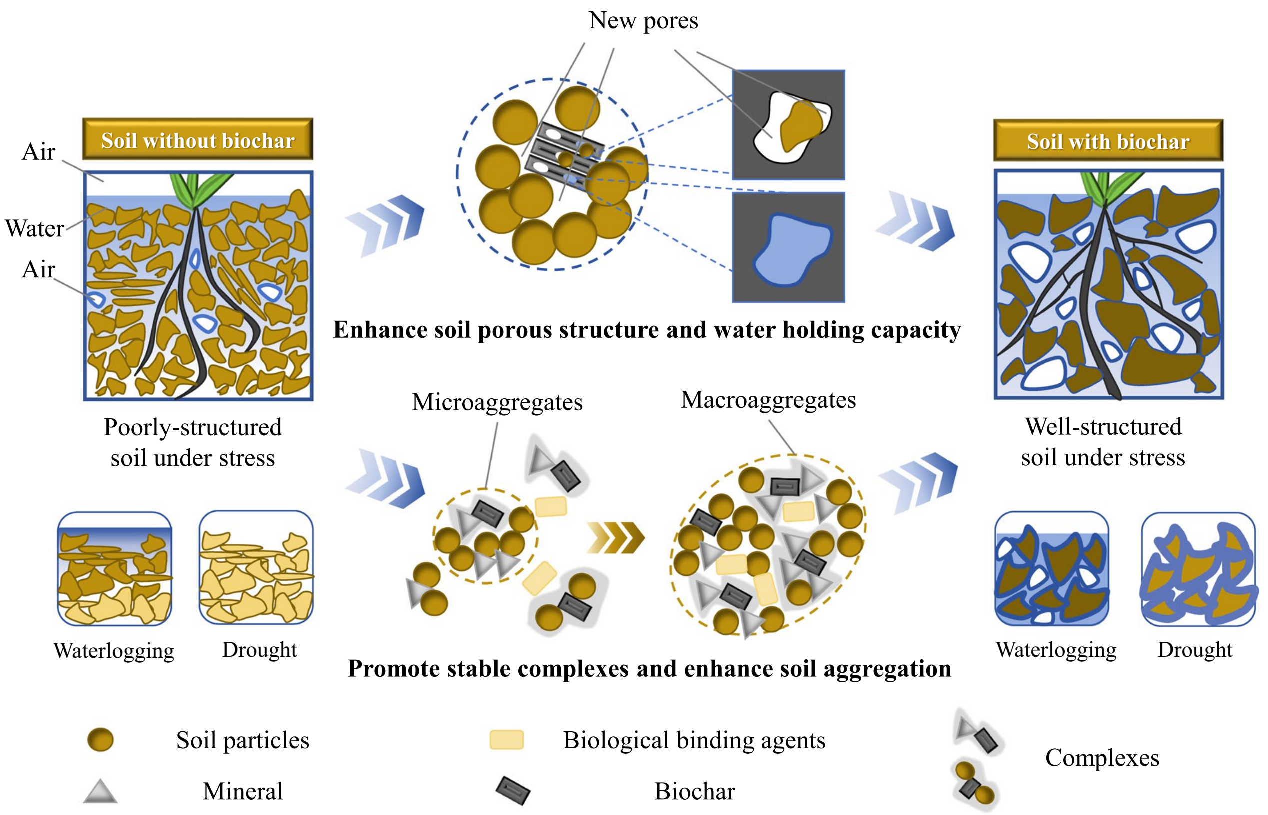


Fig. 2 The effect of biochar on promoting soil structure by improving soil physical properties and aggregate stability (Hardie et al. 2014; Yang and Lu 2021; Zong and Lu 2020; Ali and Elshaikh 2022)

growth under stresses by influencing soil properties, including nutrient elements, organic matter, and physical properties. The existing literature has extensively explored the intricate relationship between biochar and crop resilience in stress conditions. However, there is a lack of holistic and structured insight into how biochar bolsters stress tolerance and influences crop growth through root development. Therefore, this review endeavors to integrate current research in order to methodically and comprehensively delve into the intricate workings of enhanced stress resistance and growth facilitation in crops facilitated by biochar application. The specific objectives include elucidating: (1) The holistic impact of biochar amendments on soil's physical, chemical, and microbial attributes under stress conditions. (2) The intricate ways biochar amendments stimulate crop root development in stress scenarios, consequently nurturing enhanced crop growth. This review critically dissects the role of biochar in enhancing crop resilience under stress, offering a nuanced perspective on the future challenges and prospects associated with utilizing biochar for soil enhancement.

2 Biochar incorporation improves soil physical properties

Soil's physical characteristics significantly impact its function and crop growth (Yang and Lu 2021). Plants need well-aerated, moist soil with proper mechanical strength to thrive (Mckenzie et al. 2011). However, the use of modern agricultural machinery, irrational farming, and geographical conditions have led to soil compaction stress (Nawaz et al. 2013), which can degrade soil physical structure, thus stunting crop root growth (Moraes et al. 2020). As a potential alleviation management, biochar has several significant characteristics that can greatly benefit soil physical structure. Biochar's ample pores and vast specific surface area can help optimize compaction parameters by reducing soil bulk density and tensile strength (Blanco-Canqui 2017) while increasing water retention (Razzaghi et al. 2020). Additionally, by increasing the number of soil macroaggregates, biochar can further improve soil structure, thereby mitigating other stresses such as drought or saline (Fig. 2).

2.1 Improve soil porous structure

A healthy agricultural soil structure is achieved by a combination of well-developed soil aggregates and pore systems (Amoakwah et al. 2017). Soil pore plays an important role in improving water content and gas exchange, which is related to soil resistance to mechanical stress, hypoxia stress, and water stress (Moraes et al. 2020). Optimal levels of biochar input have been found to enhance soil pore structure (Sun et al. 2015) by increasing soil porosity and pore connectivity (Fang et al. 2019; Zhou et al. 2021), thereby improving crop growth by affecting root development in coastal salt-affected soil (Saifullah et al. 2018). The mechanisms behind biochar's ability to enhance soil porous structure are as follows (Hardie et al. 2014): (1) Large biochar particles create new voids, increasing soil porosity. (2) The inherent high porosity of the biochar allows for its integration into the soil porosity, introducing additional pores into the soil. (3) Small soil particles may enter the large pore size of biochar and build new pores, thus increasing the soil's porous structure. It is worth noting that the effectiveness of biochar in improving soil pore structure is intricately linked to several factors, including the size of biochar particles, soil properties, and the quantity of biochar input. Overuse of biochar actually reduces soil porosity and pore connectivity when an excess of biochar is introduced to the soil, filling up soil pores and reducing soil pore connectivity (An et al. 2022). Pore destruction caused by biochar aging also makes its effect on improving soil structure disappear (Yi et al. 2020), which decreases the melioration effect several years after biochar application (Yue et al. 2023). However, biochar's ability to enhance soil porous structure in saline soil can be improved by acid-modification, ball milling, or high pyrolysis temperature with larger pores and more internal pores (Lin et al. 2024; Wang et al. 2023).

2.2 Increase soil aggregates stability

The ability of soil to withstand mechanical stresses caused by rainfall, puddles, and compaction depends largely on soil aggregate stability (Canasveras et al. 2010). Soil aggregates are unstable and prone to disintegrating into fine particles, resulting in water and wind erosion, sedimentation that obstructs soil pores, and the development of surface crusts (Haque et al. 2021). Strengthening the stability of soil aggregate offers numerous benefits, including preserving and protecting organic matter, fostering soil porosity and structure, promoting root growth, facilitating crop available water infiltration, improving downward movement of salts, enhancing drought and saline resistance, and supporting microbial activity (Alghamdi 2018; Luo et al. 2018).

Enhancing the formation and stability of soil macroaggregates by incorporating biochar also contributes to alleviating soil mechanical and water stress. Incorporating biochar into the soil can increase soil macroaggregates (>2 mm) quantity and reduce soil micro aggregates (<0.25 mm) quantity, resulting in enhanced soil aggregates mean weight diameter (MWD) (Chen et al. 2022a) and stability. Biochar input is particularly important in drought, saline, or coastal clayey soil as it increases the aggregate stability and soil resistance to mechanical stress and thus enhances crop growth (Ali et al. 2017, 2021b; Zong et al. 2023). Three primary factors contribute to the efficacy of biochar in improving soil aggregate size and stability. First, biochar can promote soil microbial activity, leading to the formation of soil aggregates. Biochar input generally increases soil pH, which further improves soil microbial biomass carbon utilization and nutrient concentration (Cusack et al. 2009). Additionally, the newly formed pores after biochar incorporation, ranging from a few microns to tens of microns, provide habitats for microorganisms. The labile carbon from biochar serves as a carbon source to jointly promote microbial activities. This leads to increased exudate production by microorganisms and soil aggregates forming (Palansooriya et al. 2019; Zong and Lu 2020), thereby enhancing soil aggregation and stability. Secondly, biochar input can increase soil organic carbon, which can bind soil particles together and facilitate the aggregation of soil particles, leading to enhanced soil aggregate stability (Yang and Lu 2021). In addition, the pore structure and surface of biochar can encapsulate, adsorb, and protect soil mineral and organic matter, thereby facilitating the forming of stable soil organic–inorganic complexes, which can also accelerate the formation of aggregates (Burgeon et al. 2021; Prayogo et al. 2014). To further enhance the stability of aggregates in saline-alkaline soil, Fe-modified biochar has been prepared to form organo–Fe complexes and thus increase the soil organic carbon content (Chen et al. 2024).

2.3 Decrease soil bulk density

Bulk density is a crucial factor that affects soil productivity, indicating soil compaction (Blanco-Canqui 2021), affecting crop resistance to drought and salt stress (Ali et al. 2017), and thus contributing to the facilitation of root growth. Biochar incorporation has been found to play a pivotal role in determining soil bulk density, water-holding capacity, nutrient availability to plants, and microbial processes (Haque et al. 2021). Adding biochar to sandy soil with high water stress can increase porosity and macroaggregates and reduce bulk density (Chen et al. 2022a; Tran et al. 2022). Blanco-Canqui (2021) found that biochar addition significantly reduced soil bulk density in 60% of cases after conducting 126 tests in sandy soil. Nevertheless, the impact of biochar on soil density is still a subject of debate, as it depends on several factors, including feedstock, biochar input amount, and soil properties. In addition, biochar's long-term effectiveness in reducing bulk density is controversial due to the rapidly declining trend of change in bulk density (Blanco-Canqui 2021). After years of aging, biochar in the soil may transfer downwards (Dong et al. 2019) and be mechanically fragmented, causing a mass loss and turning it into smaller particles that can enter soil pores and fill the sand voids (Madari et al. 2017), and potentially cause an increase in soil bulk density.

2.4 Increase soil water holding capacity

As mentioned earlier, applying biochar to soil can also increase soil water retention capacity, thereby alleviating saline and drought stress in crops (Ali and Elshaikh 2022). This is mainly due to its rich pore structure and hydrophilic functional groups (Alessandrino et al. 2023; Amoakwah et al. 2017). Biochar can potentially enhance pore distribution, which is closely associated with water storage (Novak et al. 2012). Although the porosity and pore size of biochar prepared from various source materials differ significantly (Lu and Zong 2018), most biochar pores are over 5 μm in diameter (Zong and Lu 2020). These large voids can directly increase the water storage ability and improve soil water retention capacity under high matric potential (More than or equal to −0.1 MPa). Meso-porosity is also a key biochar characterization to increase water-holding capacity and decrease hydrophobicity (Adebajo et al. 2022). In drought conditions, biochar's porous structure facilitates rainwater infiltration into the topsoil through large pores while retaining water in its small pores after heavy rain. This results in an elevation of soil moisture content (Abel et al. 2013; Asai et al. 2009). Additionally, applying biochar with porous structure and low-density characteristics to soil has been found to result in a physical dilution effect, increase the diameter size of soil aggregates (Zong and Lu 2020), and create fillers or pores by changing the soil pore system (Haque et al. 2021), increasing the new pores in soil and storing moisture. Studies have shown that biochar can effectively stabilize soil water-holding capacity by reducing its hydraulic conductivity (Amoozegar and Warrick 1986). Soil with high hydraulic conductivity does not retain water and nutrients, leading to reduced soil productivity (Chen et al. 2018). In soils with different textures, sandy soils present a significant increase in water retention capacity after biochar input due to enhanced soil pores, pore-throat size, and tortuosity (Liu et al. 2017). Blanco-Canqui (2017) mentioned that biochar enhances saturated hydraulic conductivity in fine-textured soils and conversely decreases it in coarse-textured soils.

2.5 Improve soil mechanical properties

Tensile strength and cohesion are indicators of soil compaction that depend on soil aggregate strength and influence root growth and erosion resistance of root-soil composite (Chen et al. 2022b). By improving soil pore structure and increasing soil aggregate size, biochar amendment into the soil also reduces soil tensile strength and cohesion. Awe et al. (2021) demonstrated that in paddy soils, biochar input enhanced soil shear strength, reduced stiffness degradation, and improved soil microstructural stability. The soil tensile strength and cohesion reduction can improve the soil cultivability of farming operations and reduce the mechanical resistance of the root system to promote crop growth (Yang and Lu 2021). There are several mechanisms for biochar's effect on reducing soil tensile strength and cohesion. Firstly, biochar input reduces tensile strength and cohesion by creating physical segmentation. The large biochar size can physically separate soil particles after incorporation. Biochar inner pores enable some soil particles to enter, which also physically divides soil particles. Secondly, biochar increases the number of soil macroaggregates, creating extra voids between soil particles, reducing the binding force between them, and further reducing the tensile strength and cohesion. In addition, biochar input increases soil organic carbon, promoting plant growth in soil micro-cracks, thus reducing the binding force between soil particles.

3 Biochar effects on soil chemical properties

Biochar boasts particular physical and structural characteristics that establish an ideal environment for plant roots to flourish even under stress. Moreover, biochar is replete with substantial ash components alongside abundant N, P, and K fertilizers and mineral nutrient elements, making it beneficial to the soil under nutrient starvation and crop uptake under other stresses (Bagues et al. 2024; Pandit et al. 2018). Biochar's surface is also enriched with oxygen-containing functional groups, rendering it a superior preference for augmenting soil with nutrients while mitigating heavy metal and organic pollution stresses (Fig. 3).

3.1 Supplements soil nutrients

3.1.1 Adjusts soil pH

Soil acidification can reduce nutrient availability and increase the mobility of some toxic heavy metals (Huang et al. 2023). Maintaining proper soil pH is essential for maximizing crop growth, and biochar is a valuable tool for achieving this goal and alleviating acid stress (Bolan et al. 2023). Biochar is effective in buffering soil pH due to its alkaline properties resulting from its carboxyl and

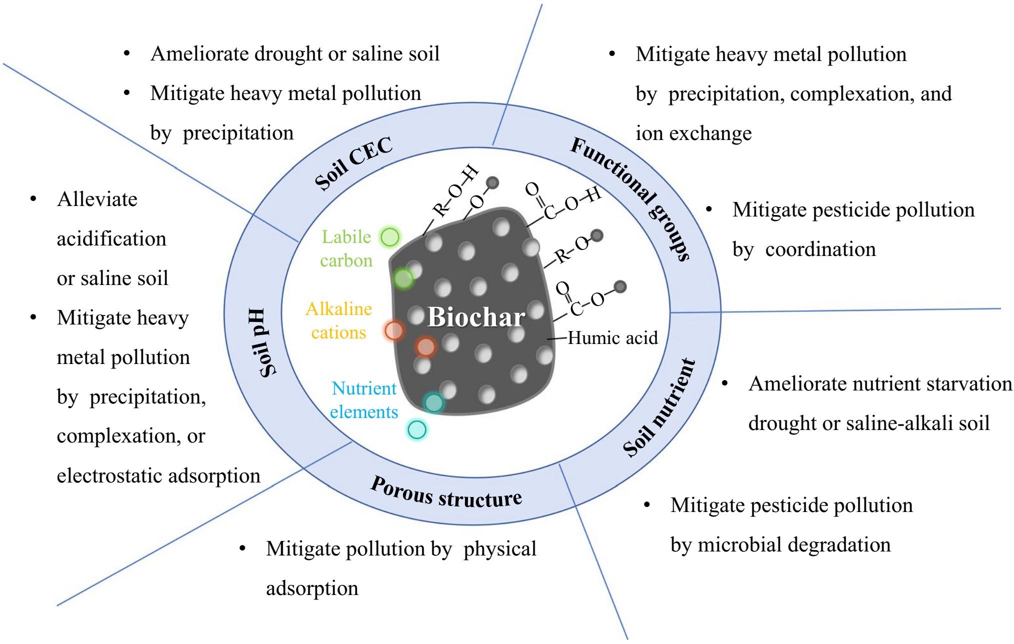


Fig. 3 The impact of biochar on promoting soil chemical properties under stresses (Mosharrof et al. 2021; Wu et al. 2015; Tomczyk et al. 2019; Li et al. 2017; Kookana et al. 2011)

phenolic functional groups on the surface. Additionally, the dissolved alkaline cations inherent in biochar ash can raise soil pH (Mosharrof et al. 2021), known as the liming effect. It's important to note that this effect is more obvious but less long-lasting than the soil pH regulation effect brought by carboxyl and phenolic groups, which have a more stable impact on soil pH that becomes more apparent with time (Ch'Ng et al. 2019; El-Naggar et al. 2018; Jiang et al. 2022). However, the liming effect of biochar does not always have a positive impact. It could result in lower yield of some pH-sensitive crops like legumes in the short term but increase the yield several years later due to biochar's slow release effect of nutrients and its long-term impact on soil pH. In saline soil, acid modification by increasing oxygen-containing functional groups has been widely used (El-Sharkawy et al. 2022).

3.1.2 Supplements soil nutrients

Natural geographical conditions, excessive tillage, or saline or water stress can negatively affect soil fertility and crop growth, leading to nutrient deficiency or imbalance (Baijukya et al. 2021). Biochar input is effective in increasing soil nutrient content of low-fertile soils, especially nitrogen (N), phosphorus (P), and potassium (K) levels (Liu et al. 2013). These elements are crucial for plant growth and are present in the biomass materials for biochar preparation. During biochar pyrolysis, most of the N, P, and K elements are concentrated and enriched in the resulting biochar. Wu et al. (2015) discovered that the total N, P, and K contents of common biochars are 0.1–7.8%, 0.27–7.3%, and 0.09–5.8%, respectively. Therefore, biochar incorporation can greatly enhance the content of N, P, and K in soil. In addition, biochar incorporation can significantly increase K largely by increasing the exogenous water-soluble K content, which in turn promotes the crop's absorption of K. Compared to N and P, the available K content of biochar is generally higher after biomass pyrolysis (Wu et al. 2015). The water-soluble K content in biochar is typically the highest among these nutrients (Yu et al. 2005), although the content of N, P, and K varies depending on the raw materials and pyrolysis processes used to yield biochar. Generally, herbal biochar tends to exhibit higher N, P, and K content than woody biochar.

Apart from increasing the N, P, and K levels, biochar increases the mineral nutrients that are essential for plant growth, such as calcium (Ca), magnesium (Mg), copper (Cu), manganese (Mn), zinc (Zn), iron (Fe), and other trace elements. Ca and Mg, in particular, are crucial for the metabolic activities of plants, as Ca is an essential component of plant cell walls, while Mg is the central element of plant chlorophyll molecules, an important part of plant enzymes. According to previous studies, Ca and Mg content can be as high as 0.18–350 and 0.36–27 g kg^{-1} (Bourke 2007; Raveendran et al. 1995; Skodras et al. 2006) in biochar. Biochar addition to soil can not only directly increase available nutrient levels (Zhao et al. 2014), but also enhance crop nutrient acquisition under saline-alkali stress (Zhao et al. 2020). To further decrease salinization indexes in saline-alkali soil, calcium-modified biochar with more Ca and Mg ions can reduce total alkalinity through precipitation and ion exchange (Li et al. 2023).

3.1.3 Increases soil cation exchange capacity

Increased soil CEC is one of the key factors in enhancing soil resistance to drought or saline stress (Akinbile et al. 2016; Artiola et al. 2012). To enhance soil CEC, biochar amendment is a common strategy (Afaf et al. 2023; Nguyen et al. 2018). The formation of oxygen-containing functional groups resulting from biomass pyrolysis, namely carboxyl and hydroxyl groups, is considered the principal factor behind the CEC of biochar (Tomczyk et al. 2019). Biochar CEC varies depending on the raw material and pyrolysis temperature during production. Generally, biochar prepared from biomass with high ash content exhibits a higher CEC (Lehmann et al. 2011) owing to the promotion of oxygen-containing functional groups on the biochar surface by alkali metals. In addition, when the temperature of biomass pyrolysis rises, volatile organic acids are gradually lost (Lehmann et al. 2011), and the specific surface area increases, thereby reducing the surface electrical density of the biomass (Hossain et al. 2020), resulting in a decrease in biochar CEC and its ability to increase soil CEC. However, a review by Laghari et al. (2016) demonstrated that the feedstock played a more critical role in determining CEC than the pyrolysis temperature.

Furthermore, the increased cation exchange capacity of biochar helps relieve heavy metal stress tolerance by working on reducing pollution through adsorbing and precipitating heavy metal ions (Dai et al. 2020). Wang et al. (2024) found that biochar with higher CEC showed higher adsorption efficiency for Cu and Pb.

However, fresh biochar does not have a desirable CEC compared to aged biochar (Lehmann et al. 2011). After experiencing the aging process and being oxidized in soil, the oxygen functional groups develop (even the aromatic rings may be replaced by COO− oxygen-containing functional groups (Mao et al. 2012) after a long aging process). Organic matter adsorption enables it to increase the charge density (Li et al. 2018b), thereby enhancing the soil CEC. The retention effect of nutrients and mineral elements is also the main reason why one-time biochar returning to the field can increase crop yield continuously (Gai et al. 2014; Gao et al. 2016).

3.2 Reduces soil pollutant concentration

3.2.1 Reduces metal pollution in soil

Trace elements, such as Cu, Mn, Zn, and Fe, are crucial to crop growth. However, excessive trace elements can negatively affect the structure and function of plant cells, thereby impeding crop growth and leading to crop pollution (Xiang et al. 2021b). Biochar can be an effective solution for reducing the mobility of toxic metal elements in soil contaminated with trace elements and heavy metals. Research has shown that biochar demonstrated significant potential in reducing the availability of Cu, Zn, Mn, Fe, Al, Cd, and Pb in the soil through adsorption (Albert et al. 2021; Hailegnaw et al. 2020; Mosharrof et al. 2021; Yang et al. 2016; Yuan and Xu 2011). Biochar is also remarkable in alleviating heavy metal stress in crops under other stresses. For instance, biochar has been recognized as a beneficial amendment for alleviating Cd stress in wheat and Pb stress in maize under drought stress (Adejumo et al. 2020; Anwar et al. 2023).

One of the fundamental processes by which biochar can alleviate heavy metal toxicity in soil is its strong CEC. This mechanism can transfer heavy metal elements from carbonate or phosphate precipitation, effectively reducing their biological toxicity. Biochar contains abundant P, Ca, and Mg elements, and metal elements in the soil, including Mn, Cu, Zn, and Cd, can exchange cations with Ca and Mg carbonates, forming insoluble formations (Lei et al. 2020; Muhammad et al. 2021). In addition, enriched with P, biochar enhances its alkaline property, thereby facilitating the release of phosphorus from the soil, which further limits the bioavailability of Zn and Cd from the formation of phosphates. Hodson et al. (2000) even considered the P/Zn molar ratio as a crucial indicator affecting Zn stability in soil treated with biochar.

The huge surface area and surface functional groups of biochar can enhance the binding affinity of heavy metals to its surface. The presence of organic functional groups, namely carboxyl, amino, and hydroxyl, facilitates the adsorption of heavy metals in soil (Li et al. 2017). Apart from the precipitation mechanism, the organic functional groups of biochar also provide adsorption sites for metals through complexation or ion exchange, effectively reducing their bioavailability. According to He et al. (2017), fruit tree biochar prepared at 400 °C has been shown to carry humic acid as high as 100 mg L^{-1} carbon, and these biochar-loaded organics increased Cu adsorption by up to 28.2%. In addition, the labile carbon carried by biochar increases soil dissolved organic carbon content while providing a new adsorption site for heavy metals, including Cu, Mn, and Cd (Hailegnaw et al. 2020; Jansen et al. 2002; Lu et al. 2017; Pietikäinen et al. 2000). This highlights biochar's potential as a promising solution for mitigating heavy metal toxicity in soil.

Biochar's liming effect is also important for heavy metals adsorption and precipitation enhancement. The ash component of biochar is rich in alkaline cations. After incorporation into the soil and dissolution in water, biochar helps regulate soil pH, thus promoting the precipitation of heavy metals, including Cd, Fe, Al, Zn, and Cu (Siebers and Leinweber 2013). Furthermore, increased soil pH also facilitates the complexation and electrostatic adsorption of organic matter and heavy metals (Mcbride 1982). For example, a pH increase can promote the adsorption of hydrolyzed $CuOH^+$ species by biochar (Atanassova and Okazaki 1997). As a result, the bioavailability of heavy metals is reduced, thus minimizing their potential harm.

Additionally, biochar application leads to a rise in soil pH, which subsequently causes the precipitation of Al^{3+} as insoluble Al oxide/hydroxide (Ritchie 1994) or the conversion of Al species into $Al(OH)^{2+}$ and $Al(OH)_2{}^+$ monomers. These substances can be readily adsorbed through ion exchange with –COOH or phenolic –OH groups on the biochar surface (Qian and Chen 2014; Qian et al. 2013). Furthermore, the increase of soil pH accelerates the separation of organic matter, thereby increasing the deprotonated acidic functional groups (increasing the CEC) in the soil, further promoting metals' adsorption onto the organic matter surface. For instance, biochar has been found to facilitate the binding of Al, thus reducing its bioavailability (Evans 1989). Additionally, rice straw biochar is rich in Si, which creates Al–Si compounds after incorporation, further decreasing Al availability in soil (Qian et al. 2016).

3.2.2 Reduces pesticide concentration

Pesticide application is common in modern agriculture to foster healthy crop growth. However, given the long persistence of pesticides, excessive use of pesticides can reduce soil quality and harm soil microbes (Anwar et al. 2023; Khorram et al. 2016; Meng et al. 2019; Vangronsveld et al. 2009; Zhou and Song 2004). To address these negative effects under pesticide stress, incorporating biochar into the soil is an excellent solution. Biochar can not only enhance the adsorption of different pesticides but also reduce their bioavailability (Kookana et al. 2011; Yang and Sheng 2003; Yu et al. 2006), thus mitigating pesticide contamination risks to groundwater (Ahmad et al. 2014; Laird et al. 2010). Ali et al. (2019) demonstrated a noteworthy decrease (86–95%) in organochlorine biological uptake in growing vegetables after incorporating various biochars. Although reversible and irreversible biochar adsorption occurs for pesticides, irreversible adsorption is primarily dominated by surface-specific adsorption, micropore entrapment, and coordination into the condensed structure (Sopeña et al. 2012; Wang et al. 2010; Yu et al. 2010). In addition, biochar input increases new soil organic carbon, which stimulates soil microbial activity, further facilitating microbial degradation of pesticides (López-Piñeiro et al. 2013; Qiu et al. 2009; Zhang et al. 2006). Therefore, biochar's capability to reduce pesticide pollution is directly proportional to its organic carbon level, specific surface area, and pore structure (Kookana et al. 2011).

4 Biochar input promotes soil nutrient cycling

Soil nutrient cycling can be improved by using biochar as it helps alleviate multiple stresses (Carr et al. 2019; Parida and Das 2005; Xia et al. 2023). The surface characteristics of biochar, such as its abundant oxygenated functional groups and porous structure, make it effective in retaining nutrient content, reducing nutrient loss in the soil, optimizing soil microbial community structure, and promoting nutrient cycling. All these benefits help crops resist various stresses (Egamberdieva et al. 2019; Kul et al. 2021).

4.1 Promotes soil nitrogen cycle

Nitrogen is a major factor that limits crop growth and yield (Xia et al. 2023). However, nutrient starvation is not the only stress that can adversely affect the nitrogen cycle. Waterlogging (Lian et al. 2023), drought (Hu et al. 2023), and saline (Rupp et al. 2021; Sun et al. 2022) soils can limit the availability of nitrogen to crops by promoting denitrification, reducing nitrogen fixation and nitrification, or increasing leaching loss. Although nitrogen fertilizers have been admitted as an ameliorator of soil under stress, excess nitrogen can lead to soil acidification (Zhang et al. 2016) and water pollution. In contrast, biochar has an advantage in ameliorating soils. Apart from directly increasing the nitrogen content, biochar also promotes nitrogen utilization of crops by retaining nitrogen and reducing leaching loss (Liu et al. 2022; Lu et al. 2020; Pratiwi et al. 2016; Xia et al. 2023) (Fig. 4). Moreover, Azadi and Raiesi (2023) also found that applying sugarcane bagasse biochar increased potential net ammonification (177–218%), nitrification (70–83%), and N mineralization (92–110%), thus enhancing microbial biomass N (MBN) and urease activity in saline Pb-polluted soils. Biochar can effectively reduce nitrogen loss induced by surface runoff, which is the main route for nitrogen loss. Biochar incorporation can also reduce nitrogen loss by promoting the nitrogen metabolism process. Firstly, biochar can accelerate the process of transforming organic nitrogen into ammonia by increasing soil urease activity and the abundance of ammonia-oxidizing bacteria (AOB) and ammonia-oxidizing archaea

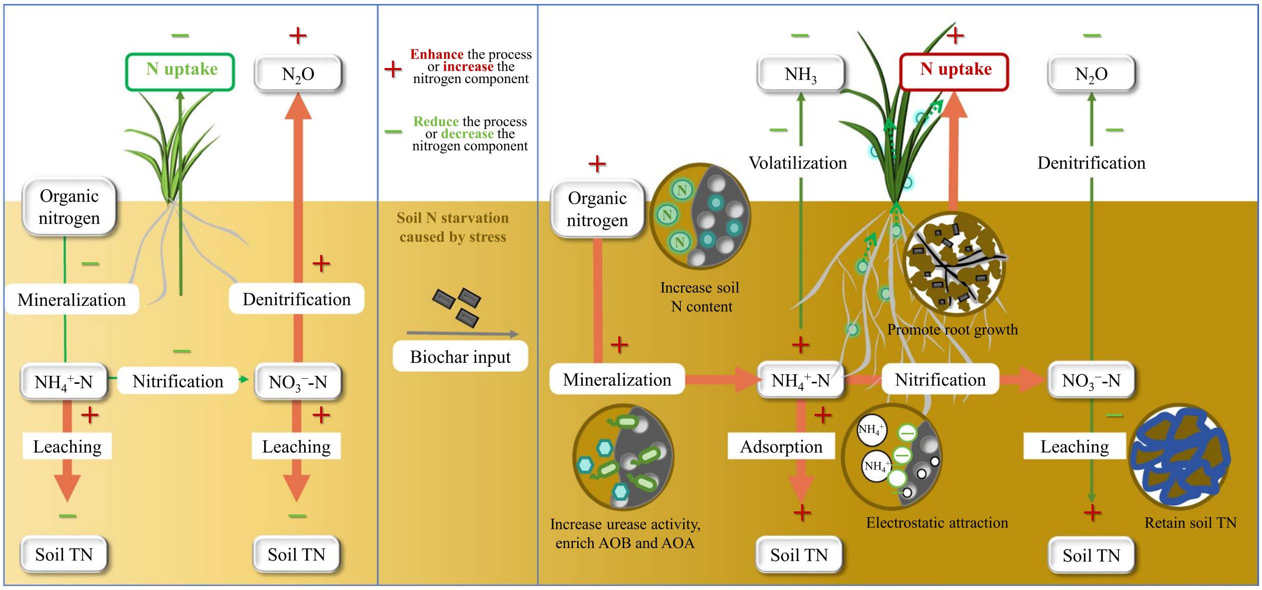


Fig. 4 The effect of biochar on promoting soil nitrogen cycle under stresses (Liu et al. 2022; Lu et al. 2020; Pratiwi et al. 2016; Xia et al. 2023)

(AOA). Then, the elevated ammonia nitrogen can be converted into nitrate nitrogen through nitrifying bacteria for root utilization (Liu et al. 2022). Biochar can also trap nitrogen through functional groups that exchange with N through positively/negatively charged ions and porous structures that retain nitrogen (Van Zwieten et al. 2010). Specifically, carboxyl can adsorb ammonia nitrogen through electrostatic attraction, hindering denitrification and reducing nitrous oxide and ammonia emissions in soil. Nevertheless, it is not clear how effective biochar is in reducing soil nitrous oxide and ammonia volatilization emissions under different soil management modes and soil physicochemical properties. However, biochar input can provide many benefits, such as reducing soil bulk density and improving soil structure, thus increasing microbial activity and root biomass (Song et al. 2020), improving N uptake by crop roots, and increasing nitrogen utilization. Therefore, biochar can help retain soil TN, improve nitrogen uptake and utilization by roots through affecting the nitrogen transformation process, consequently leading to a rise in nitrogen use efficiency of crops even under stresses.

4.2 Promotes soil phosphorus cycle

Phosphorus is an essential plant macronutrient that plays a vital role in various physiological processes, such as photosynthesis and energy transfer (Kahura et al. 2018), which makes it also a key role in regulating plants' physiological responses to abiotic stresses, including drought, saline, heat, and heavy metal (Khan et al. 2023a). By adding biochar to the soil, the availability of P can increase through multiple mechanisms. Biochar acts as a nutrient supplement and adsorbs P through hydrogen bonding mechanism due to its huge specific surface area and rich charge density from the oxygen functional group (Soinne et al. 2014). In acidic soils, biochar also promotes the release of available P by increasing soil pH due to the immobilization of P binding with Al and Fe minerals (Maru et al. 2020). Biochar can also increase alkaline phosphatase activity and increase available P content by increasing the expression of alkaline phosphatase (*phoD*) with increased soil pH (Yang and Lu 2022). Liu et al. (2022) discovered that, on account of increasing soil pH, adding wheat straw biochar reduced cumulative TP leaching in soils, confirming great importance of biochar's liming effect on soil P availability. Additionally, biochar can promote P uptake by plant roots (Dey et al. 2021) and total soil P (Egamberdieva et al. 2022) under saline stress by increasing the abundance of tricalcium phosphate-solubilizing bacteria. Modified biochar has also been found to increase available P levels in Cd- and Pb-contaminated alkaline soil (Zhang et al. 2022).

4.3 Improves soil microbial community structure and soil enzyme activity

4.3.1 Soil microbial community structure

The preservation of soil integrity, functionality, and sustainability is contingent upon the diversity and richness of microbial populations (Abdullah et al. 2021; Zhao et al. 2014). These properties play a crucial role in several essential biochemical processes, including nutrient cycling and biodegradation of toxic contaminants through enzymatic reactions (Xu et al. 2019). However, soil microbial communities are sensitive to stresses (Raiesi and Dayani 2021), which can be optimized after biochar application by enhancing biological functioning and diversity, and enzyme activity (Azadi and Raiesi 2021; Zhao et al. 2024; Zhu et al. 2022b).

After incorporation, biochar changes soil bacterial and fungal community structure by affecting soil nutrient availability and physical structure. Herrmann et al. (2019) proposed four mechanisms for biochar interaction on microbial communities: (1) the pore structure of biochar may prevent predators or competitors, thereby creating a favorable ecological niche for bacteria and fungi; (2) increased nutrient and labile organic carbon input; (3) reduced nutrient leaching and contaminates toxicity, and (4) enhanced water holding capacity. However, present studies hold different opinions on bacterial and fungal community structure changes following biochar incorporation into soil (Ali et al. 2019, 2022b; Herrmann et al. 2019; Yabe et al. 2017), which result from various feedstock and soil physiochemical environments. Hence, the function of biochar within the microbe community is different, especially when it is applied to reduce organic and inorganic contaminants pollution (Herrmann et al. 2019). Generally, after biochar application, bacteria showed little to no significant community structure change in many soil environments, while fungal community structure showed a significant change. This is because bacteria are relatively more flexible and responsive than fungi. Therefore, many studies reported that biochar application into soil showed limited bacterial community structure, but it is widely acknowledged that biochar input improves the abundance of Proteobacteria and Actinomycetes, while decreasing the abundance of Chloroflexi and Acidobacteria (Ali et al. 2019; Cole et al. 2019; Li et al. 2019). The reason is that Proteobacteria mainly exit in eutrophic environments, and Actinomycetes are known to play a critical role in the turnover of organic matter (Ali et al. 2019; Fierer et al. 2007), while Chloroflexi and Acidobacteria are often found when soil is oligotrophic and with low pH (Jenkins et al. 2017).

Compared to bacteria, fungi tend to adapt more slowly to new environments. Hence, the fungal community usually changes significantly after biochar incorporation into the soil (Luo et al. 2017; Yao et al. 2017). Generally, biochar input reduces fungal abundance (Imparato et al. 2016; Kolton et al. 2017; Zheng et al. 2016) due to enhanced saprophytic competition from readily degradable organic carbon sources and increased soil pH. This, in turn, reduces fungal diversity while inhibiting the growth of fungal pathogens (Dai et al. 2018). Nonetheless, recent studies have presented a contrary finding (Gao et al. 2021b; Luo et al. 2017). Importantly, soil microbial community changes mainly benefit crop growth after biochar input, which can significantly improve soil quality, structure, and stress tolerance. For instance, Khan et al. (2023c) found that date palm waste biochar addition promoted sandy soil fertility under drought, heat, and saline stress by enriching plant growth-promoting microorganisms. Xia et al. (2023) showed that adding 2% maize straw biochar to acidified soil enhanced the utilization of soil carbon sources by influencing soil microbial activity, thus reducing the Al^{3+} stress. Azadi and Raiesi (2021) also indicated that 1% sugarcane bagasse biochar at 400 ℃ protected soil microbial communities under Cd and saline stresses by retaining Cd and supplying C substrate for microbial uptake and activity.

4.3.2 Soil enzyme activity

Soil enzyme activity is a crucial parameter in assessing soil health, as it is highly sensitive to soil contaminants and closely interacts with microbial activity (Bandara et al. 2020; He et al. 2019). Biochar application can increase enzyme activity that enhances stress resistance, such as catalase and dehydrogenase (Beheshti et al. 2018; Campos et al. 2020; Chen et al. 2019; Das et al. 2021; Liu et al. 2023; Mierzwa-Hersztek et al. 2020). In addition, soil enzymes are also essential for nutrient cycling, such as N, P, K, and their impact on plant nutrient absorption (Nie et al. 2018; Sarkar et al. 2016). Extensive research has concurred on the advantageous effects of biochar on enzyme activity promotion related to nutrient cycling, such as urease, sucrase, and phosphatase (Cao et al. 2023; Du Qian et al. 2021; Xiaotong et al. 2022; Zhao et al. 2022). Chen et al. (2020) reported a rise of urease activity by 19–213%, sucrase activity by 4.6–12.5 times, and catalase activity by 19–150.8% in the soil after incorporating different biochar. The mechanism for enzyme activity enhancement is the improved soil environment brought by biochar application, which includes high mineral and nutrient content input and high porosity. Further, the huge surface area of biochar also promotes soil enzyme activity by creating an ideal habitat for microorganisms to thrive, leading to its robust growth and reproduction (Bandara et al. 2020; Gul et al. 2015). Moreover, organic pollutants and heavy metal ions can inactivate enzyme proteins and inhibit soil enzyme activity (Chen et al. 2019; Tan et al. 2018). Adding biochar reduces heavy metal and organic contaminants in soil, thereby promoting soil enzyme activity. Chen et al. (2008) demonstrated a significant reduction of Cd and phthalate diester concentrations in soil after biochar application and further established a significant and negative correlation between the enzyme activities and the contaminants above. Furthermore, the enzyme activity is inhibited under acidic conditions, which leads to the disruption of ionic and

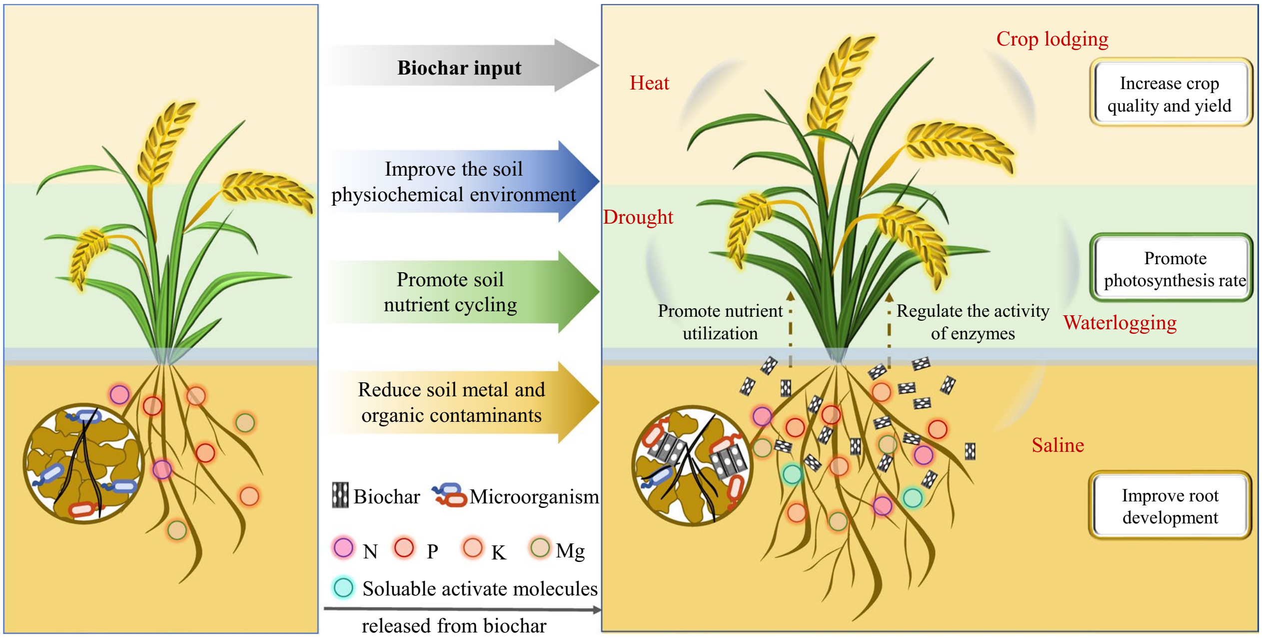


Fig. 5 The effect of biochar on enhancing crop growth under stresses (Jabborova et al. 2023; Chaganti and Crohn 2015; Xiang et al. 2017; Huang et al. 2021; Qian et al. 2024; Abideen et al. 2020; Chen et al. 2021)

hydrogen bonds in the active center of the enzyme and the alteration in the three-dimensional shape (Frankenbergerr and Johanson 1982). Campos et al. (2020) revealed that biochar incorporation positively correlated soil pH and dehydrogenase activity. Hence, the liming effect of biochar is also important for promoting enzyme activities.

5 Biochar application benefits on crop growth

Various studies have substantiated the efficacy of biochar incorporation into the soil to enhance stress tolerance by improving the soil's physicochemical properties alongside the composition of its microbial community and enzyme activities. Furthermore, it has been found to decrease soil metal and organic contaminants. These benefits are attributed to the promotion of root development, which leads to stronger stress resistance of roots, better nutrient uptake, increased photosynthesis, and improved crop quality and production. (Fig. 5).

5.1 Biochar promotes crop root growth

Biochar input generally improves the whole plant root growth, including root volume, uptake capability (Ali et al. 2022c; Li et al. 2022; Maccarthy et al. 2020; Zhang et al. 2013), and root biomass (Xiang et al. 2017). Research has indicated that biochar application in soil can effectively improve root shape mainly by creating a conducive physical space environment and nutrient supplementation. Biochar can also reduce root growth resistance by decreasing soil bulk density and improving soil mechanical environment (Bengough and Mullins 1990; Haifeng et al. 2016). This results in an increase in the open angle, root system width, and fine roots (Abiven et al. 2015). Under heat stress, biochar input can improve soil bulk density, bacterial community structure, and organic matter content, thereby improving root and rhizome traits (Huang et al. 2021). Additionally, biochar input directly supplements soil nutrient content, indirectly enhances nutrient cycling, and augments nutrient availability, guaranteeing crop roots have enough nutrients for growth (Prendergast-Miller et al. 2014). By increasing essential nutrient availability and soil enzyme activity, biochar input can enhance root diameter, surface area, and volume under drought and saline stress (Jabborova et al. 2023, 2022). Biochar also improves the rhizosphere environment of crop plants by enhancing the proportion of Proteobacteria to Acidobacteria, in which Proteobacteria are responsible for symbiotic nitrogen fixation and nutrient cycling remineralization (Babujia et al. 2016; Smit et al. 2001), while Acidobacteria are often accompanied by a reduction in plant productivity (Lewis et al. 2012). Notably, Han et al. (2023) observed that cotton straw biochar led to the maintenance of maize root length during the grain-filling stage, whereas the control group showed a reduction of 21–34%, which indicated that biochar could delay root senescence.

Biochar's effect on crop roots is more prominent in improving root system development. Xiang et al.

(2017) further noted that the increase in root tip and root length caused by biochar input was much greater than that of biomass. According to most studies, rather than taproot (Zhang et al. 2013), biochar input primarily increases the growth of lateral roots (Ghassemi-Golezani and Farhangi-Abriz 2021; von Wangenheim et al. 2020), which are beneficial to the effective absorption of water and mineral elements (von Wangenheim et al. 2020), especially to ensure plant water absorption under drought stress. Furthermore, biochar incorporation promotes lateral root formation through auxin accumulation, abscisic acid, ethylene reduction, and nitrate transporters repression (Huang et al. 2021; Kazan 2013).

However, compared to germination, root elongation is more sensitive to harmful components that biochar may carry, such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), environmentally persistent free radicals (EPFRs) (Xiang et al. 2021a). Therefore, the type and dosage of biochar should be carefully considered. Visioli et al. (2016) found that the root length of cucumber and sorghum could be affected at 0.5% of conifer and poplar biochar input, with marked impairment at > 5% of all biochars. To promote root growth, it is recommended to add biochar within 2%. Additionally, the enhancement of some biochar properties may lead to negative effects on the root system. For example, biochar nanoparticles play an important role in the immobilization of pollutants due to their negatively charged surfaces and small sizes (Bhandari et al. 2023). However, it can attach to root surfaces and probably form a shell-like structure, which can greatly inhibit the net influx of heavy metal ions into root cells (Yue et al. 2019) but hinder nutrient uptake and growth of roots simultaneously (Yin et al. 2024). Therefore, the application effects and risks of new biochar materials need to be carefully evaluated.

5.2 Mechanisms for root development in improving the ability to resist stress

5.2.1 Increases the ability of soil to resist saline stress

In soils with high salt ion concentrations and high pH, plant root growth is limited due to ion toxicity, osmotic imbalance, high pH, and lower soil organic matter levels (Alkaraki 2008; Elgharably 2011). However, biochar application can alleviate this stress and further improve crop growth (Chaganti and Crohn 2015). In addition to guaranteeing a favorable physicochemical environment (Akhtar et al. 2015) for crop root growth, biochar can also increase the permeability coefficient by improving the K^+/Na^+ ratio and K availability (Abrishamkesh et al. 2015; Chakraborty et al. 2016) and enhancing rhizosphere microorganisms activity (Khorram et al. 2016; Van Zwieten et al. 2010) under saline stress. A good root system development after biochar application can further enhance the oxidase activity, which can further enhance the antioxidant defense system and plant cell resistance in saline soils. Recent research has highlighted the remarkable influence of biochar on promoting plant growth in saline-alkali soils. Biochar application can lead to a substantial rise in superoxide dismutase, catalase, and peroxidase activities, thus increasing the stomatal conductance and chlorophyll content of growing plants (Abbas et al. 2022). In addition, biochar utilization can improve plant growth by degrading $O_2^{\bullet-}$ and H_2O_2 levels and elevating the antioxidant activity and malondialdehyde content in plant cells exposed to salinity stress (Farhangi-Abriz and Torabian 2017). Mehmood et al. (2020) also discovered that biochar minimized the deleterious effects of excessive salinity on soybean growth under saline stress conditions by altering root architecture and enhancing key role genes such as antioxidant defense systems and stress responses.

5.2.2 Increases soil resistance to drought stress

The porous structure is important for biochar to assist crops in combating drought stress. As mentioned before, biochar application can develop crop roots that are crucial for water absorption and survival in drought conditions. The size and morphology of root biomass determine its resistance to drought stress (Brennan et al. 2014; Xiang et al. 2017). Coarse roots are responsible for anchoring and determining the penetration depth into the soil layer, while fine plant roots explore soil moisture and increase the water quantity (Kim et al. 2020). Therefore, plants adopt various survival strategies under drought-stressed conditions, including deep root penetration, increased fine root density, and enhanced capability of roots to penetrate small soil pores (Bañon et al. 2004). Studies have highlighted the capability of biochar to enhance the water-absorbing capacity of crops by increasing their fine root growth and length under drought stress conditions (Kartika et al. 2021; Zhang et al. 2023).

5.2.3 Increases soil resistance to waterlogging stress

Recent research has shown that incorporating biochar into soil is a promising solution for water retention and the prevention of waterlogging. Biochar has the ability to facilitate soil moisture infiltration and drainage capacity (Liu et al. 2017). Under anoxic conditions, crop roots can struggle to breathe, and low redox potential can result in the accumulation of harmful matters, namely Fe^{2+}, Mn^{2+}, organic acids like H_2S, and other toxins to levels beyond the required limit (Xie et al. 2015), inhibiting nutrients absorption by roots. Fortunately, biochar's high porosity increases soil permeability, decreasing the likelihood of waterlogging. Biochar's macropores and the reconstructed soil pore structure can also increase the hydrophobicity, further increasing water repellency. In particular, biochar can reduce toxic substances in soil, further promoting the development of crop root systems, which is an important reason for enhancing crop stress resistance.

5.2.4 Increases soil heat stress resistance

Biochar can potentially enhance resistance to heat stress by increasing soil nutrients, improving soil structure, and promoting root growth, ultimately leading to better rhizome traits. This can accelerate the water transport of soil–plant–atmosphere systems, which can help with evapotranspiration cooling and thus prevent heat damage (Jagadish et al. 2015; Mcbride 1982). Nitrogen is also crucial in enhancing the heat resistance of crops, and biochar has been found to promote its utility, thus alleviating the adverse impacts of heat stress on various crops such as rice, maize, barley, and potato (Liu et al. 2019; Martinez-Gomez et al. 2022; Ordóñez et al. 2015; Tawfik et al. 1996). This is because nitrogen availability correlates with the cumulative pattern of crop heat shock proteins, which play an essential role in pyrolysis tolerance (Parsell et al. 1993). Studies have shown that biochar input can optimize rice root morphology, architecture, and physiological traits, including N assimilation and transport proteins, shoot N uptake and utilization, while down-regulating heat-shock and related proteins in roots and leaves, thus improving its heat stress tolerance (Huang et al. 2021). Additionally, increased soil K and P content after biochar input also helps reduce heat stress damage to plants (Hasanuzzaman et al. 2013). Biochar may also aid in P consumption, increasing antioxidant levels and ATP production, thus alleviating damage caused by heat stress-induced reactive oxygen species (ROS) and providing energy to resist heat stress (Bamagoos et al. 2021).

5.2.5 Increases crop lodging resistance

The lodging of rice can lead to lower yields and decreased quality, and inadequate root support leads to easy lodging of tall stalk crops (Sparks 2023). Deep and luxuriant roots after biochar input may reduce root lodging risk due to the improved root-pulling power (Jia et al. 2018; Qian et al. 2024). Additionally, biochar can reduce the length of the rice straw base while increasing its flexural section modulus, outer diameter, and wall thickness (Miao et al. 2021). Meng et al. (2021) also demonstrated that biochar incorporation could significantly increase the area, xylem area, and phloem area of the large vascular bundle, helping increase the bending resistance of rice stalks. Furthermore, Miao et al. (2023) found that 30 t ha^{-1} rice husk biochar application increases the stem plumpness and wall thickness of rice cultivars by 18–21% and 28–32%, respectively, due to co-deposited silica, hemicellulose, and lignin in cell walls, thus enhancing lodging resistance and rice yield.

5.3 Promotes crop photosynthesis

Photosynthesis is a vital process for C assimilation and growth in diverse plants, affecting carbohydrate synthesis and dry matter partitioning processes (Song et al. 2012; Zlatev and Lidon 2012). However, it is sensitive to saline and drought stresses (Kamran et al. 2021). Several factors influence it, including leaf structure (e.g., leaf mass per area) and soil chemical properties (e.g., nitrogen level) (Xu et al. 2015). Biochar has been shown to promote plant photosynthesis directly by optimizing soil physical properties and increasing soil nutrients, and indirectly by improving leaf structure and nutrient accumulation. A meta-analysis by Gao et al. (2021b) found that although biochar had varying effects on the photosynthesis rate in different scenarios, its application increased the photosynthesis rate by an average of 23% owing to the improved soil nutrients. Additionally, biochar application improves soil nutrients such as N, P, K, and Mg, which promotes the absorption and utilization of CO_2 by crops and dry matter accumulation (Lu et al. 2016; Nan et al. 2020; Singh et al. 2018; Zhang et al. 2014). Biochar input improves N accumulation in plant leaves, further improving chlorophyll fluorescence traits (Ali et al. 2021a). Increasing P after biochar addition can prevent photosynthesis inhibition due to stomatal conductance recovery, thus enhancing plant resilience to abiotic stresses (Khan et al. 2023a). Under drought stress, the activity of photosynthesis can be improved by increasing water use efficiency, stomatal conductance, chlorophyll content, and photosynthetic rates after biochar input (Abideen et al. 2020; Batool et al. 2015). Under saline stress, biochar application can increase stomatal conductance and keep stomata open by adjusting the Na^+/K^+ ratio, sustaining the plant osmotic adjustment and improving the leaf area index, leaf water status, and foliar chlorophyll thus improving the photosynthesis and yield (Chen et al. 2023; Ran et al. 2020).

5.4 Increases crop quality and yield

Biochar application in cropland has several advantages that could improve plant growth and enhance crop yield, even under stress (Chen et al. 2021). A meta-study review by Ahmed et al. (2016) discovered a 13% rise in crop yield after biochar input. Furthermore, biochar amendment has been proven to increase the yield of rice (Anwari et al. 2019), maize (Soothar et al. 2021), wheat (Raza et al. 2023), soybean (Zhang et al. 2020c), and more, under abiotic stresses including drought, saline, heat stress. In addition to the widely recognized production-increasing effect, biochar can also improve crop quality, particularly in rice, by increasing the ratio of amylose and amylopectin, which is an important parameter for promoting rice quality. Higher proportions of amylose represent better crop grain quality. Ali et al. (2022a) recently demonstrated that biochar input improved the amylose and amylopectin levels by 14% and 8%, respectively. Apart from increasing soil nutrients and improving soil structure for crop growth, biochar promotes the absorption and utilization of nitrogen fertilizers, which are essential for rice grain quality traits such as appearance, starch content, and protein content (Anas et al. 2019; Ying et al. 2020). Firstly, biochar complexes carry several soluble active molecules (benzoic acid, acetoxy acid, carboxylic acid, triol, and phenolic substances) that allow direct plant uptake, promoting the formation of organic (Gong et al. 2020). These molecules are involved in starch synthesis-specific protein/gene binding, activating new metabolic pathways that affect grain quality. Secondly, biochar promotes crops' nitrogen utilization, which can increase the biosynthesis of starch and sucrose, the related activities of amylase and protease (Ali et al. 2020a, 2020b), and related gene transportation. This improves crop photosynthesis and carbohydrate accumulation (Li et al. 2018a). Furthermore, biochar also increases total amino acid content in the crop grain with high available soil nitrogen (Khan et al. 2023b). The rich silicon brought by biochar also helps to improve the photosynthesis of plants by promoting the transportation and synthesis of carbohydrates for higher-quality crops (Gong et al. 2020; Kim et al. 2002).

Studies have also demonstrated that biochar input in tobacco cultivation is beneficial to both yield and quality. Biochar input can significantly improve the appearance quality, total nitrogen, nicotine, and potassium content, and smoking properties of tobacco leaves (Pan et al. 2015; Zhang et al. 2020b; Zhu et al. 2016). It can also modulate the nicotine content in tobacco leaves to an optimal range (Zhang et al. 2020c). Nonetheless, additional research is required to understand the mechanism of the impact of biochar on tobacco leaf quality. Biochar input has also been found to enhance the quality of fruits and vegetables. As a soil conditioner, biochar can significantly promote fruit flowering, growth, and yield. According to Sharma et al. (2022), biochar input has been associated with potential benefits for the growth and yield of fruit plants such as grapes, peaches, citrus, and apples. Furthermore, Zhang et al. (2020a) discovered the potential of biochar input in reducing the total acidity of Red Globe grapes and increasing soluble protein and firmness. Notably, several studies have reported significant improvements in tomato fruit quality with biochar input. The glucose, fructose-ascorbic acid content, total acidity, vitamin C, lycopene, and sugar-acid ratio in tomato fruit significantly increase after biochar input (Almaroai and Eissa 2020; Suthar et al. 2018). However, the direct mechanism behind improving tomato quality through biochar is unclear and requires further investigation.

6 Future prospective

This review offers a thorough and systematic integration of various mechanisms of biochar affecting soil stress tolerance and crop growth. It also serves as a reference guide for those seeking to implement biochar into their crop management strategies in order to boost yield. The effects of biochar on crop growth and yield enhancement can vary depending on the environmental conditions and the feedstocks of the biochar. However, biochar's physical and chemical properties, the main influencing factor of crop yield under stresses, could be filtered through checking and experimentation. Furthermore, biochar is a cost-effective material with great potential for targeted modifications to enhance its functionality and minimize any negative effects.

However, geographical location can greatly affect the efficacy of biochar in continuously enhancing soil development, particularly in soils under stress, such as coastal saline-alkali soil. While some research has shown that biochar can alleviate crop damage caused by environmental stresses, its efficiency may decline over time due to mass loss and field aging (Blanco-Canqui 2021). Additionally, excessive biochar input can also inhibit the improvement of crop grain quality and destroy original soil properties under stress (Khan et al. 2023b). To maximize the potential of biochar and explore the benefits of modified biochar for further canonical application and strategy design, it would be helpful to establish a database for each explored case, taking economic and environmental considerations into account. While current research suggests that biochar input generally aids in resisting stresses and improving crop yield, the direct mechanisms and key factors behind this are not yet fully understood. Identifying these factors and exploring the long-term effectiveness of biochar can help optimize its use for agricultural benefits.

In addition, microplastics have emerged as a significant soil pollutant that has recently attracted attention. Recent studies have highlighted the promising potential of biochar in addressing the negative impacts of microplastic pollution on soil quality, but the exact mechanism is still unclear. Clarifying the underlying mechanism of how biochar interacts with soil microplastics can lay the groundwork for developing specific biochar products that degrade microplastics.

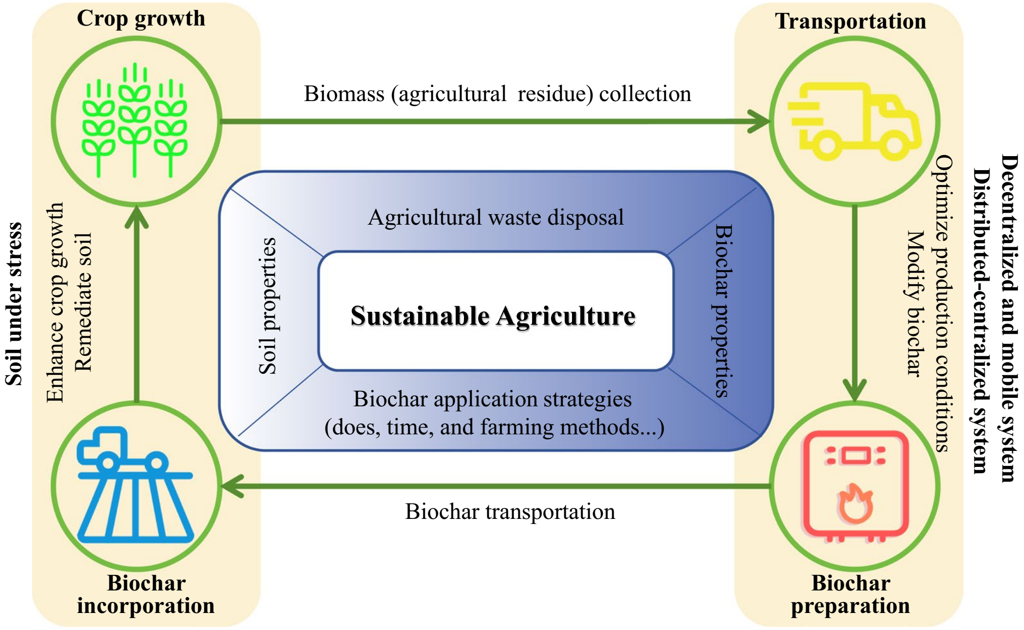


Fig. 6 A potential strategy of biochar for sustainable agricultural management

It is important to consider both carbon sequestration and emission reduction benefits, as well as economic benefits when implementing biochar strategies to increase crop production and make rational use of land resources, especially in the context of increasing demand for carbon neutrality. Notably, only a small amount of biochar is prepared with feedstocks harvested from the field in situ. Long transportation distances can result in a large amount of carbon emissions (Yang et al. 2020), which may offset the advantages of large-scale distributed-centralized system such as higher pyrolysis efficiency, low workforce input, and co-product energy offsets (Zhu et al. 2022a). On the contrary, decentralized and mobile systems are more flexible in space and time to achieve on-site conversion, which is more applicable to developing countries and off-grid communities (Kang et al. 2021). When promoting and applying on a large scale, the performance characteristics of biochar, biomass resources in neighboring areas, and carbonization methods (centralized or decentralized system) should be fully considered. The full life cycle impact of biochar amendment to soil under stresses should also be included in evaluating treatment effects. It is critical to establish a practical biochar incorporation strategy that can be widely implemented (Fig. 6).

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Author contributions

All authors contributed to the study conception and design. Wenchen Chi: material preparation and analysis, writing-original draft. Qiong Nan: Conceptualization, writing-original draft, supervision, revising, writing-review, and editing. Yuxue Liu: Revising, writing-review, and editing. Da Dong: Revising, writing-review, and editing. Yong Qin: Revising, writing-review, and editing. Shengjie Li: Revising, writing-review, and editing. Weixiang Wu: Conceptualization, funding acquiring, review.

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Data availability

All data in the manuscript are previously published.

Declarations

Competing interests

The authors declare no conflicts of interest.

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