



COUNTERACTING SALT STRESS IN PLANTS THROUGH APPLICATION OF BIOCHAR: A REVIEW

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ABSTRACT

Soil salinity is one of the major abiotic stresses that adversely affects crop productivity by inducing osmotic and ionic stress, nutrient imbalance, oxidative damage, and impaired physiological processes. Conventional approaches for managing saline soils are often expensive and unsustainable, necessitating more sustainable alternatives. Biochar, a carbon-rich material produced through the pyrolysis of biomass, has emerged as a promising soil amendment for mitigating salt stress. This review summarizes the mechanisms through which biochar enhances plant tolerance to salinity. Biochar improves soil physicochemical properties, increases cation exchange capacity, enhances water retention, promotes nutrient availability and maintains a favourable K_z /N_{az} ratio by reducing sodium uptake. It also strengthens antioxidant defence systems, lowers reactive oxygen species accumulation, improves hormonal balance, enhances chlorophyll synthesis and photosynthetic efficiency, and promotes better growth and yield under saline conditions. Overall, biochar represents a sustainable, cost-effective strategy for improving soil health, enhancing crop resilience and ensuring agricultural productivity in salt-affected soils.

Key words: Biochar, Plant physiological responses, Salinity, Salt stress mitigation, Sustainable soil management.

Introduction

Environmental stresses like extreme temperatures, soil salinity, drought and flood have negatively impacted the production and cultivation of crops. Among these, soil salinity is considered as one of the most destructive environmental stresses. Salinity in soil has led to a significant decrease in cultivated land area, crop productivity and crop quality. According to FAO (2024), salinity is found to affect about 1.4 billion hectares of land area. Salinity also lowers soil fertility resulting in up to 70% reductions in crop yields. At least 10% of land is made up of salt-affected soils, therefore managing them sustainably is essential to supplying the world's expanding food needs. In general, high saline levels in soils are either due to natural factors or due to man-made factors. Natural factors such as limited precipitation, high evaporation, the presence of saline parent rock, and other hydrological conditions are the primary sources of salinity in arid and semiarid regions. Salinity is also caused by inadequate

irrigation practices, irrigation with poor quality irrigation water, salt buildup from excessive mineral fertilizer dosages, grazing, and deforestation. In addition to reducing the yield of most crops, salinity negatively impacts the ecological balance by altering the physicochemical characteristics of the soil (Hu and Schmidhalter, 2004). Various strategies to mitigate the harmful effects of salt stress on plants include scraping, flushing and leaching in soil (Inoue, 2012) to remove excess salts from the root zone, application of different irrigation methods (Belkheiri and Mulas, 2013) and enhancing the salt tolerance of plants (Hichri *et al.*, 2017 and Shams *et al.*, 2019). However, these approaches are often costly and time-intensive, forcing the farmers to try other methods to alleviate salinity.

Biochar: as a sustainable solution to soil salinity

Biochar, a carbon-rich organic substance produced through the pyrolysis of organic waste materials (Lehmann and Joseph, 2015), is now being used as a

natural alternative to enhance soil quality and promote the effectiveness of salt leaching in saline soils (Lee *et al.*, 2022). The application of biochar is known to improve soil carbon sequestration, soil permeability, soil fertility and microbial growth. It is also found to improve the water holding capacity and nutrient availability, thus enhancing better plant growth (Zhu *et al.*, 2017). Biochar also enhances the soil cation exchange capacity and nutrient use efficiency thereby increasing the crop yield. Using biochar as a natural soil amendment in saline soils, offer a sustainable approach for alleviating the harmful effects of salinity. Although numerous studies have demonstrated the beneficial effects of biochar under saline conditions, the underlying physiological, biochemical and soil-mediated mechanisms remain scattered in the literature. Therefore, this review summarises the recent advances in biochar-mediated alleviation of salt stress and highlights future research directions.

Effect of salinity in plants

Among all abiotic stresses, salinity stress is one of the most damaging and deleterious stresses in plants. Salt stress tends to reduce the water uptake by plants, leading to the development of osmotic stress inside the plants. This osmotic stress induces a series of physiological and biochemical processes, which alters the nutrient imbalance, ROS production, and membrane leakage (Mushtaq *et al.*, 2020). Generally, saline soils have a higher concentration of Na⁺ and Cl⁻ ions. Due to osmotic stress in plants, there will be an accumulation of Na⁺ ions to toxic concentrations. This leads to nutritional and hormonal imbalance, ion toxicity, oxidative and osmotic stress, and enhanced susceptibility of the plant to pathogens.

Reduction of soil porosity and soil hydraulic properties are some of the consequences of high soil salinity (Hasanuzzaman and Fujita, 2022).

Sodium and potassium exhibit an antagonistic relationship in plant uptake systems. Under saline conditions, plants preferentially absorb Na⁺ over K⁺, which triggers enhanced K⁺ efflux from cells and elevates the cellular Na⁺ /K⁺ ratio (Parvin *et al.*, 2016; Rahman *et al.*, 2016). This excessive Na⁺ influx disrupts ion channel function, displaces essential nutrients and induces membrane depolarization, ultimately impairing nutrient uptake and assimilation processes (Zhao *et al.*, 2007; Nahar *et al.*, 2016; Gaikwad *et al.*, 2022). Salt stress further compromises plant physiology by altering water relations, transpiration rates, stomatal conductance, and nutritional balance, while simultaneously promoting oxidative damage—all of which collectively contribute

to reduced crop productivity. The detrimental effects of salinity on crop yield and production (Fig. 1) manifest through multiple interconnected mechanisms, including disruption of morphophysiological and biochemical processes (Kaveh *et al.*, 2011) and significant reductions in photosynthetic efficiency (Khataar *et al.*, 2018).

Along with its direct effects on plants, salinity frequently results in an excessive build-up of reactive oxygen species (ROS), which can interact with other essential components of plant cells and cause oxidative damage in plants, such as DNA damage, lipid peroxidation, enzyme inactivation, protein oxidation, hormone and nutritional imbalances.

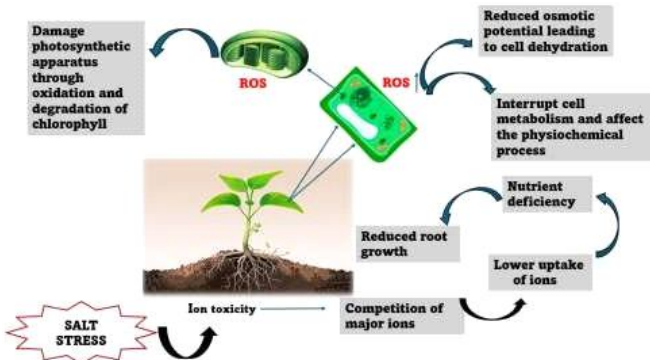


Fig. 1 : Effects of salt stress in plants.

Table 1 : Yield reduction due to salinity stress on different crops.

Crop	Yield reduction (%)	References
Rice (<i>Oryza sativa</i>)	30-50	Eynard <i>et al.</i> (2005)
Barley (<i>Hordeum vulgare</i>)	10-60	Abd El-Monem <i>et al.</i> (2013)
Wheat (<i>Triticum aestivum</i>)	10-50	Zorb <i>et al.</i> (2018)
Bajra (<i>Pennisetum glaucum</i>)	5-25	Yadav <i>et al.</i> (2020)
Sorghum (<i>Sorghum bicolor</i>)	15-20	Daniells <i>et al.</i> (2001)
Maize (<i>Zea mays</i>)	50-60	Zorb <i>et al.</i> (2018)
Chickpea (<i>Cicer arietinum</i>)	10-30	Atieno <i>et al.</i> (2017)

Managing crop production and yield under salt stress is a complex task. Even though, plants possess several defence mechanisms to counteract the toxic effects of salinity (reducing the uptake of harmful ions, sequestering toxic ions in vacuoles, synthesizing various osmolytes, and boosting both enzymatic and non-enzymatic antioxidant activities), under severe salinity conditions, these protective mechanisms become insufficient to

protect the plants from damage.

Biochar: Properties and characteristics

Biochar is a carbon-rich, porous material produced by the thermal decomposition of biomass under oxygen-limited conditions (pyrolysis) usually at a temperature $<700^{\circ}\text{C}$ (Lehmann and Joseph, 2015). The high salt adsorption ability of activated charcoal has long been known. Likewise, biochar also exhibits salt adsorption capacity and could be applied to mitigate salinity (Akhtar *et al.*, 2015). As a carbon-rich material, biochar serves as a crucial soil amendment, improving plant health, soil quality, and tolerance to salt stress. However, the effectiveness of biochar depends on the various feedstocks used and the pyrolysis temperature. Numerous research works using various feed stocks of biochar for mitigating salinity are now available (Table 2). Biochar-mediated increase in plant growth and yield can be linked with improved soil physicochemical and biological characteristics, enhanced cation exchange capacity (CEC), better nutrient and water uptake, increased soil organic matter and a reduction in Na^{+} uptake. Furthermore, BC also improves chlorophyll synthesis and antioxidant activities and regulates the production of assimilates, which ensures better plant growth under saline conditions (Soliman *et al.*, 2022).

Table 2 : Different types of biochar for mitigating salinity stress on plants.

Biochar type	Pyrolysis temperature	Reference
Rice husk biochar	400°C	Sudratt and Faiyue (2023)
Corn cob biochar	350°C	El-Sayed <i>et al.</i> (2021)
Maize straw biochar	550°C	Hannachi <i>et al.</i> (2023)
Wheat straw biochar	550°C	Sun <i>et al.</i> (2020)
Wood biochar	$250\text{--}300^{\circ}\text{C}$	Soothar <i>et al.</i> (2021)
Rice straw biochar	450°C	Mehmood <i>et al.</i> (2020)

Effect of biochar on nutrient retention and uptake under salt stress

The application of biochar can significantly influence soil nutrient retention and their availability to plants. Biochar retains more nutrients in soil due to its high cation exchange capacity (CEC), porous structure, and ability to adsorb and hold nutrients like nitrogen, phosphorus, and potassium. By retaining nutrients, biochar acts as a reservoir, releasing them slowly to plants as needed. This reduces nutrient losses due to leaching and runoff, making nutrient availability more efficient reducing the need for frequent fertilizer applications. Biochar's high CEC allows it to attract and hold positively charged nutrient ions

(cations) like potassium, calcium, and magnesium, preventing them from being washed away by water.

Also adding biochar to soil improves electrochemical properties, such as root zeta potential, thereby increasing nutrient uptake by plants (Farhangi-Abriz and Golezani, 2022). Root zeta potential is a measure of the electrical charge difference between the root surface and the surrounding soil solution. The roots of plants generally have a negative zeta potential which helps to attract positively charged cations like K^{+} , Ca^{2+} and Mg^{2+} leading to their improved uptake. Biochar also carries a negative surface charge due to the presence of functional groups like hydroxyl ($-\text{OH}$) and carboxyl ($-\text{COOH}$). When biochar is applied to soil, these functional groups in biochar, contribute to the negative surface charge of the root, making its zeta potential more negative (Farhangi-Abriz and Golezani, 2022). This creates a favourable electrostatic environment for attracting and absorbing cations like K^{+} , Ca^{2+} , Mg^{2+} from the soil solution. Farhangi-Abriz and Golezani (2022) studied the effect of biochar on reducing root zeta potential of safflower and mint. It was found that the application of biochar had significantly reduced the zeta potential of plant roots, making it more negative. This reduction in zeta potential is attributed to an increase in negatively charged functional groups such as carboxyl and hydroxycinnamic acids which were induced by the application of biochar. Higher negative zeta potential strengthens the electrostatic attraction between root surfaces and nutrient cations, thereby increasing the CEC and root activity. As a result, plants grown in biochar-amended soil exhibit improved absorption for essential nutrients. Moradi *et al.* (2019) had reported reduced sodium concentration with increased organic carbon, total N, P and K in soils treated with biochar. Rekaby *et al.* (2019) had also observed that application of biochar had significantly improved the N content in soil compared to control in barley. When biochar was applied at 1%, the soil available N was 15.11 mg kg^{-1} . In the case of N uptake by barley, there was significant increase with the application of biochar compared to the control. The increase in plant N uptake was 71.49% when 1% biochar was applied to soil. However, when the concentration of biochar was increased to 3%, the significant increase in plant uptake was reduced to 20.48%. In the case of phosphorus, the application of biochar had significantly reduced the soil available P. The P uptake by barley (2.69 mg/pot and 2.98 mg/pot) was found to be significantly increasing with levels of biochar (1% and 3%). The soil available K was found to be significantly higher in both levels of biochar compared to control. Mahmoud *et al.* (2019) reported

that application of biochar had significantly improved N, P and K uptake in maize. In the control plots, the uptake of sodium was found to be significantly higher. When wood sawdust biochar and maize stalk biochar were applied at 19 t ha⁻¹, the Na⁺ absorption and accumulation in maize grains was found to be reduced by 72.38% and 72.21%, respectively. This indicates the ability of biochar to exclude Na while enhancing the uptake of N, P and K in plants.

Effect of biochar in regulating ion uptake and transport – maintaining K⁺/Na⁺ ratio

Under saline conditions, plants tend to absorb and accumulate more sodium and chloride ions compared to essential nutrients like potassium, calcium and magnesium from soil. This disrupts the protein synthesis and interferes with the enzyme activity in plants (Munns and Termaat 1986; Hasegawa *et al.*, 2000) leading to premature senescence of older leaves and causing toxicity symptoms like chlorosis and necrosis in mature leaves. Generally, the ionic size of K⁺ and Na⁺ ions (K⁺) are different. Potassium ions are comparatively larger (about 138 pm in radius), while sodium ions (Na⁺) are smaller and are about 102 pm in radius. However, under saline conditions, Na⁺ influx is facilitated through pathways that generally function for K⁺ influx, as the ionic radii of Na⁺ and K⁺ in their hydrated forms are similar, making it difficult to discriminate between the two ions. As a result of this failure in discrimination, plants growing in saline soils suffer from Na⁺ toxicity and K⁺ deficiency (Assaha *et al.*, 2017). Biochar can retain beneficial cations like K⁺, NH₄⁺, Mg²⁺ more strongly than Na⁺. This improves potassium availability to plants while restricting sodium uptake. Kim *et al.* (2015) has reported that biochar enhances selective uptake of K⁺, by lowering the uptake of Na⁺ thereby, helping to maintain a higher K⁺/Na⁺ ratio in plants. This was confirmed by the studies of Mahmoud *et al.* (2019), who observed higher K⁺/Na⁺ ratio in maize plant with incremental levels of biochar regardless of the source of feed stock. Sudratt *et al.* (2023) had also reported increased shoot K⁺/Na⁺ ratio in rice when rice husk biochar 30% (w/w) was applied to saline soil.

Effect of biochar on water uptake under salt stress

The relative water content in plant is a measure of the leaf's hydration status. It is a measurement of the actual water content in the leaves relative to its maximum water holding capacity at full turgidity. It is used to measure the water deficit in a leaf due to stress factors like drought, heat or salinity. Under saline stress conditions, the higher concentration of salts in soil solution will increase the osmotic potential in the root zone creating

an osmotic gradient inside the plants which draws water away from plant roots. This will make it harder for the plant roots to absorb water from soil. The accumulation of toxic ions like Na⁺ and Cl⁻ in plant tissues can also disrupt the cellular function and damage root system thereby impairing water uptake. Maintaining good leaf water status is crucial for sustaining physiological functions under salt stress (Munns and Tester, 2008). The application of biochar in soil enhances water retention in soils due to its highly porous nature (Lehmann and Joseph, 2015). This will naturally increase the water availability to plants and can even improve the root structure of plants compared to no biochar applied soil. Ababsa *et al.* (2023) had reported decreased relative water content in wheat with increased salinity stress levels. The improvement in relative water content was observed with application of biochar. As the doses of application of biochar increased, the relative water content in wheat was also found to increase. Arkian *et al.* (2025) observed that application of Sesamum residue biochar improved the relative water content in triticale by 23.9 and 24.4% compared with the control at EC of 8 dS m⁻¹ and an EC of 12 dS m⁻¹, respectively.

Effect of biochar on leaching of Na⁺ and Cl⁻

Sodium and chloride ions accumulated during salt stress need to be leached out to reduce the toxic effect of salinity. Biochar due to its higher surface area and porous structure serves as binding sites for various cations (e.g., K⁺, Ca²⁺, Mg²⁺, NH₄⁺). These cations, especially the calcium in soil, improves the soil aggregation by binding together the negatively charged soil particles (like clay and organic matter) and facilitates the leaching out of sodium from the soil (Clark *et al.*, 2007). Calcium has a slightly smaller ionic radius than sodium and being a divalent cation, calcium (Ca²⁺) ions are held more strongly by the negatively charged soil particles than the monovalent sodium (Na⁺). This reduces the uptake and accumulation of sodium (Wu *et al.*, 2023; Kamal *et al.*, 2024) and chloride (Sun *et al.*, 2020) in plants. Sun *et al.* (2020) also observed that application of biochar and fulvic acid had reduced the Na⁺ and Cl⁻ contents in soil compared to the control and had increased the levels of K⁺, Ca²⁺ and Mg²⁺ in saline soils. Thus, application of biochar and fulvic acid adsorb various salts present in soils mitigating the salinity of soil.

Effect of biochar on ROS production and antioxidant defense system.

When plants are under salt stress, there is higher production of H₂O₂ and O₂⁻ (leading to oxidative stress) and lipid peroxidation (indicated by higher

malondialdehyde content). This oxidative damage disrupts cellular function, impairs growth, and reduces productivity. To mitigate these effects, plants activate antioxidant defense systems, including enzymatic antioxidants such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), which help to scavenge ROS and maintain cellular redox balance. Kul *et al.* (2021) reported that application of biochar in saline soils lowered ROS accumulation and lipid peroxidation in tomato. Shahzadi *et al.* (2024) had also reported that application of biochar had relieved wheat from salt stress by decreasing the MDA and H_2O_2 in leaves. Application of biochar helps to reduce oxidative stress caused by salinity by improving antioxidant enzyme activity and decreasing the levels of harmful reactive oxygen species.

Farhangi-Abriz and Torabian (2016) reported that under increasing salinity concentrations (6 and 12 dS/m NaCl), the leaf concentrations of MDA, H_2O_2 and $O_2^{\bullet-}$ increased sharply, indicating enhanced oxidative damage in bean seedlings. However, when biochar was applied at 10% and 20%, there was significant decrease in MDA, H_2O_4 and $O_2^{\bullet-}$ levels in both root and leaves compared to control under saline stress. Numerous studies depict increased antioxidant activity due to application of biochar. Under salinity stress, the application of biochar (4.5%) had significantly improved the activity of SOD, POD and uptake of NPK in fava bean (Fazal and Bano, 2016). The application of 10% biochar was found to increase the activity of CAT, POD and SOD in sorghum (Hussien *et al.*, 2020). Ndiaye *et al.* (2022) observed decreased MDA, EL, and H₂O₂ production and increased activities of CAT, POD and SOD in wheat when biochar was applied at 15 t ha⁻¹. The application of biochar has significantly affected the proline and H_2O_2 contents in Chinese cabbage compared to the control under salinity stress.

Effect of biochar on regulating hormonal balance

Salinity stress disrupts plant hormonal balance by increasing levels of abscisic acid (ABA), which induces stomatal closure, while decreasing auxins and cytokinins which results in inhibited growth and accelerated leaf senescence. The activity of gibberellic acid is also disrupted, leading to reduced growth under salt stress. This will result in stunted growth and yellowing of leaves. The application of biochar decreases the concentration of ABA, which in turn improves plant performance under saline conditions (Lashari *et al.*, 2014). Yang *et al.* (2022) has reported that the decrease in ABA in plants might be due to the improved availability of soil water, downregulation of ABA leaf biosynthesis or signalling pathways (e.g., PYL, SAPK2). Zhang *et al.* (2023) had

also observed decreased ABA concentration in leaf and xylem sap of tomato seedlings under salt stress due to biochar application. Biochar made from poultry waste was found to be significantly higher in terms of reducing ABA concentration. Zhong *et al.* (2025) evaluated the effect of wheat straw biochar to alleviate salinity stress in alfalfa. Biochar was applied at different rates (0, 25, and 50 g kg⁻¹) against five salinity levels (0, 25, 50, 75, and 100 mM NaCl) and it was observed that biochar application increased IAA and GA content in leaves of alfalfa under salinity when compared to control. The application of the 25 g kg⁻¹ wheat straw biochar was found to be significantly better in terms of production of IAA and GA compared to the other treatments. The higher dose of biochar (50 g kg⁻¹) had reduced the positive effects due to changes in soil properties. High concentration of biochar had increased the alkalinity, reduced the nutrient availability and had caused hydrophobicity, which might have lead to the poor water uptake and lower photosynthetic activity in alfalfa.

Salinity stress is known to decrease the soil water potential and limit the plant cell's capacity to absorb water. This will reduce the turgor pressure in cells, thereby restricting further cell expansion. These alterations due to increased salinity lead to shrinkage of tissues and loss of water from plant cells (Van Zelm *et al.*, 2020). Under these conditions, plants synthesize and accumulate organic osmolytes in varying concentrations to regulate the osmotic potential to protect cellular integrity. Osmolytes (compatible solutes) like proline (Ahmad *et al.*, 2010) and sugars (Bohnert *et al.*, 1995) are uncharged, polar, and soluble molecules that usually do not interfere with cellular metabolism, even at high concentrations. These compatible solutes stabilize cellular structures and enzymes, act as metabolic signals and scavenge ROS. Osmoprotection through compatible solutes is thus an important mechanism for plants to mitigate the negative effects of salinity stress in plants. Kamal *et al.* (2024) observed that proline levels, ascorbic acid and total soluble sugar increased in the leaves of tomato across all treatments with biochar. There was 137% increase in proline content due to application of poultry manure-based biochar composting (1:2) @ 3 t ha⁻¹ + SBTF against the control. Zhong *et al.* (2025) reported that biochar restored the osmoregulatory substance concentrations of proline and soluble sugar and significantly reduced ABA leaf content in alfalfa under salinity.

Biochar improves plant photosynthetic efficiency under saline conditions

Salinity stress impacts plant growth and development by hindering photosynthesis. Manan *et al.* (2016) had

reported that salinity stress reduces the relative water content and chlorophyll production in plants, leading to a marked decline in photosynthetic activity. Earlier Thomas *et al.* (2013) and Akhtar *et al.* (2015) had also reported that when biochar was applied to saline soils, the stomatal density, conductance and leaf gas exchange was found to be enhanced resulting in improvement in photosynthetic performance. This was confirmed by Shabbir *et al.* (2021), who reported that the addition of biochar had contributed to improved stomatal conductance and chlorophyll synthesis, thereby improving photosynthetic efficiency in quinoa crop.

Effect of biochar on chlorophyll production

Increased ROS accumulation in plants caused by Salinity leads to increased oxidation and degradation of chlorophyll (Taibi *et al.*, 2016) in plants. The further production of chlorophyll a and b is also reduced due to salinity causing yellowing and chlorosis in plants. Application of biochar is found to reduce the accumulation of ROS in plants, helping them to withstand the detrimental effects of salinity. This positive effect is due to several interconnected mechanisms. Due to the increased uptake of N and Mg, there is improvement in chlorophyll content in biochar applied plants. Abbas *et al.* (2022) had reported that application of biochar had significant effect on chlorophyll content for quinoa in both normal soil and saline soil. As the rate of biochar increased, the chlorophyll content was also found to increase in both soils. The saline soils that were amended with cotton shell biochar (@ 1%) was found to be on a par with normal soils in terms of chlorophyll content for quinoa. In the case of RWC, the application of biochar (@ 2%) was found to be on a par with the plants that were raised on normal soils.

Similar report of increased total chlorophyll was also observed by Kamal *et al.* (2024) due to application of manure-based biochar. There was significantly higher total chlorophyll content in tomato, indicating enhanced photosynthetic potential, compared to the control. This increased chlorophyll had significantly influenced the number of tomato fruits per plant. Rathinapriya *et al.* (2025) observed that under salinity stress, application of biochar increased photosynthetic pigments and reduced proline and H_2O_2 contents in cabbage.

Effect of biochar on Stomatal conductance

Stomatal conductance in plants is a measure of the degree of stomatal opening in plants. Generally, osmotic stress and oxidative damage caused by salinity stress in plants, leads to stomatal closure and reduced stomatal conductance (Yang *et al.*, 2020). Increased ABA contents

leading to stomatal closure in plants raised under saline conditions. This closure of stomata, limits the uptake of carbon dioxide, reducing photosynthesis and crop yield. Chen *et al.* (2023) has reported that the application of biochar had improved the absorption of water and K^+ ions and there was reduced Na and ABA contents which helped in maintaining the leaf stomatal opening in Chinese cabbage. Akhtar *et al.* (2015) studied the residual effects of biochar to explore the mechanisms for reducing Na^+ uptake and improving growth, physiology and yield of wheat under salinity stress and observed that salt treatment at 25mM concentration had an adverse impact on stomatal conductance in wheat compared to control. When biochar was applied at 5% (w/w), the stomatal conductance of wheat was found to be improved. However, wheat failed to perform under higher concentration of salt. Abbas *et al.* (2022) had reported that salinity had significantly reduced the stomatal conductance and relative water content (%) in Quinoa grown under saline soil. When the soil was amended with cotton shell biochar @ 1% and 2%, there was 24% and 41% improvement in stomatal conductance and 18% and 36% increase in RWC%, when compared to saline soil control.

Effect of biochar on Stomatal density

Stomatal density is the number of stomata (pores for gas exchange) per unit area of leaf. Generally, stomatal density tends to decrease under higher salinity conditions as a mechanism for plants to conserve water under high salt conditions. Application of biochar was found to increase stomatal density in cotton plants (Hou *et al.*, 2023). This increase in stomatal density due to application of biochar is caused by interfering with plant water relations and hormone signalling (ABA). Akhtar *et al.* (2015) observed that salt treatment at 25mM and 50 mM had an adverse impact on stomatal density in potato compared to control. When biochar was applied at 5% (w/w), it improved stomatal density against no biochar under both salt concentrations.

Effect of biochar on growth and yield under salinity

Salinity causes significant yield losses in most of the crops, particularly during the reproductive stage. Salt stress disrupts plant water relations, creates nutritional imbalances, lowers stomatal conductance, and induces oxidative damage, all of which collectively contribute to yield reduction. Salinity disrupts morpho-physiological and biochemical processes, thereby reducing photosynthesis and biomass accumulation, which ultimately causes premature senescence of reproductive organs. These combined effects negatively influence yield response variables and ultimately reduce overall agricultural

productivity (Kaveh *et al.*, 2011; Khataar *et al.*, 2018). Numerous studies report increased plant growth and development due to the application of biochar. The application of biochar is reported to increase the growth and biomass of wheat (Lashari *et al.*, 2013), rice (Ran *et al.*, 2019), tomato (Kul *et al.*, 2021) and maize (Helaoui *et al.*, 2023) that were grown under salt stress.

Kul *et al.* (2021) studied the effect of biochar on the growth and physiological parameters of tomato under salinity and observed that application of biochar improved the morphological parameters under both saline and non-saline conditions. With increase in rate of application, there was an increase in all the parameters with the highest increase rates in shoot fresh weight (113.7%), shoot dry weight (74.8%), the number of leaves (24.9%), root fresh weight (115.5%), root dry weight (62.5%) were obtained from 10% biochar amendment under saline conditions. Sudratt and Fayue (2023) reported that the application of biochar had significantly improved growth and yield parameters of rice. With the increasing rate of application of biochar, an increase in active tillers (%), panicle length (cm), grain number/panicle, filled grain (%), 1000 grain weight (g), and grain weight/pot (g) can be observed under saline conditions. Ahmed *et al.* (2024) found that application of biochar increased the number of fruits per plant, single fruit length (cm), single fruit diameter (cm), and weight of a single fruit (gm) of okra in saline soil. Murtaza *et al.* (2024) found that under saline stress conditions, biochar application significantly improved root length, root surface area, root projected area, root diameter and root volume in plants compared to control, which indirectly affected the leaf water content.

Future prospects

Counteracting salt stress in plants through application of biochar requires a multifaceted approach that addresses both fundamental mechanisms and practical applications. To identify the most effective biochar for salt adsorption and soil improvement, research using various feedstocks is essential. Understanding seed germination mechanisms under saline conditions with biochar amendments helps determine its role in reducing osmotic stress and ion toxicity for crops. Biochar engineering and modification (*e.g.*, through activation or mineral coating) can enhance its cation exchange capacity, water retention and ability to immobilize salts. Exploring synergistic approaches, such as combining biochar with organic amendments or microbial inoculants, can further enhance soil structure and plant resilience. Long-term field studies are needed to validate the sustained impacts of biochar on salinity mitigation, as short-term effects

may differ from long-term dynamics. Assessing the economic viability and policy support ensures that biochar application is both scalable and incentivized for farmers in saline-prone regions. Finally, achieving a deeper mechanistic understanding of biochar–soil–plant interactions under salinity stress will enable tailored, science-based strategies for sustainable agricultural productivity in saline soils.

Conclusion

Salinity is one of the most detrimental abiotic stresses limiting global agricultural productivity as it impairs plant growth, physiology, and yield. Conventional strategies for managing saline soils are often costly, time-consuming, and unsustainable. In this context, biochar emerges as a natural, low-cost, and eco-friendly amendment with significant potential to alleviate salt stress. Biochar helps crops withstand salinity by enhancing cation exchange capacity, promoting selective ion uptake, improving soil structure and water retention, stimulating antioxidant defence systems and boosting photosynthetic efficiency. The wide range of experimental evidence presented confirms that biochar not only mitigates the negative effects of salinity but also improves soil fertility and crop yield, thereby offering a sustainable solution to the challenges of saline agriculture.

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