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Review

Putting Biochar in Action: A Black Gold for Efficient Mitigation of Salinity Stress in Plants. Review and Future Directions

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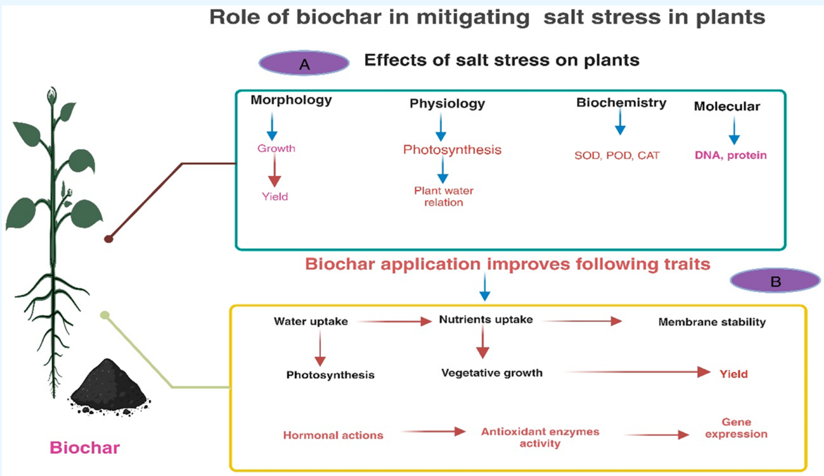

ABSTRACT: Soil salinization is a serious concern across the globe that is negatively affecting crop productivity. Recently, biochar received attention for mitigating the adverse impacts of salinity. Salinity stress induces osmotic, ionic, and oxidative damages that disturb physiological and biochemical functioning and nutrient and water uptake, leading to a reduction in plant growth and development. Biochar maintains the plant function by increasing nutrient and water uptake and reducing electrolyte leakage and lipid peroxidation. Biochar also protects the photosynthetic apparatus and improves antioxidant activity, gene expression, and synthesis of protein osmolytes and hormones that counter the toxic effect of salinity. Additionally, biochar also improves soil organic matter, microbial and enzymatic activities, and nutrient and water uptake and reduces the accumulation of toxic ions (Na^+ and Cl), mitigating the toxic effects of salinity on plants. Thus, it is interesting to understand the role of biochar against salinity, and in the present Review we have discussed the various mechanisms through which biochar can mitigate the adverse impacts of salinity. We have also identified the various research gaps that must be addressed in future study programs. Thus, we believe that this work will provide new suggestions on the use of biochar to mitigate salinity stress.

1. INTRODUCTION

Salinity stress is the second most important abiotic stress negatively affecting crop productivity and global food security.[1] The intensity of salinity stress will be higher in the future owing to rapid climate change and global warming.[2] Irrigated lands are some of the biggest sources of food production and they produce one-third of the world's food supply, which is severely affected by salt stress.[3] It is projected that the world's population will reach 9.6 billion by 2050; therefore, agricultural production must be substantially increased to meet the food needs.[3] Nonetheless, salinity stress is impeding the steady food supply[4,5] and causing a significant reduction in yields of major crops, i.e., maize, rice, and wheat.[6] Soil salinization negatively affects plant establishment by increasing soil osmotic pressure.[3] Salinity-induced osmotic stress causes water scarcity in plants and leads to a reduction in plant growth. Further, salinity also cause ionic toxicity and nutritional imbalance, therefore

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Table 1. Effect of Salinity Stress on Growth and Physiological and Molecular Processes of Plants

salinity stress	plant species	major effects	refs
3000 mg kg^{-1}	eggplant	salinity stress reduced the chlorophyll contents, RWC, fruit NPK, fruit length, and total yield	41
6 dS m^{-1}	tomato	saline conditions reduced the chlorophyll synthesis, membrane stability, RWC, and chlorophyll contents and increased accumulation of toxic ions	42
300 mmol L^{-1}	maize	saline conditions reduced germination potential, shoot length, and chlorophyll contents and increased MDA and Na concentrations and antioxidant activities	43
6 g/kg	*Jatropha curcas*	saline conditions reduced plant growth, leaf area, leaf biomass, photosynthetic pigments, and chlorophyll fluorescence	44
200 mM	alfalfa	a significant reduction in root length, leaf length and width, and growth and photosynthetic efficiency was observed under saline conditions	14
10 g L^{-1}	wheat	saline conditions reduced germination rate, capacity, germination time, and mean germination and growth traits	45
10 dS m^{-1}	maize	salt stress reduced root and shoot growth, leaf area, RWC, photosynthesis, chlorophyll, and uptake of zinc and potassium	46
200 mM	cotton	salinity stress reduced the root and shoot length and their fresh biomass and increased proline synthesis and activities of CAT and POD	47
10.23 dS m^{-1}	wheat	saline conditions reduced root and shoot growth and chlorophyll synthesis and increased the levesl of proline and soluble sugars and CAT and APX activity	48
8 dS m^{-1}	wheat	salinity increased MDA, H_2O_2, Na, and Cl accumulation, electrolyte leakage, and antioxidant activities and decreased growth, chlorophyll synthesis, RWC, and uptake of Ca, Mg, and K	49

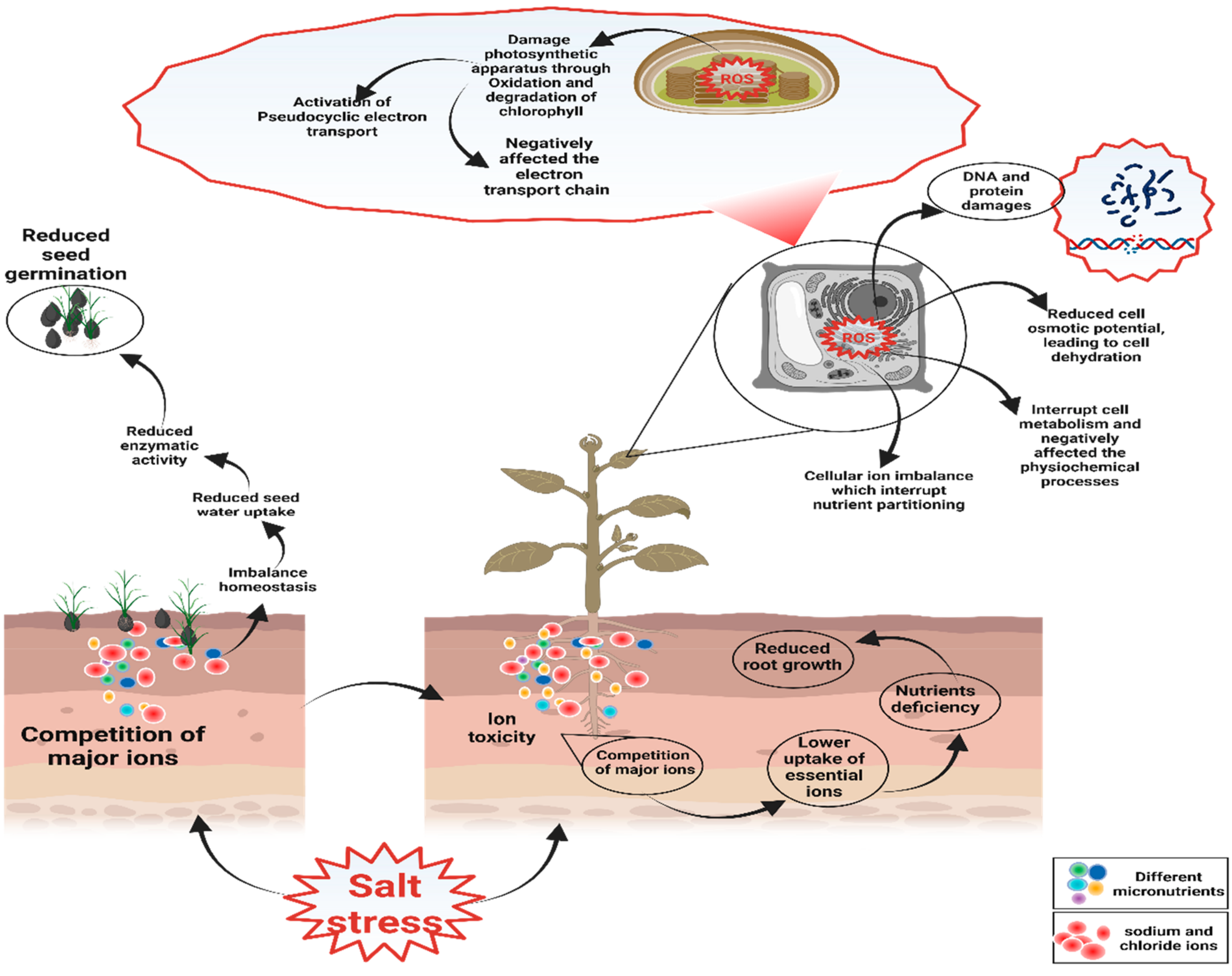

Figure 1. Salinity inhibits seed germination and chlorophyll synthesis, reduces photosynthetic efficiency cell hydration, and induces oxidative stress and nutritional imbalance, thereby reducing plant growth and biomass production.

resulting in a significant reduction in plant growth.[7−9] Salinity stress negatively affects plant physiological processes including photosynthesis, nutrient acquisition, and water uptake.[8−11]

Photosynthesis is one of the most important processes that provides energy and organic molecules for the growth and development of plants.[10] However, plant photosynthesis is progressively reduced with increasing salinity stress owing to reduced carbon dioxide (CO_2) availability, disturbed light harvesting, hindered electron flow, and carbon assimilation.[12] Salinity stress also restricts the root water uptake by diminishing the water potential owing to the presence of the higher concentration of salts in soil solution.[13] Moreover, salinity also reduces the cell water concentration and consequently decreases the rates of cell elongation and cell division.[14]

Managing crop production under saline soils is a complex and challenging task owing to osmotic and ionic stresses.[15] Salinity also harms the cellular membranes, disturbs the nutrient balance and enzymatic activities, and causes metabolic dysfunctions.[16] Saline conditions also increase the production of reactive oxygen species (ROS) that disrupt the cell redox balance and cause damage to essential molecules and cell organelles.[17] However, plants have excellent systems, including a reduction in the uptake of toxic ions, the compartment of toxic ions in vacuoles, the production of various osmolytes, and increased enzymatic and nonenzymatic antioxidant activities, that can counter the toxic effects of salinity.[18] Nonetheless, when salinity stress is severe, plants cannot protect themselves from the damaging effects of salinity. Therefore, appropriate measures must be taken to reduce the negative impacts of salinity stress on plants to ensure food productivity and global food security.[19]

Biochar (BC) is a carbon-rich product and it is also known as black gold.[20] Recently it received attention across the globe for its to improve crop productivity and mitigate the toxic effects of abiotic stresses.[8,20−22] BC application improves soil carbon sequestration, soil permeability, soil fertility, and microbial growth, which improves the water holding capacity and nutrient availability and thus ensures better plant growth.[23] Biochar also increases the soil cation exchange capacity and nutrient use efficiency and therefore leads to an increase in crop yield.[24] Biochar application also reduced the toxic effects of salinity by binding Na^+ on its exchange site and increasing soil K^+ and moisture contents. Besides, this BC also possesses a higher salt adsorption capacity that could reduce the Na^+ uptake and thus mitigate the adverse impacts on soil salinity.[25] Additionally, BC also improves physiological functions and mitigates ROS production, which can reduce the toxic effects of salinity stress on plants.[26] Therefore, the present Review describes various mechanisms through which BC can mitigate the adverse impacts of salinity stress on plants. This Review also highlights the different research gaps that must be addresses in future studies. Further, the toxic effects of BC on plants and limitation of biochar are also discussed. This Review will provide new suggestions on the use of BC for mitigating the toxic effects of salinity stress.

2. SALINITY STRESS IMPACTS AND CONSEQUENCES ON PLANTS

Salinity stress negatively affects all plant processes ranging from germination to growth, productivity, and physiological and molecular processes (Table 1). Salinity stress suppresses plant growth, and it depends on several factors, including plant species, salt concentration, and stage of plant growth.[27] Salinity stress also shrinks and dehydrates cells, which affects the cell division and results in decreased root and leaf growth.[4] Further salt stress also restricts the ability of plants to absorb water, which can cause a significant reduction in plant growth and development.[28] Photosynthesis is a vital process for plants, and salinity stress reduces chlorophyll synthesis, damages photosynthetic apparatus, and reduces the CO_2 supply, which causes a reduction in photosynthesis.[29,30] The decrease in chlorophyll synthesis under saline conditions occurs because of increased oxidation and degradation of chlorophyll initiated by increased ROS accumulation.[31] Further, salinity-induced pseudocyclic electron transport also inhibits the electron transport chain, which causes excessive ROS production.[30] The increased ROS production damage proteins, membranes, and DNA (Figure 1) and disturbs the ultrastructure of chloroplast by inducing thylakoid swelling and starch accumulation.[32]

The disturbed nutrient acquisition under saline conditions is linked with a reduction in nutrient availability owing to the competition of major ions (Ca^{2+}, K^+, and Mg^{2+}) with Na^+ and Cl^-.[33] Nitrogen is an essential nutrient needed for plants, and an increase in Cl^- uptake and accumulation under saline conditions can decrease the N uptake.[34] Salinity stress also negatively affects the phosphorus uptake and salinity-induced excessive Cl^- reduces the P uptake, possibly owing to the high ionic strength of the media and low solubility of the Ca ± P minerals. Potassium is also an important nutrient needed for plants; however, under saline conditions, there is intense competition between Na^+ and K^+, which therefore reduces the K^+ uptake. An increase in Na^+ concentration under saline conditions significantly decreases K^+ and Ca^{2+} concentrations and leads to a significant reduction in plant growth.[35] Under saline conditions, the osmotic potential of plant cells becomes more negative owing to the increased concentration of salts in soils, which produces the osmotic gradients that drive water out of cells and results in a reduction in turgor pressure.[36] Salinity stress also reduce relative water content, transpiration, and photosynthesis, therefore leading to a significant decrease in plant performance under saline conditions.[37] Besides this, salinity stress also impairs the synthesis of proteins, energy metabolism, and cell signaling and ultimately leads to a serious decrease in plant growth and development.[38] Apart from this, salinity stress also reduces root and shoot length and plant fresh and dry biomass production; however, this varies according to the plant species, the stage of plant stress, and the concentration of salts in the growth medium.[39,40] Further, saline conditions also induced leaf yellowing due to senescence and caused leaf necrosis.[19] Leaf shedding is also another important negative effect of salinity stress that leads to lower fresh and dry matter production and a decreased number of flowers, and this aspect is more visible in older leaves owing to the accumulation of Na^+ for a longer time period.[19,39]

3. BIOCHAR PRODUCTION AND STANDARDS

The feedstock plays an important role in the final properties and functioning of BC.[50] There are different kinds of biochars that can be used for agricultural purposes (Table 2). Biochar has lower carbon mineralization and non-CO_2 emissions owing to its greater persistence as compared to the original biomass. The selection of parent materials is an important factor that significantly affects the potential of BC to mitigate climate change.[51] Biochar classification and standards regulate the selection of the feedstock and thermal conversion processes, which is important to develop BC technology to reduce greenhouse gas (GHG) emission.[52] Different guidelines and standards have been proposed for BC by different organizations like the International Biochar Initiative (IBI), the European Biochar Community (EBC),[53] and the Biochar Quality Mandate (BQM).[54] The different BC standards

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Table 2. Different Types of Biochar Used to Mitigate the Toxic Effects of Salinity Stress on Plants

biochar type	pyrolysis temperature	refs
rice husk biochar	400 °C	56
corn cob biochar	350 °C	57
tree wood biochar	600 °C	58
maize straw	550 °C	59
wheat straw biochar	550 °C	60
wheat straw biochar	550−600 °C	61
wood biochar	250−300 °C	62
rice straw biochar	450 °C	63
mixed-wood biochar	700 °C	64
maize straw biochar	600 °C	65
coniferous wood chips	500 °C	66
sewage sludge biochar	550 °C	67
shrimp waste biochar	300 °C	68
poultry manure biochar	550 °C	69
cotton stalks	400 °C	70
mulberry wood biochar	530 °C	71
tomato biochar	500 °C	72
grape pruning residues	400 °C	73
softwood pellets biochar	550 °C	74
olive pruning biochar	400 °C	75
mango wood biochar	500 °C	76
mulberry biochar	530 °C	77
wheat straw biochar	550 °C	78
municipal solid waste biochar	500 °C	79
pine and poplar wood biochar	300 °C	80
rice husk and corn stalk biochar	350 °C	81
peanut shell biochar	350 °C	82

include quality requirements, environment threshold levels for heavy metals and pollutants, feedstock type, production technologies, and transportation distance. According to IBI,[53] the pyrolysis product must contain less than 10% organic C, while EBC suggested BC must contain >50% organic carbon and BQM suggested that stable organic carbon in BC should be at least 10% (w%).[53,54] IBC and EBC classified the BC into five different categories based on their application: liming material, carbon storage material, fertilizer product, particle-size classes, and use in different potting mixes and soilless agriculture. Even though the current standards and guidelines do not specify the application rules for BC in particular types of soils, BC used in salt-affected soils must still adhere to the specifications for feedstock, production techniques, and quality control set by IBI, EBC, BQM, or local or national laws and regulations. Additionally, the specifications for BC quality and stability should take into account the particular difficulties presented by soils with poor soil structure, low carbon content, high salt content, and limited nutrient availability. Saline soils contain higher electrical conductivity (EC), which can cause osmotic stress to plants, and therefore BC with a higher nutrient value must be selected for salt affected soil.[55] It is important to note that there are several restrictions and difficulties with the present biochar standards and guidelines. Developing a uniform classification of biochar feedstock, properties, and applications is extremely difficult due to its complexity and diversity. In general, the choice and use of biochar must be optimized depending on the unique issues of each salt-affected soil. Additionally, inconsistencies and obstacles to international trade and collaboration resulting from the lack of universal adoption of a single set of standards must be resolved in the future.

4. BIOCHAR IS AN IMPORTANT AMENDMENT TO MITIGATE SALINITY STRESS

Soil salinity is a serious abiotic stress that causes a marked reduction in crop productivity and threatens global food security.[83] The extent of soil salinity is considerably increasing, which is a serious concern across the globe. It has been reported that every year saline area is increasing at a rate of 10% owing to anthropogenic activities.[28] Biochar is a carbon-rich product that plays an important role in mitigating the adverse impacts of salinity stress.[84] Biochar improves plant functioning and soil properties that improve the salt tolerance in plants,[85] and different mechanisms through which BC counter the toxic effects of salinity are discussed below.

4.1. Biochar Improves Water Uptake and Maintain Membrane Stability to Counter Toxic Effects of Salinity. Salinity stress induces osmotic stress, which decreases the plant water uptake and consequently reduces the leaf water contents. However, BC is a promising soil amendment that mitigates salinity-induced osmotic stress and maintains plant water relations by increasing K^+ uptake and decreasing Na^+ uptake.[86] Potassium is an important osmoprotectant that maintains plant function and therefore improves plant water relations.[86,87,88]. Aquaporins play an important role in water uptake,[50] and the application of BC up-regulates aquaporin genes, which improves the water uptake and ensures better leaf water status.[89] Biochar supplementation also improves the activity of water transport genes and the soil water holding capability, which ensures better leaf water status under saline conditions.[88] However, this study was conducted in lab conditions, and there is dire need to conduct the field studies to validate the study results.

Soil salinity damages the cellular membranes by increasing malondialdehyde (MDA) and H_2O_2 production, and salinity -induced membrane damage leads to the loss of important osmolytes.[34,90] Lipids and fatty acid composition play an important in membrane functioning and stability.[91] Biochar application can increase the concentration of unsaturated fatty acids, which improves the membrane stability and reduces the loss of important osmolytes.[92] Biochar application under saline conditions also improves antioxidant activities and increases osmolyte accumulation, which protects the membranes from the toxic effects of MDA and H_2O_2.[93] Biochar-mediated reduction of MDA and H_2O_2 production also reduces the electrolyte leakage by making the membranes stronger.[86,92]

4.2. Biochar Maintains Nutrient Uptake to Counter Salinity Stress. Nutrient homeostasis plays an important role in mitigating the adverse impacts of salinity. However, salinity stress disturbs nutrient homeostasis, resulting in a significant reduction in plant growth.[88] Biochar is a promising soil amendment that mitigates adverse impacts of salinity and improves the uptake of nutrients, which can counter the toxic effects of salinity. The application of BC increases the concentration of Ca^{2+}, which induces cell signaling, therefore improving salt tolerance in plants.[88,94] BC supplementation also improves the uptake of P, Mn, K, Fe, and Zn in a dose-dependent manner, which counters the toxic effects of salinity and improves plant performance under saline conditions.[66,93,95]

Under saline conditions, the uptake of Na^+ is significantly increased, which disturbs the plant's nutrient uptake; however,

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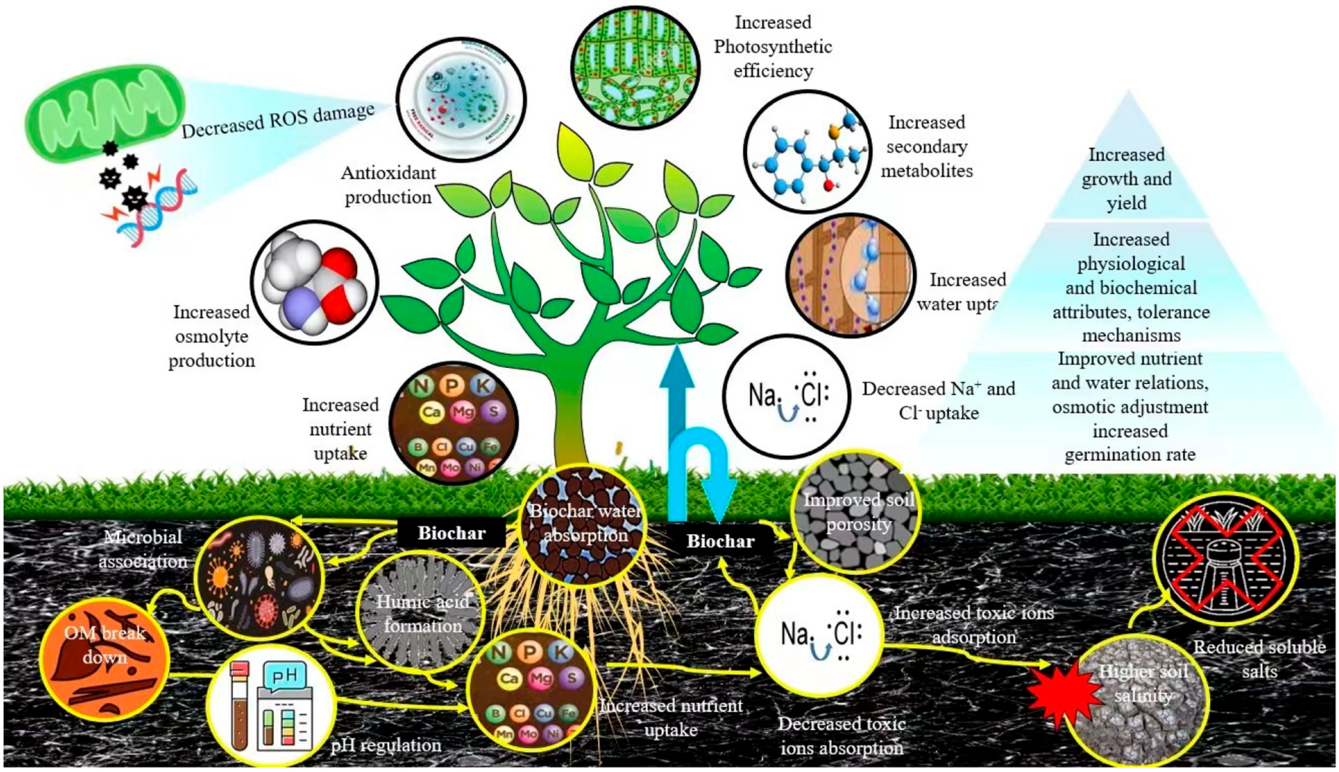

Figure 2. Biochar application reduces Na^+ and Cl^- uptake and improves soil fertility, root growth, chlorophyll synthesis, stomatal opening, osmolyte and hormone synthesis, antioxidant activities, and membrane stability, therefore improving plant performance under saline conditions.

Table 3. Effect of Different Biochars on Growth and Physiological Activities under Salinity Stress

salinity stress	plant species	biochar application	major effects	refs
300 mM	eggplant	6%	BC application increases plant height, growth, fruit yield, WUE, photosynthetic and transpiration rates, and water potential and reduced ABA synthesis	59
50 mM	*Glycyrrhiza uralensis*	6%	BC addition countered the toxic effects of salinity and improved root and shoot growth, carbon and nitrogen concentration, and root surface area and volume	65
3000 ppm	wheat	4.8 ton/ha	BC supply improved plant height, grains production, RWC, membrane stability, soil pH, and uptake productivity of Ca, Mg, K, and water	57
17 dS m^{-1}	maize	4.5%	BC application increased chlorophyll synthesis, leaf fluorescence, and NPK uptake	62
5000 mg kg^{-1}	borage	5%	BC addition increased proline synthesis, RWC, water, osmotic and turgor potential, and membrane stability	8
4.3 dS m^{-1}	potato	825 kg/ha	BC addition increased chlorophyll contents, RWC, leaf gas exchange characteristics, proline synthesis, and nutrient uptake	106
40 mM	soybean	3%	BC application increased chlorophyll synthesis, total soluble proteins, and P and N uptake	63
150 mM	jute	2 g kg^{-1}	BC application increased plant growth, RWC, chlorophyll contents, and uptake of N and P	107
20 dS m^{-1}	quinoa	1%	BC application improved root and shoot growth, RWC, membrane permeability and stability, and K uptake	108
5 dS m^{-1}	maize	10 t ha^{-1}	BC application increase leaf area, chlorophyll and carotenoid contents, RWC, maize productivity, and NPK uptake	109

BC application reduces the uptake of Na^+ (Figure 2), which in turn increases the absorption of other nutrients, particularly K.[96] BC supplementation also causes a small increase in soil EC, and the BC-mediated increase in soil EC releases different nutrients from soil.[71,77] Biochar also replaces Na^+ on soil exchange sites and reduces the availability of Na^+, which improves the availability of Ca and Mg in plants.[58] Biochar has a higher surface area, cation exchange capacity (CEC), and porosity, which reduces the uptake Na^+. Further, BC has large surface areas which makes it an imperative amendment to adsorb the Na^+ and leads to an increase in the availability of beneficial nutrients.[97] BC also improved the K/Na^+ ratio and the uptake of K, which is an important osmoprotectant that ensures better plant growth under saline conditions.[98] Thus, BC can improve nutrient homeostasis to counter the toxic effects of salinity. Most of the aforementioned studies were conducted under controlled conditions. Therefore, it is important to conduct wide range of field studies on salt's effect on soils to determine the fate of BC on nutrient homeostasis.

4.3. Biochar Improves Plant Photosynthetic Efficiency to Counter Salinity Toxicity. Photosynthesis is one of the most important processes in plants needed for the production of assimilates; however, salinity stress negatively affects plant photosynthesis by decreasing relative water content (RWC) and chlorophyll synthesis.[21] The application of BC increases the synthesis of chlorophyll (Figure 2) owing to the fact BC increases the availability of N and Mg, which are

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Table 4. Effect of Different Biochars on Osmolyte Accumulation, Oxidative Stress Markers, And Antioxidant Activities under Salinity Stress

salinity stress	plant species	biochar application	major effects	refs
0.2 mol L^{-1}	tomato	5%	BC application increased the seedling growth and concentration of ABA in xylem sap	69
12 dS m^{-1}	sorghum	10%	BC addition increased CAT, POD, and SOD activities, which counter the toxic effects and ROS	117
2.3 dS m^{-1}	tomato	5%	BC supplementation increased proline synthesis and total yield	118
150 mM	wheat	4.5%	BC application improve composition of fatty acid, SOD and POD activity, and uptake of NPK	92
3000 mg kg^{-1}	fava bean	15 t ha^{-1}	BC supply decreased MDA, EL, and H_2O_2 production and increased CAT, POD, GR, and SOD activities	
2.55 dS m^{-1}	wheat	5%	BC application reduced MDA and H_2O_2 production and increased CAT, POD, and SOD activities	26
150 mM	maize	5%	BC increased proline synthesis and activity of POD to counter the toxic effects of salinity	119

building blocks in chlorophyll synthesis.[99] The application of BC also improves stomata movements, CO_2 fixation, and chlorophyll synthesis, which ensures better photosynthetic efficiency under salinity stress.[87,100,101] BC application has been reported to protect the photosynthetic apparatus from salinity-induced damage by decreasing ROS production through an increase in antioxidant activities.[89,102]

Biochar application also improves enzymatic activities and chlorophyll synthesis (Table 3), which keeps leaves green and therefore photosynthesis.[86,88] The application of BC also improves uptake of Mg^{2+}, which ensures better chlorophyll synthesis and as a result photosynthesis.[8,103] Besides this, the BC supply also reduces NADP reduction rates through the negative feedback of increasing nicotinamide adenine dinucleotide phosphate (NADPH) in the plant. Moreover, BC also provides more energy for photosynthesis by reducing the NADPH rate and therefore increases photosynthesis.[104] Additionally, application of BC also improves Hill reaction activity, integrity of PS-II, and electron transport efficiency and decreases ROS production, which in turn improves the overall photosynthetic efficiency.[105] However, more studies are direly needed to underpin the molecular mechanism of BC-mediated improvement in plant photosynthesis under saline conditions.

4.4. Biochar Supply Increases Antioxidant Activities and Genes Expression to Counter Toxic Effects of Salinity Stress. Under saline conditions, ROS production is significantly increased, which damages major molecules and cellular organelles.[25] However, the application BC reduces ROS production by increasing antioxidant activities.[2525,40] Biochar application increases the activity of AsA- glutathione (GSH), which prevents ROS accumulations and protect plants events plants from the salinity induced toxic effects.[88] Nonetheless, sometimes BC can reduce the antioxidant activities, possibly due to less Na^+ accumulation and BC-mediated reduction in salinity-induced oxidative damage.[93,101] Biochar application improves the AsA and GSH concentration and improves the capacity of plants to detoxify the ROS.[110] The increase in ascorbate peroxidase (APX), monodehydroascorbate reductase (MDHAR), and glutathione reductase (GR) activities was also reported by different authors following the addition of BC application in plants growing under saline conditions.[63,83,107] In another study, Sofy and his colleagues found that BC application increased catalase (CAT), peroxidase (POD), and SOD activities while Hasanuzzaman and his coauthors found that BC amendments improved the Gly-1 and Gly-II activities, therefore reducing the toxic effects of salinity.[83,107] Most of these studies were conducted at lab conditions under controlled conditions; therefore, more studies are direly needed at field conditions to determine the impact of BC on plant antioxidant activities under saline conditions. It has been reported that biochar application reduced hydrogen peroxide (H_2O_2) and malondialdehyde (MDA) through increasing SOD and CAT.[111] Biochar supplementation also increases nonenzymatic antioxidant activities and proline synthesis, which help the plant to cope with salinity-induced osmotic stress.[111]

Gene expression plays an important role in countering the toxic effects of salinity. The application of BC improves the up-regulation of water transporter genes, which in turn increases biomass production and carbon assimilation in plants.[88] Aquaporins play an imperative role in water uptake,[112] and it is documented that combined use of BC and selenium nanoparticles up-regulates aquaporin genes, which improves water uptake and thus prevents the toxic effects of salinity.[113] Ion transport proteins like NHX1, HKT1, and SOS1 play a key role against salinity stress, and application of BC can up-regulate these genes to counter the salt stress.[88]

4.5. Biochar Improves Hormone and Osmolyte Accumulation to Counter Toxic Impacts of Salinity. Osmolyte accumulation plays an imperative role against the salinity stress.[114] The application of BC increases the concentration of diverse osmolytes (Table 4, Figure 2), like proline and glycine betaine, and secondary metabolites, which strengthens the antioxidant defense systems and protects the plants from the toxic effects of salinity stress.[88] Abscisic acid synthesis plays an imperative role against stress tolerance, and application of BC decreases the concentration of ABA, which in turn improves the plant performance under saline conditions.[115] The improved soil properties following BC application decrease the sensitivity of plant roots to osmotic stress owing to reduced Na^+ accumulation. The addition of BC under saline conditions decreases the uptake of Na^+, which in turn reduces the synthesis of ABA and thus brings favorable changes in plant function.[101] Proline is one of the most important osmolytes that plays a crucial role in plants in salinity tolerance. The application of BC has been reported to increase the accumulation of proline and GB, which ensures better antioxidant activities and therefore protects the plants from salinity-induced oxidative damages.[102] Nonetheless, a few authors found that BC application reduced the accumulation of osmolytes owing to the reduction in Na^+ uptake and salinity-induced oxidative damages.[105] Other authors also found that BC application decreases ABA and SA concentration by decreasing Na^+ uptake[105] while BC increases the synthesis of indole acetic acid (IAA), which triggers plant growth in the conditions of soil salinity.[116] Biochar application reduces ABA synthesis in plants under saline conditions ,which improves water uptake and maintains better turgor pressure.[105] These are the limited studies available about the effect of BC on osmolyte accumulation under saline conditions. Therefore,

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transcriptomics, genomics, and metabolomics studies are direly needed to explore the effect of BC on osmolye and hormone synthesis and their crosstalk under saline conditions.

4.6. Biochar Brings Favorable Changes in Physiochemical and Biological Properties to Counter Toxic Effects of Salinity. In recent times, BC has received a significant attention across the globe as a soil ameliorator to mitigate the toxic effects of abiotic stresses. The application of BC improves soil physiochemical and biological properties, which can counter the toxic effects of salinity stress.[120] Biochar possesses a higher surface area that adsorbs the toxic ions including Na^+ and Cl^-, which thereby reduces the toxic effects of salinity.[121] Biochar also decreases the uptake of Na^+, which in turn increases the uptake of Ca, Fe, K, and P and ensures better plant growth under saline conditions.[122] Further, BC also decreases soil EC, sodium exchange, and the sodium absorption ratio, which increases the nutrient uptake and prevents the toxic effects of salinity on soil and plants.[123,124] Biochar has a porous structure and large surface area that is favorable for NH^{4+} adsorption, and it also reduces the denitrification losses therefore, ensuring better nutrient use efficiency (NUE) under saline conditions.[125] The application BC has also been reported to decrease NH_3 volatilization losses, which is also a major reason for the BC-mediated increase in NUE under saline conditions.[126,127] BC application substantially increases the nutrient uptake, soil organic carbon level, and microbial activities, which are conducive to plant growth.[128] Nonetheless, this positive effect of BC largely depends on the type of BC, the application rate, soil conditions, and the feedstock used to prepare the BC.[129] Under saline conditions, soil structure is disturbed; however, BC possesses an excellent potential, and its application under saline soils improves soil structure by improving soil aggregation stability.[130] Calcium plays an important role in improving the stability of soil aggregates. The application of BC significantly increases the soil Ca concentration, which improves the soil aggregate stability[131,132] and ensures better availability of nutrients under saline conditions.[93] Soil organic carbon (SOC) is an important indicator of soil fertility,[133] and the application of BC has been reported to increase the SOC, which decreases sodium absorption ration (SAR) and exchangeable sodium percentage (ESP) that in turn reduces the toxic effects of salinity.[132]

Salinity stress imposes negative effects on soil enzymatic and microbial activities.[134] The application BC improves soil microbial and enzymatic activities by increasing the SOC and absorption of nutrients.[135] Biochar-mediated increase in soil microbial activity under saline conditions is also linked with improved soil aggregate stability, nutrient release, and stimulated increase in root exudation and soil carbon sequestration.[136] Nonetheless, some authors found that BC application had no impact on microbial biomass carbon (MBC) and even that BC application decreases MBC,[132] which could be attributed to BC properties, BC type, and conditions of BC preparation.

Mehdizadeh et al.[77] tested the impacts of *Morus alba* biochar under saline soils and found that the application of BC (2%) increased soil pH and soil EC, possibly owing to higher NaCl absorption in soils. These authors also noted a significant increase in soil carbon and N, K, Na, and Cl concentration following the application of BC. He et al.[80] also noted an increase in SOC, NPK, and Mg concentration, and they also found that BC triggers the polymerization of organic molecules by holding back or conserving organic matter compounds; thus, it can increase soil productivity. In a long-term field experiment, it was found that BC application increased CEC, NPK, Ca, and Mg uptake which mitigated the adverse impacts of salinity on plants.[137]

Generally, BC has a large surface, which increases the supply of carbon and nutrients to microbes.[138] For instance, Tang et al.[139] found the positive impact of BC on microbial activities through an increase in SOC. Biochar-mediated increase in microbial activity plays an important in carbon and phosphorus cycles, which can decrease the toxic effects of salinity-induced oxidative damage on plants.[140] In another study, Lu et al.[143] tested the impact of wheat straw BC on soil carbon and enzymatic activities and found that BC substantially increased urease, invertase, and phosphatase activity in salt-affected soils. Nonetheless, soil microbial biomass may respond differently to BC application, and few authors found an increase in microbial biomass,[141] while other authors found no changes in microbial biomass in salt affected soils after BC addition.[142]

The application of BC to saline soils also appreciably increases the abundance of dominant bacterial groups like *Proteobacteria*, *Alphaproteobacteria*, *Rubrobacteridae*, *Betaproteobacteria*, *Gammaproteobacteria*, and *Deltaproteobacteria*.[144] BC application has been found to increase the microbial population by changing the soil electrical conductivity.[145] Soil pH is an important soil parameter that directly affects the availability of carbon and nitrogen to plants.[146] Shi et al.[147] found the beneficial impact of *Actinobacteria* in improving soil productivity and plant health, which can improve salt tolerance. BC application also improved the abundance and population of soil fungi, which can help to counter the toxic effects of salinity.[144] Tang et al.[139] observed that the abundance *Proteobacteria* was higher in nutrient rice soils and was further increased after the application of BC. Further, an increase in catalase, urease, and phosphatase activities in saline was linked with improved microbial community composition.[147] Biochar addition also increases the abundance of ammonia oxidizing microbes indicating its potential to improve nitrification intensity in rice.[148] Wu et al.[149] found a significant increase in community diversity of bacteria, which can play a significant role in N and carbon cycles in soils.

4.7. Biochar Mitigates Accumulation of Toxic Ions and Improves Soil Enzymatic Activities to Counter Salinity Toxicity. The concentration of toxic ions (Na^+ and Cl^-) is significantly increased in saline soils, which decreases the uptake of important nutrients. Nonetheless, BC reduces the uptake of toxic ions, therefore improving the uptake of essential nutrients in plants under saline soils. For example, the application BC (16 Mg ha^{-1}) appreciably increased the exchange K by 44%.[150] In salt-affected soils, the availability of P is significantly decreases; however, the supply of BC to salt affected soils increases the P availability owing to the inherent capacity of BC to increase P availability. BC application also increases the growth of P-solubilizing bacteria, which in turn increases the P uptake by plants.[151] In saline soils, BC also traps excessive Na, releases essential nutrients (K, Ca, Mg, and N), and decreases osmotic stress; however, it largely depends on BC type, the characteristics of BC, and the conditions of BC preparation.[152,153] Biochar also has many benefits for saline soils, as the application of BC reduces ESP and SAR, which promotes plant growth.[154] The application of BC reduces soil ESP by different mechanisms. For instance, BC application increases soil Ca, which replaces Na in soil solution, and it also

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increases surface charge density, which increases the concentration of Ca and thus reduces the availability of Na in salt-affected soils.[123] Biochar application also improves soil porosity, which facilitates Na^+ leaching and reduces soil SAR and ESP. BC also increases the CO_2 partial pressure in the rhizosphere that mobilizes the Ca from the calcareous soils, which in turn replaces the Na from exchangeable sites.[155] The application of BC also increases the release of Ca, K, and Mg and decreases Na concentration, which favors photosynthetic efficacy and improves the plant growth and development.[156−158] BC application increased CEC, which increased nutrient retention.[159,160] A three-year field study on saline soils showed that BC application to barley plants improved nutrients availability, water holding capacity, and SOC.[161]

Biochar is an imperative soil ameliorative that improves the activities of various soil enzymes like docosahexaenoic acid (DHA), alkaline phosphatase (ALP), and catalase (CAT), which can curb the toxic effects of salinity on plants.[162] The application of BC also increases the activities of soil invertase, urease, and phosphatase, which can counter the toxic effects of salinity.[163] The study findings of Song et al.[164] showed that BC application increased the sucrose activities by 151%, while Abou Jaoude et al.[165] found that BC application significantly increased the levels of invertase, urease, and dehydrogenase under saline conditions. Other authors also found that BC applied to saline soils significantly increased the soil CAT, urease, phosphatase, and sucrose activities.[166,167,112,168]

4.8. Biochar Improves Yield and Quality under Salinity Stress. The application of BC has been reported to increase plant growth and development under saline conditions.[169,170] Biochar triggers the plant height, seed germination, root growth, and subsequently seedling growth under saline soils.[123] The germination, plant growth and biomass productivity in *Brassica chinensis* under salty soil was improved after BC application owing to improved soil physiochemical and biological properties.[64] Chlorophyll concentration is directly related to photosynthesis, and the application of BC has been reported to substantially increase chlorophyll synthesis.[171−173]

Salinity stress significantly reduces plant growth and development and leads to a considerable reduction in plant performance.[100] The application of BC has been reported to increase the growth and biomass yield of different crops, including rice, maize, tomato, and wheat, growing under salt stress.[93,174] The study findings of different authors showed that BC-mediated increase in plant growth and yield is linked with improved soil physiochemical and biological characteristics, improved CEC, nutrient and water uptake, soil organic matter, and a reduction in Na^+ uptake.[96,100] Further, BC also improves chlorophyll synthesis and antioxidant activities and regulates the production of assimilates, which ensures better plant growth under saline conditions.[88] The application of BC has been found to increase nutrient availability and soil pH, and it also reduces SAR and ESP and increases SOC and microbial activities, which induce favorable impacts on plant growth and yield.[89] Further, the application of BC also improves the final quality. For instance, BC application significantly increase the oil and protein concentration in edible plant parts by increasing nutrient uptake and decreasing the toxic effects of salinity.[105,175] Salt stress also modify the concentration of oil; however, BC application appreciably improved plant performance by increasing the concentration of stearic acid, oleic acid, and linoleic acid under saline conditions.[8]

5. INTEGRATED USE OF BIOCHAR AND OTHER AMENDMENT TO MITIGATE SALINITY STRESS

The application of BC significantly mitigates the adverse impacts of salinity stress; however, the efficiency of BC can be further increased by using BC with other amendments. For instance, BC application with compost significantly can increase the salt tolerance by increasing the SPAD value, membrane stability, RWC, and chlorophyll synthesis.[42] BC combined with vermin compost significantly also improved stomata conductance, chlorophyll synthesis, electron transport, and root activities and minimized the oxidative damage.[164] The combined use of BC with nano-Si and K effectively improved the physiological traits, nutrient uptake, antioxidant activities, proline synthesis, NPK protein concentration, carbohydrates, and tuber yield of potatoes growing under saline conditions.[106] Under saline conditions, the combined application of humic acid and BC can enhance the growth, antioxidant activities, and osmolyte accumulation of *Solanum melongena*.[176] The application of BC, compost, and HA has been reported to increase nutrient availability and chlorophyll synthesis in salt-affected barley plants.[177] Biochar-mediated increase in the synthesis of phyto-hormones has been reported to decrease in Na^+ uptak,e[178] and coapplication of BC with hormones alleviated the negative impacts of salinity by reducing Na^+ uptake and ABA synthesis and improving synthesis of IAA and cytokinins.[101] *Brassica juncea* seeds treated with salicylic acid (10 μmol/L) following BC application showed a reduction in salinity stress through increased antioxidant activities.[179] In maize and wheat coapplication of BC and phosphorus significantly increases leaf gas exchange, osmolyte accumulation, antioxidant activities, and α-amylase activity.[180]

Melatonin is an important hormone that can improve the photosynthetic rate and chlorophyll synthesis and reduce salinity-induced damage by increasing antioxidant activities.[181] Foliar-applied melatonin with BC also improved the plant height, leaf size, pods, and seed production.[182] Further, the combined application of ascorbic acid and BC to sorghum seedlings improved the salt tolerance by stimulating the antioxidant activities.[183] Some authors found that *Eupatorium adenophorum* cocomposted BC application improved maize biomass under saline soils,[184] and combined application of BC, compost and AMF also resulted in improved growth and grassland restoration.[185] In other studies, it was reported that BC (2%) application with *Funneliformis mosseae* and *Pseudomonas* improved the root morphology, root colonization, nutrient uptake, and grain production under saline soils. On the other hand, BC combined with compost and *Thiobacillus thiooxidans* increased the availability and translocation of nutrients from soil to plants.[186] Moreover, the combined use of BC and bacteria (*Burkholderia phytofirmans* and *Enterobacter*) also showed promising results and mitigated the toxic impacts of salinity by reducing Na^+ uptake, increasing nutrient homeostasis,[100,119] and stimulating the proline synthesis and antioxidant activities.[68]

6. NEGATIVE EFFECTS OF BIOCHAR IN PLANTS GROWING UNDER SALT STRESS

In the literature, limited studies are available on mechanisms lying behind the negative impacts of BC application in salt-affected soils. Biochar can induce toxic effects on plants by releasing toxic compounds,[160] damaging the root system through an increase in the release of nanoparticles and free

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radicals from BC.[68] Biochar can also release toxic substances (heavy metals, dioxins, and polycyclic hydrocarbons) that can cause toxicity to seeds, plant roots, and soil microbes.[187] Biochar applied to saline soils can also break into fine particles by the action of tillage, weathering, and biological activities, which can also impair the plant growth and development.[188] The presence of PFRs in BC has been reported to pose negative impacts on plants, microbes, and animals by causing oxidative damage and destabilizing the cellular membranes.[82] The negative impacts of BC on plant growth in saline soils are also linked with the deterioration of soil physiochemical properties. For example, BC with higher alkaline contents (carbonates abnd alkaline earth metals) can increase the soil pH and EC, which can impose negative impacts on plant growth. Therefore, BC with a higher ash concentration produced from manure and sewage sludge cannot be a suitable option to ameliorate salt-affected soils. Nonetheless, BC with higher Ca^{2+} and Mg^{2+} content often has higher CEC, which can be exchanged with Na^{+} in soil colloids.[82] Therefore, balancing BC salinity and its Ca^{2+} and Mg^{2+} concentration for achieving salt reduction needs further verification. Additionally, an increase in soil pH and salinity by BC is also linked with experiment conditions. For instance, at the lab scale, BC removes Na^{+} by absorption and cation exchange due to the absence of water leaching during the study period; however, Na^{+} still remains in soil due to absence of leaching. Therefore, to alleviate the negative impacts BC salinity on salt-affected soils, the combination of BC and modern irrigation practices like drip, surface, and subsurface irrigation can be an important research direction. The preparation of higher water retention BC with higher surface hydrophilic functional groups and porosity can play an important role in mitigating adverse impacts of salinity.[189] Additionally, hydrochars and nutrient rich materials can be combined with carbonaceous materials with low ash contents to overcome the limitations of BC in salt-affected soils.[190,191]

7. LIMITATIONS OF USING BIOCHAR

Biochar is a major source of carbon sink and can also improve the soil properties; however, it has many limitations.[125] Biochar application can cause soil compaction under inappropriate conditions; nonetheless, this problem can be solved by adopting proper management practices, including contour engineering and slop design. Biochar also contains different heavy metals, metalloids, and dioxins that can have harmful impacts on soils and plant health.[192] Therefore, the selection of better quality feedstock and a low pyrolysis temperature (less than 500 °C) can reduce this contamination problem.[193] Further, precise health and safety measures are needed for BC production, transportation, and storage.[95] The pore size of BC can also alter soil properties like aeration, habitat, and water retention. The carbon storage capacity of BC is not fully understood yet; therefore, it is necessary to study the carbon storage capacity of BC, which also depends on social, environmental, and economic factors.[147] The large BC processing plants have the capacity to process 23 000 tons of biomass per day, thus a higher capacity is needed to handle, transport, and store the biomass. Further, the hard cellulosic structure of feedstock can also result in higher production costs.[148,194] If BC is not prepared according to environmental guidelines, then it can cause different problems, including deforestation, health problems, and greenhouse gas emissions. The presence of volatile compounds can also pose problems for seed germination, microbes, and crop productivity.[195] Biochar also absorbs pesticides and herbicides and leads to a reduction in efficacy. In pyrolysis, phytotoxic and carcinogenic compounds are released and heavy metals are transferred into less toxic forms; however, this depends on the feedstock type and pyrolysis conditions.[196] The presence of PFR in BC induced negative impacts on plants, animals, and microbes by destabilizing membranes and causing oxidative damage.[197,198] Likewise, the presence of alkaline components in BC can increase pH and EC, which have negative impacts on plant growth.[199,200,201] Further, nutrients from BC can also lost during pyrolysis,[202] and the use of BC can also lead to an increase in greenhouse gas emissions. The ash present in BC is also a source of dust particles, and they can cause respiratory diseases if not properly managed.[203] In summary, these the major limitation of using BC on salt affected soils; however, these limitations can be tackled by using appropriating measures.

8. CONCLUSION AND FUTURE PROSPECTS

Salinity stress is a serious abiotic stress across the globe, and it can significantly reduce the crop productivity by disturbing plant physiological and molecular processes. Salinity-induced ionic toxicity and osmotic and oxidative stresses negatively affect plant performance under saline conditions. Nonetheless, the application of BC improves plant growth under saline conditions through substantial increase in membrane stability, nutrient and water uptake, osmolyte and hormone accumulation, antioxidant activities, and soil physiochemical and biological properties. Globally, efforts are being made to improve the role BC in plants to mitigate adverse impacts of salinity, however, many questions need to be answered.

- The role of BC in the mechanism of seed germination is poorly studied; therefore, it is imperative to determine how BC affect the germination mechanisms under saline conditions.
- The role of BC in nutrient uptake is less studied under saline conditions; thus, it is necessary to explore how BC affects nutrient uptakes by affecting nutrient signaling and nutrient channels under salinity toxicity.
- The role of BC in osmolyte and hormone accumulation is also less studied; therefore, it more in-depth studies must be performed on this aspect for the promising future of BC as soil amendment. There is dire need to conduct studies to determine the impact of osmolyte synthesis and hormone crosstalk with each other under saline soils.
- Limited studies are available about the combined use of BC and different amendments to mitigate salinity toxicity. Thus, BC can be combined with compost, hormones, osmolytes, and microbes to mitigate the toxic effects of salinity. The use of biochar and bacteria could be an ecofriendly approach to mitigate the adverse impacts of salinity.
- The physiological mechanism of BC-induced salinity tolerance are well explored. However, more transcriptomics, metabolomics, and genomic studies are needed to explore how BC can mitigate the toxic effects of salinity stress in plants. In the literature, most of the studies are conducted in indoor conditions under controlled conditions; therefore, outdoor field studies

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are sorely needed to open a new vision into the present knowledge of BC to mediate salt tolerance in plants.

- The impact of BC on soil microbial community structure and abundance must also be explored for remediating salt-affected soils.
- To improve the use of BC from different feedstock on salt-affected soils, it is mandatory to conduct studies to develop the relation among BC structure, properties, and application. BC application effectively mitigates the adverse impacts of salinity; however, different functional group biochar like nanocomposites, nutrient rice BC, microbial-loaded BC, and BC modified with acidic agents can provide a new avenue to remediate salt-affected soils.
- The inherent toxic substances present in the BC are also a major challenge in remediating salt-affected soils. Thus, studies must be conducted to determine the potential toxicity of BC in salt-affected soils.
- For the practical application of BC, it is important to reduce production and application costs. Therefore, appropriate steps should be implemented to increase the engagement from various industries to promote the commercialization and marketing of biochars.

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Notes

The authors declare no competing financial interest.

ABBREVIATIONS

APX, ascorbate peroxidase; BC, biochar; CAT, catalase; CEC, cation exchange capacity; Cl, chloride; EC, electrical conductivity; ESP, exchangeable sodium percentage; GHG, greenhouse gases; GSH, glutathione; GR, glutathione reductase; H_2O_2, hydrogen peroxide; IAA, indole acetic acid; MDA, malondialdehyde; MDHAR, monodehydroascorbate reductase; MBC, microbial biomass carbon; Na, sodium; NADPH, nicotinamide adenine dinucleotide phosphate; NUE, nutrient use efficiency; POD, peroxidase; ROS, reactive oxygen species; RWC, relative water content; SAR, sodium absorption ration; SOC, soil organic carbon; WUE, water use efficiency

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