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The Use of Soil Amendments and Foliar Application Can Improve Plant Production under Salinity Stress Conditions

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DUE TO climate change, salinity is one of the most important problems facing global food security in most agricultural lands. So, many studies were conducted to improve the crop yield and production under salinity conditions using various methods and compounds. Application of soil amendments and foliar application such as biochar, compost, vermicompost, green manure, farmyard manures, silicon, salicylic acid (SA), nano particles and plant growth promoting bacteria were used to mitigate the deleterious impacts of salinity and improve the growth characters and yield of several plants. To mitigate salinity stress, soil amendments were added to soil and led to improve morphophysiological and biochemical characters like stem length, leaves number, fresh weight, chlorophyll content, relative water content, osmotic adjustment and enzymes activity in the stressed plant. Furthermore, foliar application with some treatments especially, SA and plant growth promoting bacteria led to increase plant tolerance to salt stress via improving water status, ion homeostasis and plant anatomical structure as well as yield production. However, foliar application with these treatments caused significant decreases in lipid peroxidation, reactive oxygen species and electrolyte leakage as well as oxidative damages in the salt stressed plants. Because our aim is to increase the growth, and development as well as crop yield under salt conditions, the current review addresses the application of soil amendments and foliar application on morphological, physiological and biochemical as well as yield characteristics in the stressed crops as effective strategy for sustainable agriculture.

Keywords: Biochar, compost, ecofriendly approach, foliar application, salt stress, soil amendments.

1. Introduction

Crop production is a very important process in the botanists and agricultural researchers life. This process suffers from many threats such as plant pathogens and pests (Shahin et al., 2021; Morsy et al., 2021; Xu et al., 2022; Hafez et al., 2022; Omara et al., 2023; Ismail et al., 2023), drought (Abdelaal et al., 2021a; Hussain et al., 2018; Khazaei et al., 2020) and salinity (ALKahtani et al., 2020a; Abdelaal et al., 2021b; Abdelaal et al., 2022a). Salt stress is one of the most detrimental stresses that affect different plant stages and yield. Plants are classified depending on the salt content as sensitive (carrot and faba bean), moderately sensitive (grapevine), and tolerant (date palm) to salinity (El-Ramady et al., 2024). Salinity means high sodium concentration (Na^+) which reduce potassium uptake, and disturbs physiological, morphological and biochemical developments in plant cells resulting in yield reductions (Santos et al., 2021). Under salinity conditions; stem height, branches and leaves number and fresh weight were decreased significantly in many plants such as bean (El-Flaah et al., 2021), pea (Al-Shammari et al., 2023) and rice (Hafez et al., 2020a). Also, physiological characters were harmfully affected under salinity stress such as chlorophyll contents (Khedr et al., 2023; Elsawy et al., 2022), relative water content (RWC%) (El Nahhas et al., 2021) and enzymes activity such as catalase and superoxide dismutase (Abdelaal et al., 2020a; Alnusairi et al., 2021). Plants can counteract to salinity stress with various strategies to continue their life under stressful conditions (Abdelaal et al. 2024). These strategies include ionic adjustment, increasing Na^+ efflux to vacuoles, scavenging of ROS and membrane stability maintenance to improve the adaptation mechanisms of plants under salt stress (Imran et al., 2021). The negative effects of salinity were associated with the accumulation of reactive oxygen species (ROS) such as hydrogen peroxide and superoxide in several plants such as oleander plants (Kumar et al., 2017) and pea plants (Abdelaal et al., 2022b). Reactive oxygen species

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such as hydrogen peroxide, peroxyl radical (ROO•), superoxide, and singlet oxygen ($1O_2$) are naturally accumulated as by-products in chloroplasts and mitochondria. Additionally, these molecules were significantly increased under biotic and abiotic stress factors such as plant pathogens (Hafez et al., 2020b), drought (Abdou et al., 2023; Al-Shammari et al., 2024) and salinity (El-Shawa et al., 2020; El-Taher et al., 2022). The plants have natural defence systems against stress factors, the most important defence system is enzymatic and non-enzymatic antioxidants which can help plants to grow under various stresses such as plant pathogens, water deficit and salinity (Abd-El-Aty et al., 2024; Alkilayh et al., 2024; El-Banna et al., 2024; Alafari et al., 2024; Elkelish et al., 2020).

Application of soil amendments led to improve the soil characteristics and plant growth as well as yield production. In this regard, Abdelaal et al. (2022c) found that, application of biochar led to improve soil pH and soil organic matter % as well as increase grain yield of barley plants under drought stress. Also, adding biochar to soil led to increase seeds number, and weight of 100 seeds in faba bean under salinity stress during two seasons (El Nahhas et al., 2021). Wang et al. (2023) revealed that biochar augments dry matter accumulation and grain filling of maize plants under salinity conditions via boosting microbial environment and soil properties. The activity of enzymes in faba bean-stressed plants were approaching those of the control plants with biochar treatments under NaCl stress. Moreover, biochar treatment improves physical properties of soil, increased soil large pores and macroaggregates as well as improves chemical properties, however, decrease the percentage of exchangeable sodium and increase the soil total organic carbon (Yue et al., 2023). Furthermore, application of organic amendments led to alleviate the adverse effect of salinity stress on plants and enhance growth, and yield via enhancing the photosynthetic apparatus, improving antioxidative system, and decreasing oxidative damage (Irin et al., 2024). Inorganic fertilizer and rice husk biochar improve the yield production of upland rice plants (Isimikalu et al., 2022). Alamer et al. (2022) reported that treatment with vermicompost improves morphological characters, chlorophyll and activity of antioxidant enzymes of maize plants under salinity conditions. Also, the enhancement of antioxidants and decreasing electrolyte leakage as well as reducing oxidative stress was recorded with application of vermicompost under salinity conditions (Ruiz-Lau et al., 2020). Foliar application with safety compounds such as chitosan, and melatonin led to improve epy growth of several plants under salinity conditions. AlKahtani et al. (2021) found that silicon treatment led to a significant improve in physiological traits and antioxidative system in lettuce plants under salinity conditions. Additionally, Al-Shammari et al. (2023) reported that the treatment with nano silica and melatonin improve seed yield and physiological characters of pea under salt stress. The useful effects of the amendments in enhancing soil physical, chemical, and biological properties resulting in the better plant growth and yield under salinity stress (El-Hady et al. 2024; Elsherpiny, 2023; Farid et al. 2023).

Many studies were conducted to improve plant production under salinity stress, but the review articles which give sufficient information are still not adequate. Correspondingly, keeping in view the role of soil amendments and foliar application under salinity stress, this review explores the effect of some organic amendments and some foliar application for the mitigation of salinity stress and the various adaptation mechanisms. Also, this review aims to summarize the key role of soil amendments and foliar application as ecofriendly approach to improve salinity tolerance and increase the yield production of plants under salinity stress.

2. Application of soil amendments on growth characters and yield under saline conditions

Growth characters and yield are very important parameters which negatively affected under salinity conditions. Soil amendments play a significant role in improving the growth and development in plant under various conditions. Soil amendments such as biochar, compost, vermicompost, green manure and farmyard manures can mitigate the adverse effects of stress factors (Figure 1). These amendments improve soil quality and improve plant growth because of its content of the high-nitrogen level and several vital elements (Ali et al., 2022; Hoque et al., 2022). Also, they may enhance soil fertility by improving nutrient availability, and boosting antioxidant defence system in plant under stress conditions (Abou-Attia and Abdelaal 2007).

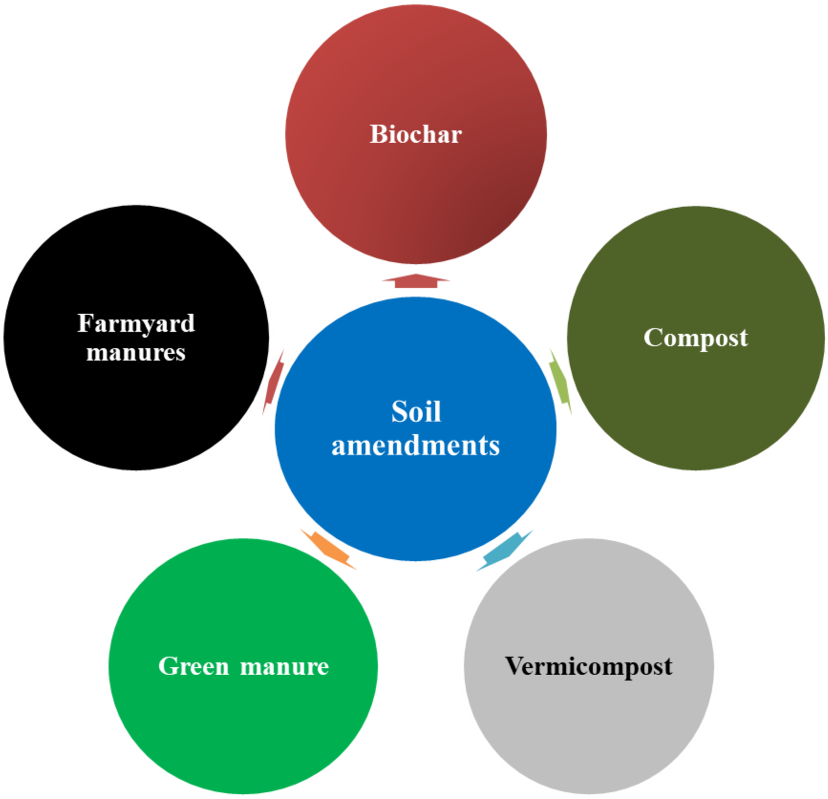

Fig. 1. Types of major soil amendments.

2.1 Effect of soil amendments on morphological and physiological traits of plants under saline conditions

2.1.1 Effect of biochar

Biochar is a multifaceted soil amendment resulting from organic components. It is a rich source for essential elements like Nitrogen, sulfur (S) and carbone which have beneficial effects on soil and plant growth. Application of biochar enhances phosphorus availability, microbial activity and soil fertility under salt stress (Jin et al., 2024; Wang et al., 2023). Morphological traits such as plant height, leaves number, leaf area, flowers number were decreased under abiotic stress (Abdelaal et al., 2022c; El Nahhas et al., 2021), however, application of biochar showed useful effect and led to improve morphological characters of stressed plants such as faba bean. The positive effects of biochar treatment might be due to the decrease in Na^+ concentration and the Na+/K+ ratio, as well as the effective role of K+ in enhancement water status, associated with modifying ion toxicity in plants under stress conditions (Ram et al., 2019). El-Desouki et al. (2024) reported that application of biochar led to improve growth characters of *Brassica napus* L. plants in acidic soil, also, biochar treatment led to increase chlorophyll fluorescence parameters and photosynthetic rate as well as the electron transfer rate. Under salinity stress, the physiological traits such as chlorophyll content were negatively affected and significantly decreased (Mohamed et al., 2022). Physiological traits such as stomatal conductance, carbone dioxide assimilation and respiration rate were decreased under salinity conditions in many plants, this harmful effect of salinity depends on species and salinity levels (Parida et al., 2004). High salinity level causes lipid peroxidation, and increases reactive oxygen species (ROS), causing oxidative damage (Siddiqui et al., 2017). Application of biochar caused a significant increase in morphological and physiological characters in many plants (Table 1). Gong et al. (2020) found that, the gene expression of StSase, SBE, and DBE dramatically increased with biochar application in rice plants. Wang et al. (2020) demonstrated that, biochar treatment led to improve maize roots, grain-filling rate, enhance nutrient and water uptake as well as grain yield. In a rice experiment, Piao et al. (2022) reported that application of peanut hull biochar led to increase photosynthetic rate and net assimilation rate as well as leaf N concentration in a soda saline–alkaline soil. Biochar application increased root length and decreased the losses of NO_3--N via leaching at 0-15 cm by 14.7% (Das et al., 2018).

Table 1. Effect of biochar on morphological and physiological characters in many plants under salinity and normal.

Biochar Source	Conditions	Role of biochar	Plant	Reference
Hardwood (80 %) and softwood (20 %)	salinity	Enhance salt stress tolerance	Potato	(Akhtar et al., 2015)
Biochar-Manure Compost	Salinity	Improve soil fertility and increase nutrient supply and translocation	Wheat	(Lashari et al., 2013)
Biochar (various compound)	Salinity	Improve physical, chemical and biological properties of soil	Some plants	(Saifullah et al., 2018)
Plant straw	Normal and stressful circumstances	Enhance soil fertility, plant growth, and development	Some plants	(Khan et al., 2024)
Tobacco biochar	Tobacco biochar	Improved tuber weight and yield	Sweet potato	(Indawan et al., 2018)
Wheat straw	Tobacco biochar	Improved tuber weight	Sweet potato	(Liu et al., 2014)
Maize straw	Normal conditions	Increase seed yield	Mung bean	(Rab et al., 2016)
Rice husk biochar	Normal conditions	Prominent boost in yield and yield related attributes	Rice	(Asai et al., 2009)
Wheat straw	Salinity	Increase permeability and nutrients concentration of soil	Wheat	Huang et al., 2019
Biochar	Salinity	Enhance nutrient availability and lower Na+ level.	Soyabean	(Farhangi-Abriz et al., 2018)
Biochar	Salinity	Increase vegetative growth and yield	Tomato	(She et al., 2018)
Biochar	Salinity	Increase plant height, and crop yield	Sorghum	(Ibrahim et al., 2021)
Wood biochar	Normal conditions	Increase root weight	Carrot	(Carpenter and Nair, 2014)

2.1.2 Effect of compost and vermicompost

Compost is an important soil amendment and contains vital nutrients such as N, P, and K (Bayoumi et al., 2019), it plays a key role in decreasing sodium ratio by increasing Ca^{2+}concentration in the soil. Application of compost enhances the micronutrients, and increase plant growth (Manirakiza and Sekr, 2020), also, it can increase fertility of soil and alleviates oxidative damages as well as promotes growth characters (Oo et al., 2015; Savy et al., 2022). Manirakiza and Sekr, (2020) reported that application of compost led to increase available micronutrients such as Fe, Mn, Cu, Zn and available phosphorous as well as organic matter. Also, chlorophyll content, plant height, fresh and dry biomass were improved with biochar treatments.

Earthworms play a pivotal role in transformation of organic waste into nutrient-rich compost which called vermicompost. Vermicompost is rich source in essential nutrients and acts as a vital strategy in decreasing the harmful effects of salinity (Tammam et al., 2023). The effect of earthworms may be due to the increase in mineralization and humification process in soil resulting in the increase in water infiltration rates, and promote growth characters (Wang et al., 2017). Several studies displayed that vermicompost meaningfully improves organic carbon content, biological properties, carbon mineralization amount, and recalcitrant carbon as well as carbon storage and sequestration in soil (Banashree et al., 2017; Ngo et al., 2014). Furthermore, physiological characters were improved and the oxidative stress was decreased however grain yields was improved under application of vermicompost (Chavez et al., 2016; Liu et al., 2019). Malal et al. (2024) reported that application of vermicompost led to improve nutrients content, soil texture and decrease the Na^{+}/K^{+} and Na^{+}/Ca^{2+} ratios as well as mitigate the negative effect of salinity on the soil microbiome. Furthermore, stem and root length, fresh weight and dry weight of Arachis hypogaea L. was increase under salinity conditions because of the treatment of soil with vermicompost (Dikshit and Venkatesan, 2024). Elsaied et al. (2024) stated that co-application of vermicompost and spray with proline gave the highest vegetative growth characters and head yield of lettuce plants.

2.1.3 Effect of green and farmyard manures

Green and farmyard manures are very significant soil amendments and play important role in improving morphological and physiological characteristics in plants. Green manure is the use of plants in succession, or intercropping with crops, these plants can be combined into the soil providing an enhancement in the physical, chemical, and biological features of soil (Meena et al., 2020). The most used plants as green manures are leguminous plants (Fabaceae), these plants have the capability to achieve the symbiosis process with bacteria in nitrogen fixation (Meena et al., 2020; Eiras and Coelho 2011). Application of organic fertilizers such as green, poultry and farmyard manures can improve nutrient uptake, chlorophyll synthesis and activity of antioxidants, resulting in increased plant tolerance against stress factors. El-Mageed et al. (2021) reported that poultry manure biochar as co-compost with soil led to improve morphological characters of eggplant. Furthermore, green and cattle manure positively affected the dry weight, and total flavonoids as well as major essential oils compounds in *Origanum vulgare* L. plants (Assis et al., 2024). Application of green manure (*Merremia aegyptia*) led to increase number of stems, stem height and shoot dry weight of lemongrass plants (Massey et al., 2021). The helpful impact of green manure and cattle manure on morphological and physiological characters was recorded in several plants (Massey et al., 2021; Honorato et al., 2022), this effect may be due to the maximum availability of essential nutrients such as K, Ca^{+2}, Mg^{+2} and Zn as well as organic matter which improve soil fertility and growth characters (Meena et al., 2020). Bidgoli et al. (2018) found that green manure application led to increase essential oil of peppermint. Also, Singh et al. (2010) stated that the application of green manure (cowpea) increased the essential oils yield of peppermint and palmarosa. With the same tend, Javanmard et al. (2022) reported that the treatment with green manure led to improve nutrients and increase essential oil in peppermint.

2.2 Effect of soil amendments on biochemical, anatomical and yield traits of plants under saline conditions

Salinity stress hinders many biochemical characters in plants (Alnusairi et al., 2021), also, yield characters were reduced under salt stress in soybean plants (Abdelaal et al., 2021c). Additionally, a reduction in the anatomical features of stem diameter, number of vascular bundles, phloem tissue thickness, and the vessel diameter of wheat plants were decreased under salt stress (Nassar et al., 2020). The plant tolerance to salinity displayed an increase in the lignification of the cell wall with Casparian strip in rice plants (Tu et al., 2014), thicker cuticles have also been observed in the tolerant variety; the thicker endodermis plays a main role in the tolerance of Na^+ entry into the xylem.

2.2.1 Effect of biochar

Yield characters such as grain-filling rate and grain weight were significantly increased with biochar treatment under soda saline–alkaline paddy fields (Table 2) (Che et al., 2024). Biochar can protect plants from harmful effects due to its high carbon level, and the presence of important nutrients for the survival and growth (Singh et al., 2016). Under salinity stress, biochemical characters such as H_2O_2, MDA, and proline content were significantly increased as a significant indicator for oxidative damage, however, application of biochar led to reduce H_2O_2, MDA, and proline content under salt stress. Moreover, CAT, and SOD activities were at their minimum levels in forage pea under salinity conditions and biochar application (Gullap et al., 2024). Biochar adjusts the biochemical characteristics of plants because of it contains several nutrients such as nitrogen, potassium, phosphorus, zinc, etc., which are very important to various plants (Tomczyk et al., 2020). Thus, biochar can enhance the availability of some nutrients to the plant under saline conditions as well as increase yield characters. El Nahhas et al. (2021) found that application of biochar and JA significantly decreased the negative impacts of salinity and enhance the plant status via decreasing the activity of enzymes and proline in faba bean plants under NaCl. Moreover, seeds number, and weight of 100 seeds were increased.

2.2.2 Effect of compost and vermicompost

The addition of compost and vermicompost led to improve the growth and biochemical characters in many plants under salinity conditions (Table 2). Under salinity stress, application of compost led to mitigate the harmful impact of salt stress in tomato plants via improving metabolites, nutritional elements and increase fruits yield (Savy et al., 2022). Also, Manirakiza and Sekr (2020) found that application of compost led to increase fresh and dry biomass were improved under salinity conditions. In the experiment of Dikshit and Venkatesan (2024), they reported that application of vermicompost led to improve biochemical characters and yield of peanut plants (*Arachis hypogaea* L.) (Table 2). The application of compost and vermicompost decreased the harmful effect of salinity and improve the biochemical parameters such as proline, ascorbic acid and phenol content in *Abelmoschus esculentus* L. under salinity stress (Suhani et al., 2023). Yanan et al. (2018) reported that the application of vermicompost led to increase the quality of the fruit, vitamin C content, and soluble sugars in strawberry plants. Also, Argüello et al. (2013) reported that adding vermicompost led to produce an increase in the vessels number, and in the phloem area in lettuce seedlings. Furthermore, treatment with vermicompost as a main source of macro- and microelements led to improve the anatomical features of ornamental plants such as the thickness of the epidermis and the mesophyll thickness of *Rosa* sp. and *Gladiolus* sp. leaves (Dogadina et al., 2020).

2.2.3 Effect of green and farmyard manures

Green and farmyard manure can use in improving the growth characters of crops via improving the biochemical and anatomical features under salinity stress (Table 3). Application of green manure (legumes) led to decrease the harmful impacts of salinity via improving the ionic homeostasis and enhancing Ca/Na ratio in soil, and decreasing electrolyte leakage (Irin 2022). Under high levels of salinity, the amount of proline and electrolyte leakage was increased however, RWC was reduced in cotton. On the other hand, the application of farmyard manure led to justify the adverse impacts of salinity and increase relative water content as well as membrane stability (Sardar et al., 2025). Moreover, application of Manure-biochar compost with mineral fertilizer led to decrease H_2O_2, and increase leaf relative water content as well as improve leaf membrane damage in tomato plants under salinity conditions (Kamal et al., 2024). In the experiment of date palm under salinity conditions, the highest epidermis thickness, cortex, pericycle, diameter of phloem and xylem were recorded with adding soil improvements (Gabash and Auda 2023).

Table 2. Effect of soil amendments on biochemical, anatomical and yield characters under saline conditions.

Type of amendments	Role of amendments	Plant	Reference
Biochar	Enhance grain yield	Rice	(Che et al., 2024)
Biochar	Adjust CAT, POD, and SOD activities	Forage pea	(Gullap et al., 2024)
Biochar	adjust the biochemical characteristics	Various plants	(Tomczyk et al., 2020)
Biochar+JA	Adjust catalase, superoxide dismutase, glutathione reductase and proline	Faba bean	(El Nahhas et al., 2021)
Compost	Improve metapelites and yield	Tomato	(Savy et al., 2022)
Vermicompost	Improve biochemical and yield characters	Peanut	(Dikshit and Venkatesan, 2024)
Compost	Improve proline and phenol	Peanut	(Suhani et al., 2023)
Vermicompost	Increase vitamin C content, and soluble sugars	Strawberry	(Yanan et al., 2018)
Vermicompost	Improve the anatomical characters (vessels number)	Lettuce	(Argüello et al., 2013)
Vermicompost	Increase the epidermis and the mesophyll thickness	Ornamental plants	(Dogadina et al., 2020)
Green manure	Decrease electrolyte leakage	Some plants	(Irin 2022)
Manure-biochar compost	Decrease H_2O_2, and increase leaf relative water content	Tomato	(Kamal et al., 2024)
Soil improvements	Increase thickness of the epidermis, cortex, pericycle, diameter of phloem and xylem	Date palm	(Gabash and Auda 2023)
Biochar and vermicompost	raised the amount of O.M. and available NPK	Panicum	(Hegab, 2024)
Soil ammendments	increased soil soil nutrient availability.	Faba Bean	(El Naqma et al. 2024)

3. Effect of foliar application and seed treatments on growth characters and yield under saline conditions

Salinity stress is a significant environmental factor that disrupt the growth characters and agricultural crop production worldwide (Abdou et al., 2023). Salinity stress negatively affected growth characters and crop yield, this negative effect is mainly attributed to the disturbance of the nutritional and water equilibrium (Figure 2) (Ali et al., 2023; Abdelaal et al. 2024). Accordingly, the damaging effects have been detected in physiological characters mainly the decrease in water uptake, and nutrient absorption, osmoregulation, photosynthesis as well as stomatal conductance. Also, the detrimental impacts of salinity may be due to the oxidative damages to cellular organelles such as chloroplasts owing to the accumulation of ROS, this effect can be mitigated with foliar application and seed treatments with the osmo-protectant compounds such as chitosan, silicon, melatonin, yeast extract, nanomaterials and PGPB (Ali et al., 2022; Al-Shammari et al., 2023; Alshammari et al., 2024; Abd-El-Aty et al., 2024).

Fig. 2. The detrimental impacts of salinity stress on growth and yield characters of plant.

3.1 Impact of foliar application and seed treatments on morphological and physiological traits of plants under saline conditions

Salinity stress induce several changes in the morphological and physiological traits of plants such as lipid peroxidation and ion balance disorder (El-Flaah et al., 2021; Kapoor et al., 2024). Also, the decrease in stem height, leaf area and branches number were detected in the salt stressed plants, these changes were associated with the decrease in cell division and cell expansion (Ramadan et al., 2023). Seed germination is highly sensitive to salt stress, this may be due to the reduction in water absorption, protein content, and storage food in seeds. Numerous studies displayed that salinity stress could reduce stem and root length, and yield of many plants (El-Tarabily et al., 2019). Salinity stress causes ion imbalance and ion toxicity in plant cells because of the accumulation of Na+ in the stressed plants, which led to decrease the uptake of other essential elements (Assaha et al., 2017).

Foliar application with melatonin (100 µM) led to improve seedling characteristics, photosynthesis, relative water contents, photochemical efficiency and antioxidant activities, and in the stressed plants compared with those in the negative control (Kang et al., 2024). This positive effect of melatonin in better salinity tolerance could be due to its role in enhancing plant morphological and physiological characters such as germination, CO_2 concentration, and photosynthesis under salinity stress. This effect was also recorded under drought stress (Al-Shammari et al., 2024). Additionally, application of chitosan improved growth characters of the stressed sweet pepper under salinity conditions. Also, chlorophyll fluorescence characters and antioxidant enzymes were improved in the stressed treated sweet pepper (ALKahtani et al., 2020a). Under salinity conditions, nano-priming (ZnO NPs) decreased salinity stress by enhancing the growth and physiological characters as well as regulating nutrient homeostasis in bean plants (Gupta et al., 2024). Several experiments have confirmed that NPs have the ability to alleviate salinity stress effects and recover plant growth (Moradbeygi et al., 2020; Zulfiqar and Ashraf, 2021). In nano-priming technique, the positive effect of NPs may be due to that NPs can pass in the seeds through the aquaporins, which are important in water and solutes movement (Wohlmuth et al., 2022), this application method for NPs is very significant to achieve best results. Application of ZnO NPs nano-priming and foliar application improved morphological parameters (Faizan et al., 2021). Theis effect might be due to the positive effect of Zn in chlorophyll synthesis, and protein synthesis by decreasing the levels of Na^{+} and Cl^{-} ions (Faizan et al., 2021). Similarly, application of ZnO NPs led to a great decrease in Na+ with a great increase of Ca^{2+} in the roots. Also, ZnO NPs can increase calcium concentration in plants to deal with the high level of Na^{+} (Schwab et al., 2016). Moreover, application of PGPB as foliar application or seed treatment is very important approach in alleviating the adverse impacts of various stresses such as salinity (ALKahtani et al., 2021), drought (Abdelaal et al., 2021a; ALKahtani et al., 2020b) and biotic stress (Hafez et al., 2020c; Alkilayh et al., 2024). The pivotal role of PGPB might be due to the symbiotic relationships between PGPB and the plant species via producing numerous substances which can significantly affect plant growth, this effect is associated with the solubilization of essential elements and the synthesis of ACC deaminase as well as siderophores (Abdou et al., 2023). In the experiment of canola seeds treated with *Enterobacter cloacae* PD-P6 improved root elongation of canola plants under salinity stress (Yaish et al., 2015). Cheng et al. (2012) reported that *Bacillus pumilus* or *Pseudomonas pseudoalcaligenes*, protect the plants under salinity stress via accumulation the antioxidants and osmoprotectants. Furthermore, *Bacillus subtilis* BERA 71 inoculation led to increase nutrient content and plant production in chickpea plants under salinity stress. This result might suggest that PGPB can provide plants with several elements N, Fe, P, and K which help plants to grow well under these adverse environments (Pirhadi et al., 2016).

3.2 Effect of foliar application and seed treatments on biochemical, anatomical and yield traits of plants under saline conditions

Reactive oxygen species (ROS) negatively affect cell membranes resulting in a significant changes in biochemical and yield characters as well as plant cellular death (Wu et al., 2014). The extreme accumulation of ROS can cause oxidative stress in nucleic acids and proteins associated with induction of lipid peroxidation in the salt stressed-plants. Also, electrolyte leakage as one of the important biochemical changes was significantly augmented in the stressed plants under several stress factors such as salinity (El Nahhas et al., 2021; Elsawy et al., 2022) and drought (Khaffagy et al., 2022; Alkhateeb et al., 2024a and b). Moreover, compatible osmolytes such as proline, flavonoid and phenolic compound can accumulate in plants under salinity conditions. Several studies showed that proline content increased under salinity stress, in many crops, such as lettuce (Das et al., 2022), and wheat (Wasif et al., 2023). Additionally, total phenol and flavonoid concentrations were observed in several plants under salinity stress (Kiani et al., 2021; Hossain et al., 2022). In the study of Kokebie et al. (2024), they reported a significant increase in phenols and flavonoids as well as MDA in soybean under salinity conditions. Moreover, Shyaa and Kisko (2024) reported that salinity stress decreased pod weight and seed yield per plant in the stressed *Phaseolus vulgaris* L.

Biochemical, anatomical and yield traits in the stressed plants can be improved with foliar application and seed treatments by several components. In this regard, application of ZnO NPs led to protect cell membrane stability by decreasing the MDA levels in moringa plants (Foroutan et al., 2019). Also, ZnO NPs plays an important role in improving osmotic process by activating the antioxidants and adjusting carbohydrate metabolism in the exposed plants to salinity conditions (Sun et al., 2021), consequently, improving water balance and compatible solutes (Li et al., 2021). Furthermore, foliar application with SA as antioxidant led to increase osmolytes content such as total sugars and proline in the salt stressed eggplant, this result could be due to the role of SA in increasing amino acid accumulation and decreasing the oxidative stress resulting in water homeostasis maintenance and osmoregulation under salinity conditions (Cárcamo et al., 2012). Also, relative water content was increased with SA treatments (1.0 mM) under salinity conditions because of the role of SA in increasing the levels of compatible osmolytes in sweet pepper plants (Amirinejad et al., 2017). Foliar application with silicon and vermicompost, caused an increase in epidermis thickness, cortex thickness, and cambium ring thickness in Red Beetroots plants (Al-Hlfie et al., 2024).

Regarding the effect of salinity on anatomical structure of plants, Swathy et al. (2017) reported that anatomical characters of cow pea stem in transverse section displayed decrease in epidermal layer and cortex layers thickness as well as pith zone under NaCl stress conditions. Also, xylem vessels diameter was decreased under salinity conditions in barley plants (Atabayeva et al., 2013) and citrus plants (Rewald at al., 2012), this negative effect on anatomical structure might be due to the reduction in cell division and elongation was recorded under salinity (El-Shawa et al., 2020; Swathy et al., 2017; Helaly et al., 2017) and drought conditions (Al-Shammari et al., 2024; Abdelaal 2015). In order to alleviate the negative impacts of salinity, some compounds were used to improve the biochemical and anatomical as well as yield characters in many plants. Foliar application of SA led to improve the anatomical characters of the salt stressed cow pea stems (Swathy et al., 2017). Also, Mady et al. (2023) found that application of SA led to improve the tolerance of eggplant to salinity stress and increase fruit length, fruit phosphorus content, as well as total yield per plant. In the experiment of Song et al. (2017) they found that the treated alfalfa plants with *Rhizobium* showed an increase in osmolytes, organic acids, antioxidants and metabolites activities under salinity conditions (Song et al., 2017). Additionally, treatment cucumber seed with *Pseudomonas aeruginosa* PW09 caused a significant increase in free phenols, proline and phenylalanine ammonia-lyase in the stressed plants (Pandey et al., 2012). Furthermore, application of *Bacillus halodenitrificans* PU62 as a seed treatments led to improve grain yield of maize plants under salinity conditions (Aslam and Ali 2018). Likewise, Feng et al. (2024), found that inoculation with *Bacillus subtilis* led to improve salt tolerance of tomato, via enhancing photosynthetic efficiency and enzymes activity, this effect may be due to the reduction in the Na+/K+ ratio. Furthermore, bacterial treatment with *Bacillus* sp. increased K^+ concentration and the K+/Na+ ratio in wheat crop (Zhao et al., 2022). Also, the application of PGPB caused a significant reduction in MDA content and boosted the salt stress tolerance in chickpea plants (Sharma et al., 2023) and wheat plants (Mehrabi et al., 2024).

4. Conclusions

Elevating salinity levels threats food security and ecosystem resulting in decreasing crop yield and productivity. Morphological, physiological, biochemical, anatomical and yield charters were negatively affected under salinity conditions, so the priorities of researchers should focus on improving plant tolerance to salinity stress, consequently, improving morphophysiological, biochemical, and yield charters. Application of soil amendments and foliar application with some compounds such as biochar, compost and plant growth promoting bacteria led to improve number of leaves, fresh weight, chlorophyll concentration, relative water content, enzymes activity and yield characters. Understanding the tolerance mechanism to salinity and the response to soil amendments and foliar application is very important to enhance the yield production in the salt stressed plants and safe the ecosystem as well as achieve the agricultural sustainability. In summary, application of soil amendments and foliar application is an effective approach to increase yield production and improve salinity tolerance.

List of abbreviations:

SA: Salicylic acid

ROS:Reactive oxygen species

RWC%: Relative water content

MDA: Malondialdehyde

PGPB: Plant growth prompting bacteria

EO: Essential oil

H_2O_2: Hydrogen peroxide

CAT: Catalase

POX:Peroxidase

SOD: Superoxide desmutase

Declarations

Ethics approval and consent to participate

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