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# Sustainable Management of Saline Soils: Insights into Organic Amendments for Enhancing Soil Health and Crop Resilience

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**Abstract**

Soil salinization, whether induced by nature or by humans, is an increasingly pressing global issue. This problem threatens agro-ecosystems since salt stress affects most farmed plants, reducing both the quality and amount of food produced. There have been a lot of new strategies and techniques developed in the last several years to help plants deal with salt stress and lessen its effects on crops. Unfortunately, not all of them are eco-friendly. That is why it is so important to find sustainable ways to improve soil production in salty environments without harming them in the long run. A lot more people are starting to pay attention to organic amendments like *vermi-compost (VC), vermi-wash (VW), biochar (BC), and bio-fertilizers (BF)*. The organic supplement lessens the effects of salt stress and boosts the development, growth, and harvest of crops. According various previous research on organic amendments after application of these organic products it enhances plant growth and yield, boost salt tolerance, and modify ionic balance, photosynthetic processes, antioxidant systems, and oxidative stress reduction. This review discusses recent studies on organic amendments in salt-stressed plants and their role in stress alleviation. The current assessment explores both existing and potential future applications of organic amendments.

**Keywords:** Soil salinization, organic amendments, biochar, vermicompost, vermiwash, bio-fertilizers.

## 1. Introduction

Worldwide agricultural soil salinity is a major abiotic factor which reducing crop growth, yield, and cultivatable land sustainability. Soil properties and feature is very important for crop cultivation and sustainable development of agriculture and soil health (Figure 1). Salt-damaged soils constitute more than three-quarters of the Earth land surface, affecting 424 million hectares of topsoil and 833 million hectares of subsoil (Mahajan, Tuteja, 2005). Salinity is a problem on a

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global scale, reducing crop yields (Celleri et al., 2022; Shahid et al., 2018). The situation is deteriorating annually, with 1.2 billion hectares of land already experiencing salinity-related issues. Moreover, the area of agricultural land affected by salinity is expanding by 10 million hectares each year. Salinity impacts plants by causing oxidative stress, osmotic stress, and ion toxicity and all these stresses created hinder in seedling growth and emergence (Balasubramaniam et al., 2023; Nikolić et al., 2023). The crops which grown in saline soil facing the problems related to photosynthetic system and inhibition of chlorophyll (chl) biosynthesis resulting in limitation or fully inhibition is show in photosynthesis process (Grattan, Grieve, 1998; Qin et al., 2010; Rahman et al., 2015; Yamane et al., 2012). High soils salinity also affected the plants nutrients absorption including nitrogen (N), phosphorus (P), potassium (K), and zinc (Zn). Because roots are essential for taking nutrients in, establishing a firm foundation, and sustaining symbiotic connections with rhizosphere microbes (Grattan, Grieve, 1998; Niste et al., 2014; Qin et al., 2010). Lowered metabolic processes, stunted plant development, and lowered agricultural yields were all results of nutrient deficiencies caused by salinity (Hu, Schmidhalter, 2005).

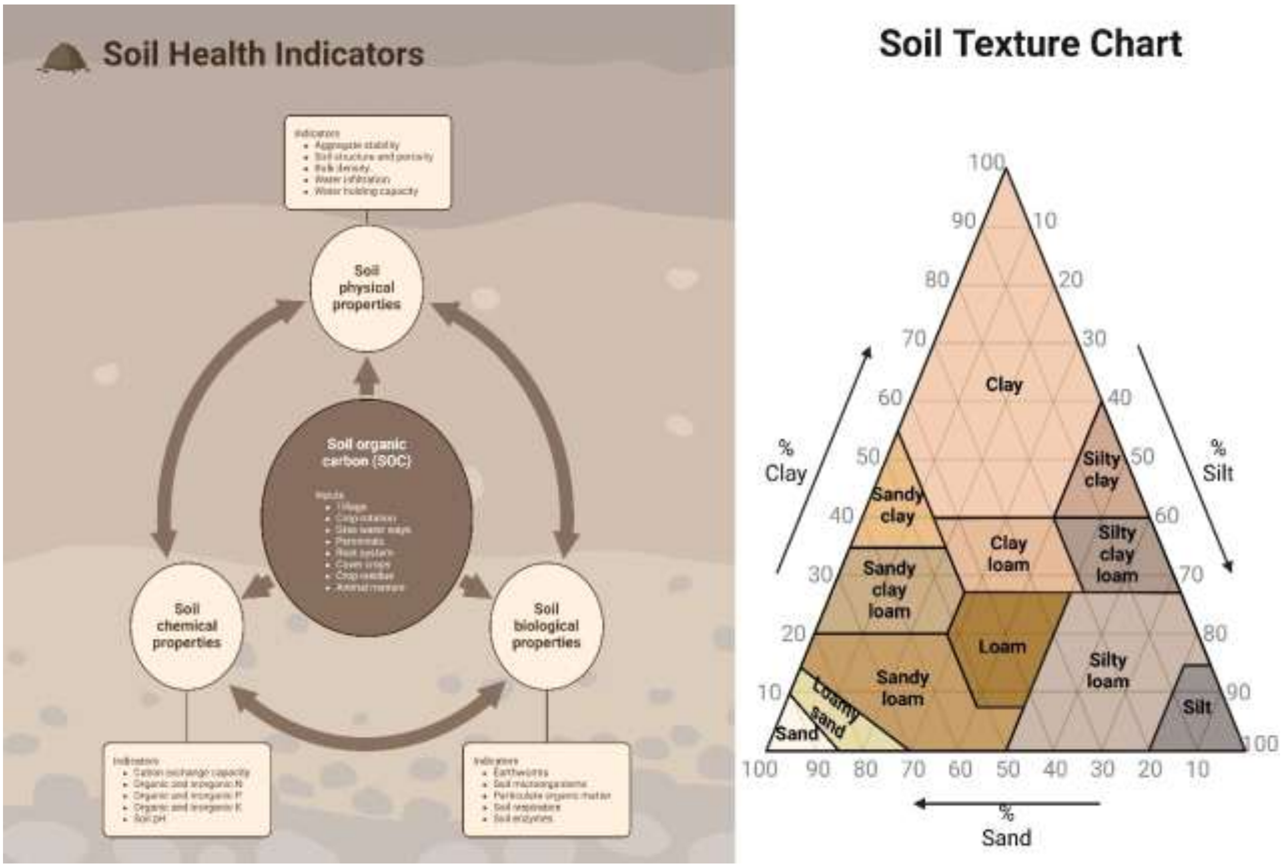


**Fig. 1.** Different types of soil with their feature

These inadequacies limited protein synthesis and carbon dioxide ($CO_2$) absorption (Hasana, Miyake, 2017). Various glycophytic crops, including rice, wheat, and maize, fail to achieve optimal yields when grown in saline soil conditions (Zheng et al., 2023). Modern agronomic practices such as *hydrophilic polymer, sulphur acids, green manuring, humic substance, farm yard manures, irrigation systems, salt-tolerant crops, salt scraping, seed bed preparation* and *sub-soiling* are some of the methods used by plant scientists to lower soil salinity levels (Meena et al., 2020; Shahid et al., 2018; Shilev, 2020). Many organic amendments, including *vermicompost (VC), vermiwash (VW), biochar (BC), plant growth promoting rhizobacteria (PGPR),* and biofertilizers (BF), have recently been utilized to reduce the detrimental effects of soil salinity (Ali et al., 2021; Hannan et al., 2020; Hoque et al., 2022; Imran et al., 2022; Kanwal et al., 2018). The main goal of this review paper is to find out how different organic amendments help plants deal with salt stress. In this review we also analysis that efficacy of organic amendments can help plants recover from salinity stress by restoring their morphophysiological and biochemical characteristics.

## 2. Results and discussion

### Salinity Stress Impact on Soil and Plant Physio-Biochemical Properties

Impact on Soil Physio-Biochemical Properties

A high concentration of dissolved salts such sodium ($Na^+$), calcium ($Ca^{2+}$), potassium ($K^+$), magnesium ($Mg^{2+}$), chloride ($Cl^-$), sulphate ($SO_4^{2-}$), carbonate ($CO_3^{2-}$), and bicarbonate ($HCO_3^-$) are the defining characteristics of saline soils. Soils with an electrical conductivity (EC) above 4 dS $m^{-1}$ at 25 °C are of this type. The permeability, structural stability, and bulk density of soil are all negatively impacted by an excess of $Na^+$ (Liu, She, 2017). Soil water retention and infiltration rates are both reduced as a result. Nitrogen ($N_2$) release in soil for plant growth is inhibited when salt concentrations are high because nitrifying bacteria are unable to carry out their work (Bai et al., 2012). When soil is too saline it inhibits respiration and enzyme activities. Soil enzyme activity, organic carbon (OC), and organic matter (OM) all get negatively impacted with higher EC under salinity stress (Sritongon et al., 2022).

Impact on Plants Physio-Biochemical Properties

The microbial activity in the rhizosphere controls the availability of nutrients which further reduces plant growth and production while under salt stress (Zhang et al., 2019). Salinity leads to osmotic stress, stunted shoot growth, and stomatal closure because $Na^+$ and $Cl^-$ accumulate in the leaves, the site of photosynthesis (Singh et al., 2022; Singh et al., 2022). By accelerating chl breakdown, it also speeds up the aging of older leaves (Shivangi et al., 2024; Singh et al., 2023). Elevated $Na^+$ levels inside cells can hinder enzyme activity, leading to diminished water interactions, photosystem II (PS II), and $CO_2$ absorption in plants (Rajput et al., 2020). It has been found that foxtail millet shoot biomass can be reduced by 24-41 % and grain production by 7-30 % when exposed to salinity stress (Rajput et al., 2024; Rajput et al., 2024a; Singh et al., 2022). High salt levels reduce antioxidant activity, lead to lipid peroxidation, protein and nucleic acid denaturation, and an increase in reactive oxygen species (ROS), which in turn cause damage to cells (Singh et al., 2023).

### Organic Amendments Based Salinity Stress Management

Biochar

Biochar is a substance that is produced when biomass is burned into charcoal. Biochar, a substance resembling charcoal produced through the pyrolysis of biomass waste under oxygen-restricted conditions for soil improvement (Lehmann et al., 2006), demonstrates potential in addressing salinization issues (Farhangi-Abriz, Torabian, 2017; Lashari et al., 2015; Lehmann et al., 2006; Sadegh-Zadeh et al., 2018a). It is rich in carbon and contains hydrogen, sulfur, oxygen, nitrogen, and minerals. C constitutes almost 70 % of its composition, with the rest varying based on the feedstock. Recent years have seen increased soil and crop production as a result of its positive environmental and economic effects. In addition to improving soil fertility (Yang et al., 2015), biochar modifies pH (Rasa et al., 2018), increases CEC (Yadav et al., 2019), sequesters carbon and increases phosphate availability (Saifullah et al., 2018). Furthermore, biochar improves the biological environment of the rhizosphere, which in turn increases soil enzyme activity and microbial development (Rasa et al., 2018; Yadav et al., 2019; Yang et al., 2015). It helps plants absorb nutrients easily and keeps them in the soil's micropores (Saifullah et al., 2018). Reduced oxidative stress from NaCl, reduced $Na^+$ adsorption ratios, and the replacement of $Na^+$ from exchangeable soil sites all work together to reduce salinity (Allen, 2007; Cheng et al., 2006; Rasa et al., 2018; Saifullah et al., 2018; Yadav et al., 2019). This potential is attributed to various mechanisms, including salt adsorption (Akhtar et al., 2015; Amini et al., 2015; Sadegh-Zadeh et al., 2018b) displacement of $Na^+$ from soil particle exchange sites (Amini et al., 2015; Sadegh-Zadeh et al., 2018b) lowering of the sodium adsorption ratio (Farhangi-Abriz, Torabian, 2017; Sadegh-Zadeh et al., 2018b), alleviation of NaCl-induced oxidative stress (Akhtar et al., 2015), and reduction of salt levels in plant seedlings (Zhang et al., 2019). Furthermore, biochar significantly enhances soil water retention capacity (Allen, 2007; Cheng et al., 2006). These properties suggest the possibility of soil desalination under altered water supply conditions. Nevertheless, biochar itself exhibits high salinity and sodicity (Lee et al., 2022; Sadegh-Zadeh et al., 2018a), particularly when produced from arid region biomass, which can contain approximately 2 and 25 times the salinity and sodium content, respectively, compared to humid region biochar (Yang et al., 2015). Additionally, the increased water holding capacity promotes soil moisture content, potentially leading to greater water loss through evaporation. The efficacy of using such a saline, sodic, and evaporation-enhancing material for managing salt-related issues under reduced water availability requires further investigation. The study found that the combined application of biochar and jasmonic acid can improve salt stress tolerance in wheat (Alharbi, Alaklabi, 2022). The application of biochar and jasmonic acid reduced growth traits, nutrients, and leaf gas exchange traits under salt stress. The combination of biochar and jasmonic acid also enhanced antioxidant enzyme activities and glyoxylase system enzymes. The accumulation of osmolytes and secondary metabolites was more evident under joint biochar and jasmonic acid treatments. Another study also shows that the impact of biochar + Arbuscular mycorrhizal fungi (AMF) on maize plants under saline stress in a greenhouse. The results show that the combined application of biochar and AMF significantly improved maize growth under saline stress (Ndiate et al., 2021). The superior mitigating effect of biochar + AMF was attributed to its ability to improve soil nutrient content, plant nutrient uptake, antioxidant enzyme activities, and the contents of various acids (Ndiate et al., 2021). Similarly, another experiment explores the long-term effects of biochar amendment on saline soil in arid and semiarid regions (Yue et al., 2023). Using silage maize, biochar improved soil physical and chemical properties, leading to increased maize growth. However, the effect diminished over three years. This study also suggests that biochar is a promising soil amendment that can enhance maize growth in saline soil for at least three years, providing valuable insights for sustainable agricultural practices in salt-affected regions (Yue et al., 2023).

Three saline irrigations (0, 25, and 50 mm NaCl solutions) and two levels of biochar (0 % and 5 % W/W) treatments were applied to the potato plants from tuber bulking to harvesting (Akhtar et al., 2015). The ability of biochar to adsorb $Na^+$ was also investigated in an adsorption investigation. Biochar was found to be able to reduce salt stress by absorbing $Na^+$. Shoot biomass, root length and volume, tuber yield, photosynthetic rate (An), stomatal conductance (gs), and midday leaf water potential were all significantly reduced as salinity level increased. On the other hand, the quantity of abscisic acid (ABA) in both the xylem and leaf sap increased (Akhtar et al., 2015). As compared to the corresponding non-biochar control, biochar addition at each salinity level improved shoot biomass, root length and volume, tuber production, An, gs, midday leaf water potential, and reduced ABA concentration in the leaf and xylem sap. Biochar supplementation ameliorated salt stress in potato plants as evidenced by decreased $Na^+$, increased $K^+$ content in xylem, and a decrease in the $Na^+/K^+$ ratio. Based on the findings, biochar incorporation could be a great way to improve agricultural yields in soils damaged by salt.

Vermicompost, Vermiwash and Humic Acid

The solid byproduct of earthworm digestion of organic materials in an aerobic environment is called vermicompost (Figure 2). Thus, vermicompost is the result of a non-thermophilic biodegradation process including earthworms and microorganisms (Tammam et al., 2023). Humus, macro and microelements, and a diverse and active microbial community are abundant in this colorless, odorless byproduct of vermicomposting. Soil physical qualities, including texture, structure, and tilth, impact a land's agronomic potential; vermicompost promotes soil health, crop yield, and tilth. Root penetration, rooting volume, water availability, nutrient mobility and uptake, and aeration are all significantly affected by the physical qualities of the soil. A soil's cation exchange capacity and other chemical characteristics are significantly impacted by its texture. In order to improve soil aeration, maintain excellent soil aggregation, defend against soil erosion, and boost nutrient availability, it is highly useful to apply vermicompost to sandy soils. This is because it helps increase the soil organic matter composition. Plants benefit from the increased nutrient content found in vermicompost because it includes a variety of nutrients that plants need, including nitrogen, potassium, sulfur, sulfur dioxide, calcium, magnesium, iron, manganese, zinc, copper, and boron. To mitigate the detrimental effects of salt, numerous research have investigated the use of different organic fertilizers on plants (Tammam et al., 2023).

Vermiwash, a liquid biofertilizer derived from decomposed organic matter and earthworm secretions, enhances soil fertility and plant growth due to its nutrient-rich, biologically active composition. It contains auxins, cytokinins, potassium, and water-soluble nutrients like nitrogen, phosphorus, and potassium, along with beneficial microbes that reduce plant diseases and promote nutrient cycling. Environmentally friendly, it serves as a sustainable alternative to synthetic fertilizers, improving soil quality without harming wildlife or human health. Being liquid, it is easily absorbed when sprayed on leaves or applied to soil. It boosts soil microbial activity, increases organic matter and nutrient availability, promotes seed germination, root growth, and photosynthesis, and mitigates abiotic stressors such as salinity, drought, and heavy metal toxicity.

Humic acid (HA), considered a bio-stimulant, is believed to play a crucial role in enhancing plant growth. Studies by Canellas and Olivares (2014) and Canellas et al. (2015) indicate that HA can stimulate plant development and improve resistance to abiotic stress by modifying primary and secondary metabolic processes associated with stress tolerance. The application of exogenous humic acid has been shown to boost plant growth, increase root and shoot dry weight, and elevate stress tolerance (Rose et al., 2014). Investigations have revealed that humic acid enhances cellular membrane stability, thereby facilitating water absorption, potassium uptake, protein and hormone synthesis, root cell elongation, and the production of non-enzymatic antioxidants linked to the shikimic pathway. It is proposed that humic acid supplementation enables plants to mount an enzymatic defense against salt stress (Çimrin et al., 2010). To mitigate the detrimental effects of salt stress and foster salt tolerance, humic acid may also stimulate root growth, alter mineral uptake, and reduce membrane damage (Canellas, Olivares, 2014; Canellas et al., 2015). Moreover, it is theorized that humic acid application can improve yield components in plants grown under salt stress conditions (Paksoy et al., 2010).


**Fig. 2.** Impact of salt stress and utilization of various organic amendments to mitigate salt stress effects on plants and improve soil health

Vermicompost and vermiwash mitigated the impact of salinity stress on *Solanum tuberosum* L. growth and tuber attributes in a central point design study with 15 treatments and three replicates (Pérez-Gómez et al., 2017). Physiological measurements, including height, stem diameter, fresh and dry weight, and tuber properties such as fresh weight, pH, electric conductivity, and °Brix, were assessed which improved after application of vermicompost and vermiwash. Optimal results were obtained with 580 g plant$^{-1}$ vermicompost and 15 ml plant$^{-1}$ vermiwash for plant height and stem diameter, while 860 g/plant vermicompost, 15 ml/plant vermiwash, and 15 mM salinity stress led to higher tuber pH and lower electrical conductivity (Pérez-Gómez et al., 2017). In another investigation show the impact of vermicompost on salinity tolerance in tomato plants (*Solanum lycopersicum* L., var. Firenze) through greenhouse pot experiments. Plants were grown on four substrates: a control "T" (100 % organic soil), a vermicompost treatment "Vc" (80 % organic soil + 20 % vermicompost), a compost treatment "C" (80 % organic soil + 20 % compost), and a mixture treatment "M" (80 % organic soil + 10 % vermicompost + 10 % compost). These groups were subjected to three NaCl concentrations (0, 50, and 150 mM) in a completely randomized block design. Plant responses to salinity stress were assessed via morphological (shoot length, stem diameter, leaf number, root length, shoot and root fresh and dry weight), physiological (Chla, Chlb, and carotenoid), and biochemical (malondialdehyde (MDA) and catalase (CAT)) parameters. Significant differences were observed among the four soil treatments. Plants on the Vc substrate exhibited enhanced growth and better salinity resistance. Organic matter (vermicompost, compost, and their mixture) positively influenced the measured parameters by gradually releasing minerals and providing soluble nutrients, thereby mitigating abiotic stresses. Thus, vermicompost is a promising method for reducing salt stress in tomato plant growth, addressing challenges in cultivating crops in drier, saline environments (Bziouech et al., 2022). Vermicompost leachate (VCL) derived from earthworms is a potent biostimulant, but its hormonal impact on plants under salt stress remains unexplored. A study was conducted on *Solanum lycopersicum* L. plants grown in nutrient solution and exposed to 125 mM NaCl for a week, with or without VCL (18 $mL.L^{-1}$) (Benazzouk et al., 2020). The researchers examined mineral nutrition, hydration, and hormonal status in roots, young and old leaves, considering the phytohormone concentration in VCL. Plants treated with VCL exhibited improved growth and reduced $Na^+$ accumulation under salt stress. The treatment mitigated young leaf senescence by reducing ethylene production and increasing proline and anthocyanin levels. VCL contains high concentrations of salicylic acid, benzoic acid, and ACC, but low levels of jasmonates, cytokinins, and proline. In salt-stressed plants, VCL application did not enhance abscisic acid or ACC accumulation. However, it increased jasmonate levels and modified the cytokinin profile, promoting dihydrozeatin-types in older leaves and N6-(Δ2-isopentenyl) adenine-types in younger ones. The study concluded that VCL mitigates the impact of salinity on leaf senescence by influencing endogenous phytohormones rather than through passive absorption of exogenous hormones (Benazzouk et al., 2020).

In another study examines the use of humic fertilizer and vermicompost to mitigate salt-induced stress by influencing soil bacterial communities and aggregates during various growth stages of winter wheat (Liu et al., 2019). The research assessed soil salinity, aggregates, nutrient availability, soil bacterial community composition through next-generation high-throughput sequencing, and wheat yield. Findings revealed that both humic fertilizer and vermicompost effectively reduced salt accumulation in topsoil (by 16.8–41.1% and 13.3–42.7%, respectively) by hindering resalinisation and enhancing the proportion of soil macroaggregates (by 26.7–85.9% and 31.6–105.5%, respectively) throughout wheat growth stages. The predominant genera identified in the soil were *Skermanella, Arthrobacter* and *Sphingomonas*. Both treatments improved soil total N (by 4.7–15.6% and 2.4–25.2 %, respectively), available P (by 15.9 % and 7.3–64.4 %, respectively), and exchangeable K (by 3.9–18.4 % and 0.7–12.1 %, respectively) by boosting the abundance of *Arthrobacter* and *Pedobacter*. This subsequently led to increased shoot biomass (by 41.1 % and 52.8 %, respectively) and grain yield (by 45.1 % and 60.2 %, respectively) in wheat. In conclusion, vermicompost and humic fertilizer alleviate salt-induced stress in coastal saline soil through a comprehensive enhancement of soil physical, chemical, and biological properties. The impact of soil amendments (control, vermicompost, biochar, and vermicompost+biochar) on wheat plant growth and yield in saline sodic soil (Hafez et al., 2021). Results show that vermicompost improves wheat growth and yield, while biochar-treated plants have higher growth performance and yield. Vermicompost-biochar mixture application, followed by biochar as a singular application, leads to significant improvements in water content, chlorophyll content, stomatal conductance, cytotoxicity, leaf $K^+$ content, and nutrient uptake. The combination of vermicompost and biochar also eliminates the detrimental effects of soil salinity and water stress, enhancing crop production.

Crop development is hindered by irrigation, and salts found in all water sources can build up in soil and plants, preventing their full potential (dos Santos et al., 2019). One option to lessen the impact of salts on plants is to use vermicompost. In addition to enriching soil, this organic compost also provides plants with essential nutrients. The purpose of this study was to compare the effects of irrigation water salinity on noni (*Morinda citrifolia* L.) growth and chlorophyll levels in substrates that included and did not contain vermicompost. Three soil substrates (without humus, with 33.33 and 66.66 % of humus) were tested in a totally randomized design with a 4 × 3 factorial system, representing four levels of electrical conductivity of the irrigation water (0.5, 1.5, 3.0 and 4.5 dS $m^{-1}$) (dos Santos et al., 2019). Plant height, stem diameter, leaf count, chlorophyll index (a, b, and total) in leaves, and fresh and dry matter of shoots and roots were among the characteristics assessed three months after seedling germination. Regardless of the salinity of the irrigation water, substrates with humus improve the fertility and support the growth of noni plants; however, the beneficial effect diminishes as the electrical conductivity of the water intensifies, and the growth in height, stem diameter, biomass production, chlorophyll a, and total indexes is negatively affected by increasing salinity. The impact of vermicompost (V) on macro and micronutrients in lettuce (*Lactuca sativa* Var. crispa) under salt stress was observed that upregulated the cultivation of lettuce crop (Demir, Kıran, 2020). The experiment utilized various salt stress levels: control (SS0) at 0 dS $m^{-1}$ NaCl, medium stress (SS4) at 4 dS $m^{-1}$ NaCl, and severe stress (SS8) at 8 dS $m^{-1}$ NaCl. Vermicompost was applied at 0, 2.5 % (V1), and 5 % (V2) (w/w). Plants were cultivated in a greenhouse with controlled conditions (50-55 % relative humidity, 24/20 °C day/night temperature) for 46 days to facilitate nutrient assessment. Medium and severe salt stress increased N and Na concentrations whilst significantly reducing P, K, Mg, Fe, Mn, and Zn levels compared to the control. Vermicompost application decreased sodium concentration but substantially increased other mineral elements, with the most notable improvements observed at 5% V application. The SS x V interaction positively influenced N, P, Mg, Na, Fe, Mn, and Zn, whilst K, Ca, and Cu showed no statistically significant changes. The findings suggest that applying vermicompost in saline-affected areas may mitigate the detrimental effects of salt on plants and restore nutritional balance in lettuce cultivation (Demir, Kıran, 2020).

3.4. Bio-Fertilizer

A more sustainable agricultural practice can be advanced with the use of eco-friendly biofertilizers rather than chemical fertilizers (Olanrewaju et al., 2017). One definition of a biofertilizer is *"a substance which contains living microorganisms which, when applied to seed, plant surfaces, or soil, colonizes the rhizosphere or the interior of the plant and promotes growth by increasing the supply or availability of primary nutrients to the host plant"* (Vessey, 2003). These microbes are commonly known as plant-growth-promoting microbes (PGPM), plant-growth-promoting bacteria (PGPB), or plant-growth-promoting rhizobacteria (PGPR). In 1895, a product called *"Nitragin"* was introduced on the market. It contained rhizobium strains that could fix nitrogen (Soumare et al., 2020). To make soil phosphorus usable by plants, biofertilizers containing bacteria that dissolve phosphorus were first employed in the 1950s (Wang et al., 2020). Multiple studies have now demonstrated BF's capacity to enhance salt tolerance. Wheat seedlings exposed to BF exhibited improved growth and yield, with salt having a reduced impact due to increased chlorophyll levels and decreased proline content (Khalilzadeh et al., 2018; Mahmoud, 2008). A greenhouse experiment was conducted to investigate the effects of saline-irrigation water on okra plant growth and yield. The soil was irrigated with tap water, and biofertilizer Nitroben and ascorbic acid were applied. Results showed that salt stress reduced growth variables, but combined treatments of biofertilizer and ascorbic acid improved growth parameters. The best treatment was T11 (Soil + S2 (2.00 $dSm^{-1}$) + ascorbic acid (100 $mg.l^{-1}$) + biofertilizer), which increased total chlorophyll and ascorbic acid contents (Mahdy, Fathi, 2012). The study used microbial treatments, including *Cyanothece* sp. and *Enterobacter cloacae*, and nanomaterials like graphene, graphene oxide, and carbon nanotubes, in combination with biofertilizers at high salinity levels. Results showed that salinity stress inhibited growth, but microbial treatments reduced its effects, especially when combined with methyl salicylate. Smart use of nanomaterials could mitigate salinity inhibitory effect (El Semary et al., 2020). Salinity is a significant abiotic factor that affects safflower development and yield. A study found that zinc oxide nanoparticles (ZnO-NPs) and biofertilizer (BF) can improve salt tolerance in safflower plants (Yasmin et al., 2021). A ZnO-NP concentration of 17 mg $L^{-1}$ was sufficient to protect safflower by increasing productivity, water content, and osmolyte levels. Coapplication of ZnO-NPs and Phytoguard protected plants from salinity stress by improving antioxidant enzyme activities and decreasing proline and malondialdehyde levels. The combined treatment improved agronomic parameters under salinity stress (Yasmin et al., 2021). Another study examined the impact of humic acid concentration and biofertilization treatments on olive seedlings grown under different levels of saline water. Results showed that salinity levels (2000 ppm) produced the highest significant parameters for olive seedlings, while salinity levels (4000 ppm) led to a decline in these parameters. Increasing humic acid levels from 0.5 to 1.5 ml $L^{-1}$ significantly increased these parameters. Biofertilization treatments enhanced growth and plant biomass, with mixed treatments having a significant effect on seedling growth. The study recommends using humic acid (1.5 ml $L^{-1}$ %) with biofertilizer treatments like *Mycorrhiza* and *Azotobacter chroococcum* to mitigate the negative impact of salinity on olive seedlings (El-Shazly, Ghieth, 2019). The agricultural sector in Indonesia faces a land shortage, necessitating the use of salinity-stressed land for plant growth. Amaranth, a popular vegetable is cultivated on this land. Biofertilizers, organic fertilizers containing beneficial bacteria, are used to ensure plant growth. This study showed that biofertilizer application increased the stem metaxylem diameter of amaranth plants in salinity-stressed environments. The application did not affect plant height or leaf count (Riesty, Siswanti, 2021).

**Exploring the Potential and Limitations of Organic Amendments in Addressing Salinity Stress**

Soil properties and plant growth in salt-affected environments are considerably impacted by organic amendments. However, these techniques come with certain disadvantages, including increased demands on labour, time, space, and resources for their preparation. Moreover, some organic methods produce unpleasant odours and attract insects, whilst others generate harmful moulds and bacteria. Nevertheless, organic amendments have demonstrated effectiveness in mitigating agricultural constraints, such as salt stress. The detection and management of salinization can be enhanced through interdisciplinary approaches, including remote sensing, artificial intelligence, machine learning, and big data analysis. Additional studies are necessary to elucidate the morphological, physio-biochemical, transcriptomic, and proteomic aspects of organic amendment application in saline conditions to enhance crop yields.

## 3. Conclusion

Abiotic stressors, such as salinity, significantly reduce agricultural yields worldwide. These stressors cause cellular damage, inhibit growth, and affect plant morphology and biochemistry. However, biochar, vermicompost, vermiwash and bio-fertilizers can reduce these negative effects by promoting plant growth, increasing salt tolerance, and maintaining ionic homeostasis. Further research is needed to understand their molecular, biochemical, and physiological functions in salt stress-affected crops.

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