J. Sci. Innov. Nat. Earth: Vol. 5, Issue 2, 2025, Page No-91-95 ISSN (Online) 2583-2093 OPEN ACCESS

Journal of Science Innovations and Nature of Earth

Journal homepage : https://jsiane.com/index.php/files/index

International, Double-Blind, Quarterly, Peer-Reviewed, Refereed Journal, Edited and Open Access Research Journal

# Role of Manganese (Mn) in Plants Under Salinity Stress: A Review

**Chanchal Upadhyay[1] and Dileep Kumar Singh*[1]**

[1]Department of Botany, Kishori Raman P G College, Mathura, affiliated with Dr. Bhimrao Ambedkar University, Agra, Uttar Pradesh, India

*Corresponding Author E-mail: dkskrpg@gmail.com

DOI: https://doi.org/10.59436/jsiane.402.2583-2093

**Abstract**

Saltiness has been the subject of studies for a long time. In the past few years, there have been a lot more studies on how to reduce its effects on crops and make them more productive. We need to find effective ways to reduce salt stress that can be used in many farming settings. We also need to make plants stronger in their defenses against this kind of stress. When there are too many soluble salts, especially sodium chloride (NaCl) in the soil, they can hurt plant growth and development. This is called salinity stress. Due to osmotic stress, high salt makes it hard for plants to take in water. It also causes ion toxicity (mainly from Na+ and Cl+) and nutrient problems by stopping plants from taking in important minerals like potassium, calcium, and magnesium. These changes in physiology often lead to less photosynthesis, stunted growth, leaf chlorosis, and, in the end, less food output. Managing saltwater stress takes a combination of methods, such as making the soil drain better, using crop types that can handle salt, and using biostimulants, which make plants more resistant by keeping their physiological processes stable during stress. Manganese (Mn) can play a big part in this if we use their unique qualities, like their ability to survive in salty circumstances. It works with antioxidant enzymes like manganese superoxide dismutase (Mn-SOD) to get rid of reactive oxygen species (ROS) that are made when there is salt stress. This lowers oxidative damage. As a result, getting enough manganese (Mn) through foliar sprays, Mn fertilizerss, Mn tablets, and the use of nanoparticles (NPs) in agriculture has become much more important for reducing salt stress and improving plant health overall. This study looks at the many ways that manganese (Mn) can help plants deal with the bad effects of salt stress. By understanding these processes, we can come up with Mn-based ways to make crops more resistant to salt damage and increase their output in salty soils.

**Keywords*:*** Salinity stress, Alleviation, Manganese (Mn), Foliar spray, Nano-particles

**Received 27.03.2025 Revised 21.05.2025 Accepted 19.06.2025 Online Available 20.06.2025**

## Introduction

Stress is anything that stops plants from growing and developing normally. These variables might be abiotic (such extreme temperature, salinity, or lack of water) or biotic (like harm done by insects or herbivores). The USDA Salinity Laboratory says that soils are salty if the electrical conductivity of their saturation extract (ECc) is 4 dS $m^{-1}$ or above. The term ECc refers to the electrical conductivity measured from the extract of a saturated soil paste. This paste is made by adding enough water to the soil to make it saturated. According to the FAO, the most widely recognised definition also says that soils with an ECc of 4 dS $m^{-1}$ or more are saline. Soils having an ECc value higher than 15 dS $m^{-1}$ are also considered very salty (Yadav *et al.*, 2011). In the early 21st century, there is a lack of water resources across the world, pollution is on the rise, and both soil and water are becoming saltier. The fast increase in the human population, coupled with the diminishing quantity of arable land, presents significant difficulties to agricultural sustainability (Shahbaz & Ashraf, 2013). High levels of salt in the soil are a serious environmental problem for agricultural production since most of the plants we grow are very sensitive to too much salt in the soil, and the amount of land impacted by salt continues to grow (Shrivastava & Kumar, 2014). Scientists have found two basic kinds of soils that are influenced by salt. The first kind of soil is saline soil, which has sodium chloride (NaCl) and sodium sulphate ($Na_2SO_4$) as its main soluble salts. It may also have significant levels of calcium ($Ca^{2+}$) and magnesium ($Mg^{2+}$) chloride ($Cl^-$) and sulphate ($SO_4^{2-}$) salts. These soils have enough neutral soluble salts to hinder the development of most agricultural plants. The second kind is sodic soils, which have sodium ($Na^+$) salts that may undergo alkaline hydrolysis, such as sodium carbonate ($Na_2CO_3$) (Parihar *et al.*, 2014). Average yields for certain important crops are typically just 20% to 50% of what they may be, mostly because of drought and soil salinity. Salts dissolve quite quickly in both surface water and groundwater. Salinity is the number of dissolved salts in water and soil. Soil salinity is the buildup of salts in the soil, such as sodium chloride (NaCl), sodium sulphate ($Na_2SO_4$), magnesium sulphate ($MgSO_4$), magnesium chloride ($MgCl_2$), calcium sulphate ($CaSO_4$), potassium chloride (KCl), and sodium carbonate ($Na_2CO_3$). Salinisation is the process by which salts build up in the soil over time (Clarke *et al.*, 2015).

Plants' structural and metabolic processes are both badly affected by salinity. Seed germination, plant development, growth, and overall output are all negatively impacted (Zhang & Dai, 2019). Primary and secondary salinity stress are the two most common types. The gradual accumulation of salt due to natural processes, such as rock erosion, precipitation, or high winds, is known as primary salinity stress. The opposite is true for secondary salinity, which results from human activities including overwatering, removing land, and tree cutting (Arif *et al.*, 2020). By decreasing chlorophyll and carotenoids levels, altering the ultrastructure of chloroplasts and the PSII complex, and lowering stomatal conductance, salinity impedes transpiration, slows down photosynthetic processes, and reduces the efficiency of gas exchange (Pan *et al.*, 2020). Most crops are quite sensitive to higher soil salt, making salinity a major abiotic factor that limits agricultural production worldwide, particularly in dry and semi-arid regions (Khondoker *et al.*, 2023). When plants are under salt stress, it disrupts their ionic equilibrium, physiological processes, and physical traits. According to Jameel *et al.*, 2024, over 10% of the world's land is now affected by salinity, which poses significant challenges for crop development and survival. When plants are exposed to an excessive amount of salt, it can cause harm to their leaves and stems. Damage to lateral branch growth becomes apparent after a few weeks, and differences in total growth and injury between salt-stressed and non-stressed plants become apparent after a few months (Lauchli & Grattan, 2007). The correct growth and development of plants depend on manganese (Mn), a micronutrient that is essential for several physiological processes and critical metabolic activities (Sarkar *et al*., 2007; Ulas *et al*., 2022). Micronutrients, including manganese (Mn), are gaining more and more recognition for their crucial roles in plant physiology and stress tolerance, while managing macronutrients has long been the focus of salt tolerance. According to Millaleo *et al*., 2010 and Rahman *et al*., 2016, manganese is essential for a number of plant functions, including photosynthesis, respiration, ATP generation, fatty acid, amino acid, lipid, protein, and flavonoid synthesis, and the activation of several plant hormones. Several antioxidants, like manganese superoxide dismutase (Mn-SOD) and manganese catalase (Mn-CAT), rely on manganese (Mn) as a co-factor to protect cells from oxidative stress (Kanwal *et al*., 2024). Manganese (Mn) exists in a wide variety of ionic forms in Earth's soil and crust. In plant metabolism and growth, it plays an essential role. The soil contains manganese (Mn) in its many oxidation states. Temperature, soil pH, and moisture levels are three of several factors that affect whether or not plants can access $Mn^{2+}$ (Husson, 2013). When the pH is high or the soil is acidic, manganese (Mn) does not dissolve effectively. On the contrary, it has a tendency to cling to soil particles, impeding the access of plant roots. Conversely, soils with a pH lower than 5.0 have a higher manganese solubility, which means plants may more easily absorb it (Millaleo *et al*., 2010).

Manganese fertilizers, foliar sprays, manganese supplements, and manganese nanoparticles can help reduce salinity stress and enhance the health of crops. Manganese sulphate ($MnSO_4$) and manganese chelates are two typical types of fertilizers that make manganese easy to get. It dissolves completely in water and is good for soil. Applying manganese (Mn) to the leaves is thought to be a good way to fix deficits fast. You may put manganese fertilizers in the soil by distributing it, putting it in bands, or spraying it on the leaves. If you notice signs of salinity stress, you should spray the leaves right away. If the symptoms come back, you can spray again. A sustainable and environmentally beneficial way to get manganese is from manganese compost. Soil organic matter rises and microbial activity is encouraged, leading to the transformation of manganese into plant-useful forms (Arvum, 2024). Researchers have also investigated the possibility of employing manganese (Mn) at the nanoscale as a fertiliser, adding to the growing number of nano-based compounds used to provide micronutrients. Due to their wide range of biological actions, traditional manganese supplements improve plants' ability to withstand abiotic stress. Within this framework, there is growing optimism over the potential benefits of using manganese nanoparticles (MnNPs) in agricultural applications (White & Gardea-Torresdey, 2018). Over the course of a year, the usage of manganese (Mn) mitigated the detrimental impacts of salt on several biochemical and physiological markers. Significant improvements in total chlorophyll content (41.24%), proline accumulation (17.48%), catalase activity (16.98%), peroxidase activity (22.84%), and fruit number per plant (52.14%) were observed with simultaneous application under the highest salinity level (1500 mg/L) (Hossam *et al*., 2024). In a study conducted by Eisakhani *et al*., 2023, it was shown that the addition of manganese (Mn) significantly raised chlorophyll, protein, and proline levels under salt stress conditions, while simultaneously decreasing malondialdehyde (MDA), electrolyte leakage (EL), catalase (CAT), and superoxide dismutase (SOD) levels. Foliar treatment of manganese chloride ($MnCl_2$) improved physiological parameters in green gramme subjected to 200 mM and 300 mM salt stress, substantially alleviating the detrimental effects of NaCl (Shahi & Shrivastav, 2018). There is a lot of study going on about how nanoparticles (NPs) may be used in farming. Recent research suggests that manganese nanoparticles (MnNPs) may enhance plant resilience to abiotic stressors while exhibiting reduced toxicity (Ye *et al*., 2017).

This review summarizes the vital role of manganese (Mn) in the biological functions of plants and emphasizes how manganese (Mn) compounds influence plant responses to salinity stress at both the plant and cellular levels.

**Impact of Salinity on Plant Physiology and Biochemistry**

The intricate interplay between osmotic stress, ionic toxicity, nutritional imbalance, and oxidative damage hinders vital physiological functioning in plants when they are subjected to salinity stress (Munns & Tester, 2008; Yadav *et al*., 2011). During their development and growth, plants frequently encounter various forms of abiotic stress. Drought, extreme heat or cold, or both, and excessive salt levels are among them. Plants are vulnerable to a wide range of stresses, some of which can cause significant stunting of growth, postponement of developmental processes, reduction in overall production, and even death in extreme cases (Krasensky & Jonak, 2012). Because they come into close contact with plant roots, salts in the soil solution have the potential to stunt plant development. The plant has a difficult time absorbing water due to the high salt levels, which reduces the water potential of its tissues, including leaves (Giordano *et al*., 2021). When soil has an excess of soluble salts, a condition known as salinity sets develops, stunting plant development. The accumulation of potentially toxic ions, such as sodium ($Na^+$) and chloride ($Cl^-$), in plant tissues causes this (Zaki, 2011; Behera *et al*., 2022). One of the most harmful aspects is salinity, which reduces the soil solution's osmotic potential and makes it more difficult for plants to take up water, grow, germinate, and photosynthesise. Additionally, it disrupts vital physiological processes by creating nutritional imbalances (Munns & Tester, 2008). Plants experience oxidative damage, alterations in water movement, nutritional balance, stomatal efficiency, and transpiration rate as a result of salt stress. Collectively, these factors reduce agricultural harvests. Due to its interference with morpho-physiological and biochemical processes, salinity substantially reduces agricultural output and crop performance (Kaveh *et al*., 2011).

**Growth-**One of the most important effects of salt stress is that it slows down the development of the plant. This happens because of two key things. First, the salt in the soil water makes it harder for plants to take in water, which slows their development. This is called osmotic or water-deficit stress. Second, salts can move along the transpiration stream and build up in leaves, which can hurt cells and stop development even more. Like other abiotic stressors, salinity slows plant development. The amount of growth that is slowed depends on the kind of plant, the stage of growth, and the amount of salt in the water (Yadav *et al*., 2019). It's interesting that plants use slowed growth as a way to survive in salty circumstances (Munns, 2002). Salinity stress causes a big drop in the surface area of roots because it makes root hairs less dense and shorter. These two qualities have a direct effect on how well nutrients are absorbed. Salinity stress negatively affects important nutrients including calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), iron ($Fe^{2+}$), and zinc ($Zn^{2+}$) that are necessary for appropriate root growth. So, the fact that roots don't develop as well under these conditions makes it much harder for the plant to take in nutrients, which hurts its health and production (Robin *et al*., 2016).

**Germination-** Salinity slows plant growth by reducing cell division and proliferation, which in turn hinders the development of shoots and roots (Munns, 2002). Reduced gibberellic acid levels, increased concentrations of abscisic acid, compromised membrane integrity, and limited water absorption capacity are the mechanisms by which salinity impairs seed germination (Lee & Luan, 2012). Salinity can result in a diminished seed germination rate and an extended germination duration, while also potentially compromising embryo viability post-germination owing to the excessive accumulation of $Na^+$ and $Cl^-$ ions (El Sabagh *et al*., 2021). Salinity significantly affects seed germination in several crop species, including Oryza sativa (Xu *et al*., 2011), Triticum aestivum (Akbarimoghaddam *et al*., 2011), Zea mays (Khodarahmpour *et al*., 2012), and numerous Brassica species In Ulfat *et al* 2007. In a number of ways, high salinity prevents seeds from germinating. Seeds have more difficult time absorbing water because the surrounding medium's osmotic potential is reduced (Khan & Weber, 2008). It also causes ion toxicity, which stops enzymes from working properly in nucleic acid metabolism (Gomes-Filho *et al*., 2008), affects protein metabolism (Dantas *et al*., 2007), interferes with hormonal regulation, and limits the mobilisation and use of stored seed reserves (Othman *et al*., 2006). Salinity disrupts root structure, which in turn reduces root growth and nutrient absorption (Robin *et al*., 2016).

**Nutrients Imbalance-**One of the major physiological consequences of salinity is nutrient imbalance. This imbalance leads to ionic toxicity, membrane instability, and metabolic dysfunctions (Munns & Tester, 2008). Nutritional imbalances in plants under salinity stress may arise due to reduced nutrient availability, competitive uptake, impaired transport, or uneven distribution within plant tissues. Numerous studies indicate that salinity adversely impacts nitrogen absorption and accumulation in plants (Rogers *et al*., 2003; Hu & Schmidhalter, 2005). Salinity not only has direct impacts on plants, but it also causes plants to build up too many reactive oxygen species (ROS), which can combine with other important parts of plant cells and cause oxidative damage. This entails DNA damage, lipid peroxidation, enzyme inactivation, protein oxidation, and disturbances in hormone control and nutritional equilibrium (Hasanuzzaman *et al*., 2021). When there is too much chloride ions ($Cl^-$) in the soil, it can cause the total nitrogen intake of the shoots to go down because chloride and nitrate ($Cl^-/NO_3^-$) work against each other. Salt stress also makes it harder for plants to take in phosphorus, which is a necessary nutrient for photosynthesis, storing energy, and moving it around. When there is a lot of salt, potassium ($K^+$) and sodium ($Na^+$) ions compete very hard with each other. Plants need to keep the right balance of sodium and potassium in their cells in order to survive in salty soils (Grattan, 2002).

**Photosynthetic Pigments**

Photosynthesis is very sensitive to salt levels. Salt stress diminishes chlorophyll synthesis, compromises chloroplast ultrastructure, and impairs the functionality of photosystem II (PSII), thereby reducing $CO_2$ uptake and energy production (Millaleo *et al*., 2010; Pan *et al*., 2020). A common reaction to osmotic stress is lower stomatal conductance, which makes it much harder for plants to take up carbon dioxide and makes photosynthesis worse (Ghorbani *et al*., 2019; Hatami & Pourakbar, 2020). Chloroplasts that have too much sodium ($Na^+$) or chloride ($Cl^-$) ions in them might hinder photosynthesis. Chlorophyll is an important part of photosynthesis, hence its level is strongly related to the plant's general health (Zhang *et al*., 2005). Rice plants (Oryza sativa) subjected to 100 mM NaCl demonstrated a reduction of 30%, 45%, and 36% in chlorophyll a, chlorophyll b, and carotenoid concentrations, respectively, in comparison to untreated controls (Chutipaijit *et al*., 2011). In Vigna radiata, escalating salt levels led to a consistent decline in pigment concentrations, with total chlorophyll diminishing by around 31%, chlorophyll a by 22%, chlorophyll b by 45%, carotene by 14%, and xanthophylls by 19% compared to the control (Saha *et al*., 2010).

**Role of Manganese (Mn) in Plant -** An important element with several metabolic functions in plants is manganese (Mn) (Doncheva *et al*., 2009). The enzymes involved in photosynthesis rely on manganese (Mn), which is why it is crucial for plant health. In addition to its role in respiration, nitrogen absorption, hormone control, chloroplast formation, lignin biosynthesis, and stress defence, it is an essential cofactor for several antioxidant enzymes (Chandra & Roychoudhary, 2020; Goussias *et al*., 2002; Millaleo *et al*., 2010). It is involved in several important biochemical activities, such as making ATP, RuBP carboxylase enzyme reactions, and fatty acids, acyl lipids, and proteins. Plants are stressed out by almost everything in their environment, so not having enough manganese (Mn) can hurt their growth and development by messing up the jobs of important enzymes like scavenging reactive oxygen species (ROS), seed germination, fungal resistance, and photosynthesis. This can lead to problems like interveinal chlorosis (yellowing between leaf veins), dark brown spots on leaves, and older leaves wilting or dying too soon. The amount of manganese (Mn) went up in the shoots of tomato and soybean plants, whereas it went down in the roots of squash plants at all levels of salt. The alterations in nutrient concentrations attributable to salinity were around twice or less, with all changes being statistically significant at the 5% level or above.

Table: 1. Role of Manganese (Mn) in Plants

| Aspect | Role of Manganese (Mn) |
|---|---|
| Essential Element Type | Micronutrient |
| Absorbed Form | $Mn^{2+}$ (Manganese ion) |
| Uptake Mechanism | Active transport through root epidermal cells |
| Mobility in Plant | Relatively immobile in phloem; more mobile in xylem |
| Accumulation Site | Primarily in leaves and shoot tissues |
| Photosynthesis | Activates the water-splitting enzyme in Photosystem II (OEC complex) |
| Enzyme Activation | Cofactor for various enzymes, especially oxidoreductases, decarboxylases, and dehydrogenases |
| Antioxidant *Defense* | Essential for the function of Mn-superoxide dismutase (Mn-SOD) |
| Nitrogen Metabolism | Involved in nitrate assimilation via nitrate reductase activation |
| Lignin Biosynthesis | Plays a role in lignin formation, strengthening cell walls |
| Deficiency Symptoms | Interveinal chlorosis, brown spots on leaves, reduced growth,poor root development |
| Toxicity Symptoms | Brown spots, crinkled leaves, inhibited root growth (common in acidic soils) |

**Photosynthesis-** The water-oxidizing mechanism of Photosystem II relies on manganese (Mn), which plays a crucial role in photosynthesis. To facilitate photolysis, the process of dividing light into its component molecules, which in turn generates energy for photosynthesis, an adequate amount of manganese (Mn) is required (Alejandro *et al*., 2020). Photosystem II's Oxygen-Evolving Complex (OEC) relies on manganese (Mn) for photolysis, or the breaking of light into its component molecules—water. A key component of the photosynthetic energy cycle, this activity releases oxygen, protons, and electrons. In immature leaves, symptoms like interveinal chlorosis appear as a result of poor photosynthesis and reduced chlorophyll production caused by a magnesium deficit. Manganese plays a considerably more important role under salt stress, sustaining photosynthetic efficiency by preserving chloroplast integrity and PSII activity.

**Enzyme Activation-** Hydrolysis, phosphorylation, decarboxylation, and redox reactions are only a few of the numerous reactions that enzymes catalyse, and all of them depend on manganese (Mn). Almost every living thing requires manganese (Mn) in some form, either as an enzyme cofactor or as a metal with catalytic activity inside biological complexes (Andresen *et al*., 2018). As an antioxidant enzyme called manganese superoxide dismutase (Mn-SOD), it is crucial for the detoxification of reactive oxygen species (ROS) in conditions with high amounts of salt, dryness, or heat (Ducic & Polle, 2005). Manganese (Mn) influences the activity of enzymes in several metabolic pathways, including those involved in the metabolism of nitrogen, carbohydrates, energy production, the Calvin cycle, and the ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO) enzyme. This, in turn, aids photosynthesis. The indole-3-acetic acid (IAA) oxidase enzyme is activated, which further helps it control hormone levels. By aiding enzyme synthesis of structural compounds like lignin and flavonoids, manganese (Mn) contributes to secondary metabolism as well.

**Biosynthesis-** Chlorophyll synthesis, aromatic amino acid synthesis (including tyrosine), and secondary metabolite synthesis (including lignin and flavonoids) are all metabolic activities that rely on manganese (Mn). It has a role in nitrate absorption and isoprenoid production as well (Lidon *et al*., 2004). Additionally, manganese (Mn) contributes to key physiological functions like respiration, photosynthesis, amino acid synthesis, and hormone regulation, particularly by influencing indole acetic acid (IAA) activity through IAA-oxidase enzymes. Manganese modulates plant hormonal balance, particularly auxin metabolism, influencing growth patterns, root architecture, and stress signaling (Alejandro *et al*., 2020). Through its involvement in antioxidant defense, energy metabolism, and hormonal regulation, Mn enhances plant resilience to environmental stresses, including salinity, drought, and heavy metal toxicity (Pittman, 2005; El-Fouly *et al*., 2011).

**Manganese (Mn) uptake and translocation in plants-** Chlorophyll synthesis, aromatic amino acid synthesis (including tyrosine), and secondary metabolite synthesis (including lignin and flavonoids) are all metabolic activities that rely on manganese (Mn). It has a role in nitrate absorption and isoprenoid production as well (Lidon *et al*., 2004). The enzyme indole acetic acid (IAA)-oxidase is one mechanism by which manganese (Mn) influences respiration, photosynthesis, amino acid synthesis, and hormone control, among other important physiological processes. According to Alejandro *et al*., (2020), manganese has an effect on the balance of plant hormones, specifically auxin metabolism, which in turn affects root architecture, stress signaling, and growth patterns. Manganese (Mn) increases plant resistance to salt, drought, and heavy metal toxicity via its roles in antioxidant defense, energy metabolism, and hormone control (Pittman, 2005; El-Fouly *et al*., 2011).

Manganese (Mn) ions are the main form that plants receive from soil. This process is aided by certain transport proteins, notably those in the ZIP (ZRT, IRT-like Protein) family, and it takes place through root epidermal cells. Furthermore, it has been shown that two ZIP transporters found in Arabidopsis root stele are involved in the translocation of manganese (Mn) from the root to the shoot (Milner *et al*., 2013). The translocation of manganese (Mn) into the cell and its organelles relies on both long-distance and short-distance transport pathways. Manganese (Mn) translocation across plasma and organelle biomembranes is involved in these processes (Pittman, 2005).

**Role of Mn in Alleviating Salinity Stress-**Ionic toxicity, nutritional imbalance, and oxidative damage are some of the ways in which salinity stress hinders plant development and physiology. An important micronutrient that helps reduce these negative effects is manganese (Mn), which is involved in many biological processes including photosynthesis, antioxidant defense, nutrition metabolism, and ion homeostasis (Pittman, 2005; Millaleo *et al*., 2010; Alejandro *et al*., 2020). New research on the protective effects of Mn in salty settings has opened up exciting possibilities for strengthening crop resilience.

**Antioxidative Defense and ROS Detoxification-**One way magnesium mitigates salt stress is by enhancing antioxidant defences in plants. When plants are exposed to salt stress, they accumulate reactive oxygen species (ROS), which can lead to lipid peroxidation, protein degradation, and damage to nucleic acids (Arif *et al*., 2020; Hasanuzzaman *et al*., 2021). One of the most important enzymes in the detoxification process, manganese superoxide dismutase (Mn-SOD) converts superoxide radicals ($O_2^{\cdot -}$) to hydrogen peroxide ($H_2O_2$). Catalase and peroxidases then remove these reactive oxygen species (ROS). Chodra and Roychoudhury (2020) and Ye *et al*., 2019 found that this enzymatic pathway prevents oxidative damage and preserves redox equilibrium. According to Rahman *et al*., 2016, seedlings were able to improve their salt-stress tolerance when given an external dose of manganese (Mn). This was achieved via coordinating the glyoxalase system, antioxidant defense mechanisms, and ion homeostasis.

**Maintenance of Photosynthesis and Chloroplast Function-**According to Goussias *et al*., (2002) and Lidon *et al*., (2004), manganese plays a key role in the oxygen-evolving complex (OEC), which is essential for photolysis of water and oxygen evolution. According to Millaleo *et al*., (2010), Ghorbani *et al*., (2019), and Alejandro *et al*., (2020), chloroplast integrity and chlorophyll content are both negatively affected by salinity. On the other hand, an appropriate supply of manganese (Mn) maintains PSII activity and stabilises thylakoid membranes, which in turn preserves photosynthetic efficiency. In salty settings, increased growth and biomass buildup are caused by improved photosynthesis when Mn is supplemented (Hatami & Pourakbar, 2020).

**Regulation of Ion Homeostasis and Nutrient Balance-**Sodium ($Na^+$), potassium ($K^+$), calcium ($Ca^{2+}$), and micronutrients like manganese (Mn) are all disrupted in the absorption of these nutrients when the water is too salty (Grattan & Grieve, 2002; Hu & Schmidhalter, 2005). Application of manganese enhances food absorption and translocation and reduces sodium toxicity via modifying ion channels and membrane transporters (El-Fouly *et al*., 2011; Gul *et al*., 2019; Tabassam *et al*., 2022). Supporting NRAMP transporters with increased Mn availability helps maintain ionic homeostasis and decreases ion toxicity in salty environments (Kanwal *et al*., 2024).

**Enhancement of Osmoprotectants and Metabolite Accumulation-**Two studies, one by Saha *et al*., 2010 and the other by Chutipaijit *et al*., 2011, found that manganese indirectly helps with osmotic adjustment by promoting the accumulation of osmoprotectants such soluble carbohydrates, proline, and glycine betaine. These compounds protect cellular structures from oxidative stress and dehydration, stabilise proteins, and maintain intact membranes (Eisakhani *et al*., 2023; Jabeen and Ahmad, 2011).

**Improvement of Seed Germination and Early Seedling Growth-**Salinity stress can have a significant impact on seed germination and the early growth of seedlings. Priming or foliar spraying plants with manganese improves their water uptake, enzyme activities, and antioxidant defenses, which in turn speeds up germination, seedling establishment, and early root-shoot growth in salty environments (Akbarimoghaddam *et al*., 2011; Kaveh *et al*., 2011; Ghasempour *et al*., 2024). The addition of manganese (Mn) to the grapevine cultivar's growth medium mitigated salt toxicity and decreased sodium ion buildup in the shoots (Hatami & Pourakbar, 2020). El-Aidy *et al*., (2021) found that manganese (Mn) plays a crucial role in controlling ion fluxes across cell membranes by ensuring the integrity of the cell wall.

**Influence on Gene Expression and Stress Signaling-**Ye *et al*., (2020) and Altıntaş *et al*., (2024) cite recent studies indicating that Mn influences the expression of genes involved in stress response, ion transport, and osmotic control, which are implicated in antioxidant pathways. Metal ions modulate hormone levels and signal transduction pathways, one of which is the abscisic acid (ABA) pathway, which in turn improves plants' ability to withstand salty conditions (Lee & Luan, 2012; Alejandro *et al*., 2020).

**Application of Manganese (Mn) for Salinity Management-**Various application strategies of manganese (Mn) have been evaluated for their suitability and effectiveness under saline soil conditions. Among these, foliar spray is considered highly suitable and effective, Soil banded $MnSO_4$ shows moderate effectiveness, Mn-chelates are moderately to highly suitable, Emerging technologies like nano-manganese fertilizers (MnNPs) have demonstrated high effectiveness due to their superior solubility, and In contrast, broadcasting manganese fertilizers is not recommended for saline soils, as it leads to poor availability due to Mn fixation in alkaline and salt-affected soils, reducing its effectiveness (Table : 2). Manganese (Mn) makes up approximately 0.11% of the Earth's crust. In soils, total Manganese (Mn) concentrations typically range from 20 to 3,000 parts per million (ppm), or 0.002% to 0.30%. The amount of manganese in soil that plants may readily absorb is, however, rather little. The divalent manganese ion ($Mn^{2+}$), usually present in soil solutions containing organic molecules, is the most common and accessible form. In addition to being an important element for plant growth and development, manganese (Mn) also improves resistance to salt stress by limiting salt absorption and transport within the plant. Broadcast (10–15 lb/acre), banded (3-5 lb/acre), and foliar spray (1-2 lb/acre) are the three main approaches of managing manganese fertilizers. Because it slows down the immobilisation of Mn, banded or foliar treatment is preferable in soils with a high pH that are acidic. Fertilizerss containing nano-sized manganese (MnNPs) have recently been investigated, following the growing trend of using nano-based materials as micronutrient providers. Because of its important function in many biological processes, MnNPs improve plants' ability to withstand harsh environments. The possible advantages of nano-manganese in this setting have garnered a lot of attention due to the high levels of salt (White & Gardea-Torresdey, 2018).

**Table: 2 Different strategies of Manganese for mitigating salinity stress**

| Strategy | Suitability in Saline Soils | | Effectiveness | Remarks |
|---|---|---|---|---|
| **Foliar spray** | ✓ | High | ☆☆☆☆ | Fast response |
| **Soil banded $MnSO_4$** | ✓ | Moderate | ☆☆☆ | Localized, better than broadcast |
| **Mn-chelates** | ✓ | Moderate –High | ☆☆ | Short-lived, costlier |
| **Nano-Mn fertilizers** | ✓ | High (emerging tech) | ☆☆☆☆ | Efficient at low doses |
| **Broadcast Mn** | × Low in saline conditions | | ☆ | Risk of Mn fixation |

**Soil Application-** Soil application is a common method for supplying manganese (Mn) to crops, especially in field conditions. It can be done through either broadcast or banded methods. Broadcast application, typically at 10–15 lb/acre, is suitable for mildly saline soils but may be less effective in high-pH or alkaline conditions where manganese (Mn) becomes rapidly immobilized and unavailable to plants. In contrast, banded application involves placing 3–5 lb/acre of Mn fertilizer near the root zone, which enhances nutrient use efficiency. This method is more effective under salinity stress, as it reduces the contact of manganese (Mn) with salt-affected bulk soil, thereby improving early root uptake and plant response. The growth indices and biochemical activities of sunflower plants were shown to be improved when manganese (Mn) was administered as $MnCl_2$ or in combination with other forms. This improvement was observed in both non-saline and saline growing situations (Jabeen & Ahmad, 2011). Plants subjected to salt stress showed an improvement in their relative growth rate after supplementation with manganese (Mn). A rise in the net assimilation rate, not changes in the leaf area ratio, was the primary cause of this improvement. Supplemental manganese (Mn) plays a small and context-dependent function in mitigating the negative effects of salt (Pandya *et al*., 2005). Manganese (Mn) supplementation enhanced Mn concentration and absorption in plant shoots. Plants subjected to salt stress responded well to extra manganese, which increased both their net photosynthetic rate and relative growth rate. Table 3 lists the several manganese fertilizers sources that are accessible, including chlorides, chelates, oxides, and oxysulfates.

**Table 3. Manganese (Mn) fertilizer sources, formulas and Mn content.**

| Manganese Source | Chemical Formula | Mn Content (%) | Notes |
|---|---|---|---|
| **Soluble Forms** | | | |
| Manganese Sulfate | $MnSO_4 \cdot 3H_2O$ | 26–28 | Highly soluble; commonly used in agriculture |
| Manganese Chloride | $MnCl_2$ | 17 | Soluble; less commonly used due to chloride ion |
| Manganese Chelate | MnEDTA | 12 | Chelated; effective in high pH soils |
| **Moderately Soluble Forms** | | | |
| Manganese Carbonate | $MnCO_3$ | 31 | Limited solubility; used in acidic soils |
| Manganese Frits | – | 10–25 | Slowly available; often used in controlled-release formulations |
| **Insoluble/Oxide Forms** | | | |
| Manganese Dioxide | $MnO_2$ | 63 | Very low solubility; not plant-available |
| Manganous Oxide | MnO | 41–68 | Low solubility; slow-release source |

**Foliar Spray-** Foliar spray is an effective method for correcting manganese (Mn) deficiency, particularly under salinity stress where root uptake is hindered. Typically applied at a concentration of 0.1–0.5% $MnSO_4$ or 1–2 lb/acre, foliar manganese (Mn) directly reaches the leaves, bypassing soil-related issues such as high pH or salt-induced immobilization. This method provides a quick response, improving chlorophyll synthesis, photosynthetic efficiency, and antioxidant enzyme activity. Foliar application is especially beneficial during critical growth stages, helping plants cope with stress and maintain productivity under saline conditions. Compared to individual element application, the mixed foliar spray resulted in greater improvement in growth and yield components. This spray also helped reduce the toxicity of excessive sodium present in the growing medium, as evidenced by the fact that it enabled the plants to produce economically viable yields even beyond the threshold of salinity stress (Jabeen & Ahmad, 2011).

Foliar application of manganese (Mn) suspension improved growth characteristics and nutrient absorption, independent of when administered, in contrast to increasing concentrations of NaCl, which resulted in a decrease in plant growth and nutrient uptake. El-Fouly *et al*., (2011) found that applying Mn to wheat leaves might help the crop better handle salt stress. In water stress circumstances, the relative water content (RWC) in grapevine leaves was also enhanced by $MnSO_4$ (manganese sulphate) treatment; this enhancement was 4% for the Rotabi cultivar and 10% for the Thompson Seedless cultivar. The findings indicate that grapevine development characteristics can be improved by applying $MnSO_4$ to the leaves under water stress situations (Ghorbani *et al*., 2019). Research on manganese (Mn) foliar applications revealed that the applied Mn improved nutrient absorption. Applying manganese to rice plants increased their nutrient absorption capability and made them more resistant to salt, according to the study (Tabassam *et al*., 2022). Under both normal and saline irrigation conditions, the development of Vigna unguiculata was boosted by the foliar application of manganese (Mn) as a micronutrient (Gul *et al*., 2019). Ornamental cabbage can have its salt-induced stress reduced with the use of manganese (Mn). The researchers found that plants with manganese applied to their leaves had less ion leakage (Altintas *et al*., 2024).

**Manganese (Mn) Nano-Particles (MnNPs)**

While fertilizers and pesticides have long been staples in agricultural practice, nanomaterials have just recently emerged as a viable alternative that can reduce plant stress and increase crop yields (Ye *et al*., 2020). Ghasempour *et al*., (2024) found that plants can be less stressed by salt when they are treated with metallic nanoparticles and other modern technologies. A potential substitute for traditional manganese fertilizers, manganese nanoparticles (MnNPs) show great promise, especially in situations where salt stress is present. Due to their nano-size and high surface area, MnNPs exhibit improved solubility, mobility, and bioavailability in the plant system. They enhance plant tolerance to salinity by supporting vital physiological processes such as photosynthesis, enzyme activation, and reactive oxygen species (ROS) scavenging. MnNPs also improve nutrient uptake efficiency and strengthen antioxidant defense mechanisms, thereby reducing oxidative damage caused by salt stress. Recent studies highlight their potential in promoting growth and resilience in crops grown under saline conditions, making MnNPs a valuable tool in stress-adaptive agriculture.

## Conclusion and Future Perspectives

Manganese (Mn) is essential for plants because it reduces the harmful effects of salt stress. Plants rely on the critical micronutrient manganese (Mn) for a number of biochemical and physiological functions that allow them to continue growing and developing even when exposed to saltwater. Because of its roles in antioxidant defense, photosynthesis, ion management, and osmotic adjustment, manganese (Mn) improves plants' tolerance to salt. Manganese (Mn) is an encouraging resource for the long-term control of agricultural systems impacted by salt, which is a growing concern for world food security. By increasing their photosynthetic efficiency and feeding enough manganese (Mn) to PSII (Photosystem II), crop plants with enhanced manganese absorption capacity and utilization efficiency can grow better and produce more even when manganese is scarce. Supplemental manganese (Mn) does not increase Mn levels in salt-stressed plants to adequate concentrations, indicating that salinity hinders plant manganese (Mn) absorption. Thus, magnesium shortage is one of the main causes of salinity-induced stunting of plant development. Nevertheless, adding manganese (Mn) to the diets of plants that are salt stressed does help a little. The longer tension lasts, the more harm salt may do. On the other hand, manganese (Mn) can mitigate salt damage when given topically. Plants that are negatively impacted by salt can benefit from manganese (Mn) because it improves ion balance and increases antioxidant defense and glyoxalase systems. Applying micronutrients, especially manganese (Mn), can help plants thrive in salty and sodic environments because of the important functions they play in supporting plant development in these environments.

To further understand the molecular role of manganese (Mn), which is implicated in plant responses to salt stress, further study is required to fully determine the Mn transport and signaling pathways. Furthermore, one potential avenue to enhance Mn bioavailability in salty environments is the creation of refined nano-formulations for targeted and efficient administration. So that salt-tolerant crops may be engineered or selected with optimised Mn utilization, research should also aim to identify genotype-specific processes that contribute to Mn usage efficiency. Lastly, improving crop production and sustainability in salt-affected places would require incorporating Mn nutrition practices into precision agriculture frameworks that are designed for saline situations. Researchers hope that by understanding how plants regulate manganese (Mn) absorption, subcellular compartmentalization, and homeostasis, they will be better able to breed staple crops with manganese (Mn) efficiency.

## Reference

Akbarimoghaddam, H., Galavi, M., Ghanbari, A., & Panjehkeh, N. (2011). Salinity effects on seed germination and seedling growth of bread wheat cultivars. Trakia Journal of Sciences, 9(1), 43–50.

Alejandro, S., Holler, S., Meier, B., & Peiter, E. (2020). Manganese in plants: From acquisition to subcellular allocation. Frontiers in Plant Science, 11, Article 300. https://doi.org/10.3389/fpls.2020.00300

Altıntaş, S., Yasemin, S., Çatkın, S., & İnal, B. (2024). Effectiveness of manganese foliar spraying to mitigate salt stress in ornamental cabbage: Insights into morphological, physiological, biochemical adaptations and mTERF gene responses. South African Journal of Botany, 168, 462–475.

Andresen, E., Peiter, E., & Küpper, H. (2018). Trace metal metabolism in plants. Journal of Experimental Botany, 69(4), 909–954.

Arif, Y., Singh, P., Siddiqui, H., Bajguz, A., & Hayat, S. (2020). Salinity-induced physiological and biochemical changes in plants: An omic approach towards salt stress tolerance. Plant Physiology and Biochemistry, 156, 64–77.

Arvum. (2024). Organic sources of manganese and their application methods. Arvum Plants Lab.

Behera, T. K., Krishna, R., Ansari, W. A., Aamir, M., Kumar, P., Kashyap, S. P., Pandey, S., & Kole, C. (2022). Approaches involved in the vegetable crops salt stress tolerance improvement: Present status and way ahead. Frontiers in Plant Science, 12, 818730.

Castaings, L., Caquot, A., Loubet, S., & Curie, C. (2016). The high-affinity metal transporters NRAMP1 and IRT1 team up to take up iron under sufficient metal provision. Scientific Reports, 6, Article 37222. https://doi.org/10.1038/srep37222

Chandra, S., & Roychoudhury, A. (2020). Role of selenium and manganese in mitigating oxidative damages. In A. Roychoudhury & D. Tripathi (Eds.), Protective chemical agents in the amelioration of plant abiotic stress (Chapter 30). Wiley.

Chutipaijit, S., Cha-um, S., & Sompornpailin, K. (2011). High contents of proline and anthocyanin increase protective response to salinity in Oryza sativa L. spp. indica. Australian Journal of Crop Science, 5, 1191–1198.

Clarke, D., Williams, S., Jahiruddin, M., Parks, K., & Salehin, M. (2015). Projections of on-farm salinity in coastal Bangladesh. Environmental Science: Processes & Impacts, 17(6), 1127–1136.

Dantas, B. F., De Sá, R. L., & Aragão, C. A. (2007). Germination, initial growth and cotyledon protein content of bean cultivars under salinity stress. Revista Brasileira de Sementes, 29(2), 106–110.

Doncheva, C., Poschenrieder, C., Stoyanova, Z. I., Georgieva, K., & Barceló, J. (2009). Silicon amelioration of manganese toxicity in Mn-sensitive and Mn-tolerant maize varieties. Environmental and Experimental Botany, 65(2-3), 189–197.

Ducic, T., & Polle, A. (2005). Transport and detoxification of manganese and copper in plants. Brazilian Journal of Plant Physiology, 17(1), 103–112.

El-Fouly, M. M., Mobarak, Z. M., & Salama, Z. A. (2011). Micronutrients (Fe, Mn, Zn) foliar spray for increasing salinity tolerance in wheat (Triticum aestivum L.). African Journal of Plant Science, 5(5), 314–322.

El Sabagh, A., Islam, M. S., Skalicky, M., Ali Raza, M., Singh, K., & Hossain, M. (2021). Salinity stress in wheat (Triticum aestivum L.) in the changing climate: Adaptation and management strategies. Frontiers in Agronomy, 3, Article 661932.

Eisakhani, M. R., Ghooshchi, F., Moghaddam, H. R., & others. (2023). Mitigation of the adverse effects of salinity on red bean plants via exogenous application of glycine betaine, zinc, and manganese: Physiological and morphological approach. Russian Journal of Plant Physiology, 70(1), 51.

El-Aidy, F, Hassan, N. A., El-Waraky, Y., Abu El-Ftooh, F., Bayoumi, Y., & Elhawat, N. (2021). Boron, manganese and zinc reduce the hazardous impact of sodic-saline soil on growth and yield of pea (Pisum sativum L.). Journal of Plant Nutrition.

Ghasempour, S., Ghanbari Jahromi, M., Mousavi, A., & *et al*., (2024). Seed priming with cold plasma, iron, and manganese nanoparticles modulates salinity stress in hemp (Cannabis sativa L.) by improving germination, growth, and biochemical attributes. Environmental Science and Pollution Research, 31, 65315–65327

Ghorbani, P., Eshghi, S., Ershadi, A., Shekafandeh, A., & Razzaghi, F. (2019). The possible role of foliar application of manganese sulfate on mitigating adverse effects of water stress in grapevine. Communications in Soil Science and Plant Analysis, 50(13), 1550–1562.

Giordano, M., Petropoulos, S. A., & Rouphael, Y. (2021). Response and defense mechanisms of vegetable crops against drought, heat and salinity stress. Agriculture, 11(5), 463.

Gomes-Filho, E., Machado Lima, C. R. F., Costa, J. H., da Silva, A. C., da Guia Silva Lima, M., de Lacerda, C. F., & Prisco, J. T. (2008). Cowpea ribonuclease: Properties and effect of NaCl-salinity on its activation during seed germination and seedling establishment. Plant Cell Reports, 27, 147–157.

Goussias, C., Boussac, A., & Rutherford, A. W. (2002). Photosystem II and photosynthetic oxidation of water: An overview. Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 357(1426), 1369–1381.

Grattan, S. R., & Grieve, C. M. (2002). Mineral nutrient acquisition and response by plants in saline environments. In M. Pessarakli (Ed.), Handbook of plant and crop stress 203–266.

Gul, H., Arif, M., Husna, Khan, Y., & Sayyed, A. (2019). Effect of boron, manganese and iron on growth, biochemical constituents and ionic composition of cowpea grown under salinity. Journal of Applied Environmental and Biological Sciences, 9(3), 1–12.

Hasanuzzaman, M., Raihan, M. R. H., Masud, A. A. C., Rahman, K., Nowroz, F., & Rahman, M. (2021). Regulation of reactive oxygen species and antioxidant defense in plants under salinity. International Journal of Molecular Sciences, 22(17), 9326.

Hatami, S., & Pourakbar, L. (2020). Effects of manganese on physiological characters of grapevine cultivars under salinity stress. MOJ Ecology & Environmental Sciences, 5(2), 37–41.

Hossam, S. E.-B., El-Nady, M. F., Rezk, A. A., Tahoon, A. M., Al-Daej, M. I., & Abdulmajid, D. (2024). Effects of paclobutrazol seed priming on seedlings quality, physiological and bakanae disease index characteristics of rice (Oryza sativa L.). Phyton, 93(10), 2535–2556.

Houtz, R. L., Nable, R. O., & Cheniae, G. M. (1988). Evidence for effects on the in vivo activity of ribulose-bisphosphate carboxylase/oxygenase during development of Mn toxicity in tobacco. Plant Physiology, 86(4), 1143–1149.

Hu, Y., & Schmidhalter, U. (2005). Drought and salinity: A comparison of their effects on mineral nutrition of plants. Journal of Plant Nutrition and Soil Science, 168(4), 541–549.

Humphries, J., Stangoulis, J., & Graham, R. (2007). Manganese. In A. Barker & D. Pilbeam (Eds.), Handbook of Plant Nutrition, Taylor and Francis, 351-366.

Husson, O. (2013). Redox potential (Eh) and pH as drivers of soil/plant/microorganism systems: A transdisciplinary overview pointing to integrative opportunities for agronomy. Plant and Soil, 362(1–2), 389–417.

Jabeen, N., & Ahmad, R. (2011). Effect of foliar-applied boron and manganese on growth and biochemical activities in sunflower under saline conditions. Pakistan Journal of Botany, 43(2), 1271–1282.

Jameel, J., Anwar, T., Majeed, S., Qureshi, H., Siddiqi, E. H., Sana, S., Zamam, S., & Ali, H. M. (2024). Effect of salinity on growth and biochemical responses of brinjal varieties: Implications for salt tolerance and antioxidant mechanisms. BMC Plant Biology, 24, 128.

Kanwal, F., Riaz, A., Ali, S., & Zhang, G. (2024). NRAMPs and manganese: Magic keys to reduce cadmium toxicity and accumulation in plants. Science of The Total Environment, 921, 171433.

Kaveh, H., Nemati, H., Farsi, M., & Jartoodeh, S. V. (2011). How salinity affect germination and emergence of tomato lines. Journal of Biological and Environmental Sciences, 5, 159–163.

Khan, M. A., & Weber, D. J. (2008). Ecophysiology of high salinity tolerant plants (Tasks for Vegetation Science, Vol. 40). Springer.

Khodarahmpour, Z., Ifar, M., & Motamedi, M. (2012). Effects of NaCl salinity on maize (Zea mays L.) at germination and early seedling stage. African Journal of Biotechnology, 11(2), 298–304.

Khondoker, M., Mandal, S., Gurav, R., & Hwang, S. (2023). Freshwater shortage, salinity increase, and global food production: A need for sustainable irrigation water desalination—A scoping review. Earth, 4(2), 223–240.

Krasensky, J., & Jonak, C. (2012). Drought, salt, and temperature stress-induced metabolic rearrangements and regulatory networks. Journal of Experimental Botany, 63(4), 1593–1608.

Läuchli, A., & Grattan, S. R. (2007). Plant growth and development under salinity stress. In M. A. Jenks, P. M. Hasegawa, & S. M. Jain (Eds.), Advances in molecular breeding toward drought and salt tolerant crops,1–32.

Lee, S. C., & Luan, S. (2012). ABA signal transduction at the crossroad of biotic and abiotic stress responses. Plant, Cell & Environment, 35(1), 53–60.

Lidon, F. C., Barreiro, M. G., & Ramalho, J. C. (2004). Manganese accumulation in rice: Implications for photosynthetic functioning. Journal of Plant Physiology, 161(12), 1235–1244.

Millaleo, R., Reyes-Díaz, M., Ivanov, A. G., Mora, M. L., & Alberdi, M. (2010). Manganese as essential and toxic element for plants: Transport, accumulation and resistance mechanisms. Journal of Soil Science and Plant Nutrition, 10, 470–481.

Milner, M. J., Seamon, J., Craft, E., & Kochian, L. V. (2013). Transport properties of members of the ZIP family in plants and their role in Zn and Mn homeostasis. Journal of Experimental Botany, 64(1), 369–381.

Munns, R. (2002). Comparative physiology of salt and water stress. Plant, Cell & Environment, 25(2), 239–250.

Munns, R. (2005). Genes and salt tolerance: Bringing them together. New Phytologist, 167(3), 645–663.

Munns, R., & Tester, M. (2008). Mechanisms of salinity tolerance. Annual Review of Plant Biology, 59, 651–681.

Othman, Y., Al-Karaki, G., Al-Tawaha, A. R., & Al-Horani, A. (2006). Variation in germination and ion uptake in barley genotypes under salinity conditions. World Journal of Agricultural Sciences, 2(1), 11–15.

Pandya, D. H., Mer, R. K., Prajith, P. K., & Pandey, A. N. (2005). Effect of salt stress and manganese supply on growth of barley seedlings. Journal of Plant Nutrition, 27(8), 1361–1379.

Pan, T., Liu, M., Kreslavski, V. D., Zharmukhamedov, S. K., Nie, C., Yu, M., Kuznetsov, V. V., Allakhverdiev, S. I., & Shabala, S. (2020). Non-stomatal limitation of photosynthesis by soil salinity. Critical Reviews in Environmental Science and Technology, 1–35.

Parihar, P., Singh, S., Singh, R., Singh, V. P., & Prasad, S. M. (2014). Effect of salinity stress on plants and its tolerance strategies: A review. Environmental Science and Pollution Research, 22(6), 3739–3755.

Pittman, J. K. (2005). Managing the manganese: Molecular mechanisms of manganese transport and homeostasis. New Phytologist, 167(3), 733–742.

Rahman, A., Hossain, S., Mahmud, J., Nahar, K., Hasanuzzaman, M., & Fujita, M. (2016). Effect of salt stress on growth and physiological response in plants. Physiology and Molecular Biology of Plants, 22(3), 291–306.

Robin, A. H. K., Matthew, C., Uddin, M. J., & Bayazid, K. N. (2016). Salinity induced reduction in root surface area and changes in major root and shoot traits at the phytomer level in wheat. Journal of Experimental Botany, 67, 3719–3729.

Rogers, M. E., Grieve, C. M., & Shannon, M. C. (2003). Plant growth and ion relations in lucerne (Medicago sativa L.) in response to the combined effects of NaCl and P. Plant and Soil, 253, 187–194.

Saha, P., Chatterjee, P., & Biswas, A. K. (2010). NaCl pretreatment alleviates salt stress by enhancement of antioxidant defense system and osmolyte accumulation in mungbean (Vigna radiata L. Wilczek). Indian Journal of Experimental Biology, 48, 593–600.

Sarkar, D., Mandal, B., & Kundu, M. C. (2007). Increasing use efficiency of boron fertilizers by rescheduling the time and methods of application for crops in India. Plant and Soil, 301(1–2), 77–85.

Shahbaz, M., & Ashraf, M. (2013). Improving salinity tolerance in cereals. Critical Reviews in Plant Sciences, 32, 237–249.

Shahi, S., & Srivastava, M. (2018). Influence of foliar application of manganese on growth, pigment content, and nitrate reductase activity of Vigna radiata (L.) R. Wilczek under salinity. Journal of Plant Nutrition, 41(11), 1397–1404.

Shrivastava, P., & Kumar, R. (2015). Soil salinity: A serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. Saudi Journal of Biological Sciences, 22(2), 123–131.

Tabassam, T., Hyder, S. I., Manzoor, R., Suthar, V., & Arshad, N. (2022). Influence of manganese on nutrient uptake in rice plants under saline conditions. Asian Research Journal of Agriculture, 15(1), 36–46.

Ulas, A., Yucel, Y. C., & Ulas, F. (2022). Influence of different manganese concentrations on eggplant (Solanum melongena L.) grown in a hydroponic system. International Journal of Agriculture, Environment and Food Sciences, 6(2), 210–219.

Ulfat, M., Athar, H., Ashraf, M., Akram, N. A., & Jamil, A. (2007). Appraisal of physiological and biochemical selection criteria for evaluation of salt tolerance in canola (Brassica napus L.). Pakistan Journal of Botany, 39, 1593–1608.

White, J. C., & Gardea-Torresdey, J. (2018). Achieving food security through the very small. Nature Nanotechnology, 13(7), 627–629.

Xu, S., Hu, B., He, Z., Ma, F., Feng, J., Shen, W., & Yan, J. (2011). Enhancement of salinity tolerance during rice seed germination by presoaking with hemoglobin. International Journal of Molecular Sciences, 12(4), 2488–2501.

Yadav, S., Irfan, M., Ahmad, A., & Hayat, S. (2011). Causes of salinity and plant manifestations to salt stress: A review. Journal of Environmental Biology, 32(5), 667–685.

Yadav, S. P., Bharadwaj, R., Nayak, H., Mahto, R., Singh, R. K., & Prasad, S. K. (2019). Impact of salt stress on growth, productivity and physicochemical properties of plants: A review. International Journal of Chemical Studies, 7(6), 1793–1798.

Ye, Y., Medina-Velo, I. A., Cota-Ruiz, K., Moreno-Olivas, F., & Gardea-Torresdey, J. L. (2019). Can abiotic stresses in plants be alleviated by manganese nanoparticles or compounds? Ecotoxicology and Environmental Safety, 184, 109671.

Ye, Y., Cota-Ruiz, K., Hernández-Viezcas, J. A., Valdés, C., Medina-Velo, I. A., Turley, R. S., Peralta-Videa, J. R., & Gardea-Torresdey, J. L. (2020). Manganese nanoparticles control salinity-modulated molecular responses in Capsicum annuum L. through priming: A sustainable approach for agriculture. ACS Sustainable Chemistry & Engineering, 8(3), 1427–1436.

Zaki, F. (2011). The determinants of salinity tolerance in maize (Zea mays L.) University of Groningen, 11-15.

Zhang, Q., & Dai, W. (2019). Plant response to salinity stress. In W. Dai (Ed.), Stress physiology of woody plants, 155–173, CRC Press.

Zhang, M. H., Qin, Z. H., & Liu, X. (2005). Remote sensed spectral imagery to detect late blight in field tomatoes. Precision Agriculture, 6, 489–508.