



Mechanisms of Soil Salinity and Its Impacts under Climate Change: An Integrative Review of Physiological, Biochemical, and Agronomic Strategies for Sustainable Agricultural Management

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Abstract

Soil salinity is a critical global issue that negatively impacts agricultural productivity, especially under the accelerating pressures of climate change. This review explores the mechanisms of soil salinization, focusing on the physiological and biochemical responses of plants to salinity stress, such as osmotic stress, ion toxicity, and nutrient imbalances. It also examines the role of phytohormones, osmolytes, and antioxidant enzymes in enhancing plant tolerance to salinity. Agronomic strategies, including the use of soil amendments, advanced irrigation techniques, and microbial inoculants, are evaluated for their effectiveness in mitigating salinity's adverse effects. The review emphasizes the need for integrated management approaches combining physiological, biochemical, and agronomic strategies to ensure sustainable agricultural practices under changing climatic conditions. Future research must focus on biotechnological innovations and climate-resilient agricultural planning to enhance crop yields and secure global food security.

Keywords: *Soil Salinity, Climate Change, Plant Stress Responses, Salinity Management, Sustainable Agriculture.*

Introduction

Soil salinity refers to the concentration of soluble salts in the soil, which primarily includes sodium (Na^+), chloride (Cl^-), sulfate (SO_4^{2-}), and magnesium (Mg^{2+}) ions. The salinization of soils occurs when there is an accumulation of these salts at levels that impair soil health and plant productivity. Saline soils are typically defined by their electrical conductivity (EC), with a threshold value of 4 dS/m or more in a saturated paste extract at 25°C being considered detrimental to most crop plants (Bourjila, *et al.*, 2024; Yu, *et al.*, 2024). This salinity reduces the availability

of water to plants, disrupts nutrient uptake, and ultimately hampers growth.

Soil salinity is a critical global issue, especially in arid and semi-arid regions where natural processes such as the weathering of rocks and evaporation exacerbate salt accumulation. According to estimates, over 831 million hectares of land worldwide are affected by salinity, with approximately 20% of irrigated land suffering from some degree of salinization. Notably, 33% of the world's irrigated agricultural land, which plays a pivotal role in food production, is impacted

by soil salinity (Kumawat, *et al.*, 2023; ZONAYET, *et al.*, 2022). These statistics reveal the significant and widespread nature of salinity across global agricultural systems.

Regions such as South Asia, Australia, the Middle East, and parts of Africa are particularly vulnerable due to the climatic conditions that favor salt accumulation in the soil. In Pakistan and India, for instance, millions of hectares of irrigated lands in the Indus River Basin are affected by salinity. Similarly, in Egypt, the Nile Delta faces increased salinization due to inadequate drainage and rising sea levels, threatening the country's agricultural productivity (Hayes, 2020; Qureshi & Perry, 2021). Soil salinity is also prominent in countries such as the United States and China, where large tracts of land in irrigated zones, such as California's Central Valley and the Yellow River Basin, respectively, are impacted by salinity.

Economic and Environmental Impacts on Agriculture

The economic consequences of soil salinity are profound, given its negative impact on crop yield and agricultural productivity. Salinity diminishes plant growth by inducing osmotic stress, ion toxicity, and nutrient imbalances. For example, osmotic stress caused by high salt concentrations limits water uptake by plant roots, while excessive sodium ions displace essential nutrients such as potassium (K^+) and calcium (Ca^{2+}), disrupting metabolic processes (Naz, *et al.*, 2023). This complex interplay of physiological responses leads to significant yield reductions across various crops.

In terms of economic losses, it is estimated that soil salinity costs the global agricultural sector over USD 27.3 billion annually in lost productivity. In heavily affected regions like Australia's Murray-Darling Basin, salinity is responsible for significant declines in the productivity of crops such as wheat and barley, while in the Indus River Basin, rice and cotton yields are substantially reduced (Singh, 2022). For subsistence farmers, particularly in developing countries, the impact is even more devastating, as the loss of

crop yields due to salinity threatens food security and livelihoods.

Environmentally, soil salinity leads to land degradation and desertification, exacerbating the challenge of maintaining productive land in vulnerable regions. Saline soils lose structure over time, reducing their capacity to hold water and nutrients, and causing erosion. Additionally, saline runoff contaminates water bodies, further aggravating water quality issues. The ecological impacts are similarly significant, as salinity-induced stress on plant systems can lead to a reduction in biodiversity and the collapse of ecosystems dependent on healthy soil and plant interactions.

1.2 Influence of Climate Change on Soil Salinity

Sea-Level Rise

One of the most critical impacts of climate change on soil salinity is the phenomenon of sea-level rise. The Intergovernmental Panel on Climate Change (IPCC) projects that global mean sea levels will continue to rise throughout the 21st century, with estimates of 0.43–0.84 meters of increase by 2100 under different greenhouse gas emission scenarios (Allan, *et al.*, 2023). This rise exacerbates salinization, particularly in coastal agricultural regions, by increasing the intrusion of saline water into freshwater aquifers and soil profiles.

Coastal areas are already seeing the devastating effects of this phenomenon. For instance, in Bangladesh, where agriculture is a vital part of the economy, sea-level rise has led to increased saltwater intrusion into agricultural land, rendering it less productive or entirely unusable. A similar situation is observed in the Nile Delta in Egypt, where the infiltration of saline waters threatens one of the world's most fertile regions (Abdullahi, *et al.*, 2023). As sea levels continue to rise, the increased penetration of saltwater into agricultural zones will likely expand, affecting millions more hectares of cropland globally.

Moreover, the rise in sea levels reduces the ability of coastal soils to drain properly,

leading to waterlogging—a condition that promotes salinity buildup as salts are drawn up from deeper soil layers to the surface. This issue is compounded in regions that rely heavily on irrigation, as the introduction of saline water into the soil further exacerbates salt accumulation.

Altered Precipitation Patterns

Climate change is causing significant alterations in precipitation patterns worldwide, which directly influence the development and severity of soil salinity. Changes in precipitation affect both the quantity and distribution of rainfall, with some regions experiencing more intense and frequent droughts, while others face increased rainfall and flooding (Pizzorni, *et al.*, 2024). These altered hydrological cycles have a profound effect on soil salinity, particularly in rain-fed and irrigated agricultural systems.

In arid and semi-arid regions, decreased rainfall and prolonged drought periods exacerbate the accumulation of salts in the soil, as less water is available to leach salts away from the root zone. This is particularly concerning in regions such as North Africa, the Middle East, and parts of the southwestern United States, where water scarcity is already a pressing issue. In these areas, reduced precipitation combined with high evaporation rates accelerates the process of salinization, limiting the land's agricultural potential.

Conversely, increased rainfall in some regions can lead to flooding, which also contributes to salinization. Floodwaters, particularly in coastal and low-lying areas, often carry dissolved salts from saline bodies of water, which are deposited on the soil as the water recedes. This leads to a buildup of surface salts, which, over time, percolate into the soil, degrading its quality and productivity.

Increased Evapotranspiration

Evapotranspiration, the combined process of evaporation from the soil and transpiration from plants, plays a crucial role in the development of soil salinity. With global temperatures rising due to climate change,

evapotranspiration rates are expected to increase, particularly in arid and semi-arid regions. As a result, more water is lost from the soil and plant surfaces, while the salts dissolved in the remaining water are left behind, leading to an accumulation of salts in the root zone.

Higher evapotranspiration rates intensify salinity problems in already vulnerable regions, such as the Mediterranean Basin, parts of Australia, and the southwestern United States. In these regions, the combination of low precipitation and high evapotranspiration creates a water deficit that favors salt accumulation in the soil (Dimitriadou & Nikolakopoulos, 2021). Additionally, irrigation practices in these areas, if not properly managed, contribute to the salinity issue by further increasing the concentration of salts in the soil profile.

In agricultural systems, increased evapotranspiration also affects plant water uptake, exacerbating the effects of salinity-induced osmotic stress. As plants are forced to expend more energy to absorb water from the saline soil, their growth and productivity are negatively impacted. This leads to a vicious cycle where salinity reduces crop yields, and decreased vegetation cover in turn increases evapotranspiration rates, perpetuating the problem.

1.3 Purpose and Scope of the Review Integrating Physiological, Biochemical, and Agronomic Perspectives

This review aims to provide an integrative understanding of soil salinity mechanisms and their impacts under climate change, drawing from physiological, biochemical, and agronomic perspectives. Each of these dimensions plays a crucial role in understanding how plants respond to salt stress, and how management strategies can be developed to mitigate the adverse effects of salinization on agricultural productivity.

From a physiological perspective, the review will examine how plants experience osmotic stress, ion toxicity, and water uptake challenges due to salinity. Salinity-induced

stress on photosynthesis, membrane integrity, and nutrient transport will also be addressed, with a focus on how these physiological disruptions lead to reduced crop yields.

From a biochemical perspective, the focus will be on the molecular mechanisms of salt tolerance in plants, including the production of osmoprotectants like proline and glycine betaine, the activation of antioxidant enzymes (e.g., superoxide dismutase, catalase, and peroxidase), and the role of phytohormones such as abscisic acid (ABA) in mediating stress responses. Understanding these biochemical processes provides insights into how plants adapt to salinity and which traits can be targeted for improving salt tolerance in crop species.

From an agronomic perspective, the review will explore sustainable management strategies for mitigating soil salinity, particularly under the constraints of climate change. This includes the use of soil amendments (e.g., gypsum, biochar), advanced irrigation practices (e.g., drip irrigation), and the development of salt-tolerant crop varieties through breeding and genetic engineering. Agronomic interventions that improve soil structure, reduce salt accumulation, and enhance water-use efficiency will be highlighted as key strategies for sustaining agricultural productivity in salt-affected regions.

2. Mechanisms of Soil Salinity Development under Climate Change

2.1 Sources and Causes of Soil Salinization

Natural Processes vs. Anthropogenic Factors

Soil salinization is a phenomenon with multifaceted origins, arising from both natural processes and anthropogenic activities. The natural processes of soil salinization are primarily driven by the geochemical composition of soil and the climate of a particular region. In arid and semi-arid environments, where evaporation rates exceed precipitation, salts present in parent materials and bedrock are dissolved and brought to the soil surface through capillary action. This results in the accumulation of soluble salts in the upper soil

horizons, particularly sodium chloride (NaCl), sodium sulfate (Na₂SO₄), magnesium chloride (MgCl₂), and calcium carbonate (CaCO₃) (Chhabra, 2022). Over time, these salts can reach concentrations that are detrimental to plant growth and soil health, particularly in poorly drained soils where leaching is minimal.

In addition to natural geochemical processes, anthropogenic activities have significantly exacerbated soil salinization globally. Irrigation practices, especially in semi-arid and arid regions, have been one of the most significant contributors to salinity buildup. Poorly managed irrigation systems lead to the application of saline water, which, when combined with inadequate drainage, results in the accumulation of salts in the soil profile. For instance, in the Indus Basin of Pakistan, extensive irrigation using groundwater with high salt content has led to widespread salinity, affecting both crop yield and soil health. Similarly, in Australia's Murray-Darling Basin, irrigation without adequate drainage has caused salinization of vast tracts of agricultural land (Lytton, et al., 2021; Rothenburg, 2023).

The use of chemical fertilizers, particularly nitrogen- and phosphate-based fertilizers, also contributes to salinity through the addition of salts to the soil. In regions where over-application of fertilizers occurs, residual salts accumulate in the root zone, compounding the salinity problem. This is particularly pronounced in areas where intensive agricultural practices are coupled with limited rainfall and high evaporation rates, which prevent the leaching of excess salts from the soil.

Other anthropogenic activities that exacerbate soil salinization include deforestation and land clearing for agricultural expansion, which disrupt natural water cycles and increase evaporation rates. In coastal areas, saltwater intrusion into freshwater aquifers, often driven by the over-extraction of groundwater, has also become a significant cause of soil salinization. This process, known as saline intrusion, is particularly problematic

in deltaic regions such as the Nile Delta and the Ganges Delta, where rising sea levels and human activities have led to the infiltration of seawater into coastal agricultural lands, rendering them less productive or completely unusable.

2.2 Climate Change Factors Exacerbating Salinity

Increased Temperatures

One of the most pronounced effects of climate change on soil salinization is the increase in global temperatures. According to projections by the Intergovernmental Panel on Climate Change (IPCC), average global temperatures could rise by 1.5°C to 2°C above pre-industrial levels by the end of the 21st century (Warren, *et al.*, 2022). This increase in temperature has profound implications for soil salinity, particularly in arid and semi-arid regions where water is already scarce.

Higher temperatures intensify the process of evapotranspiration, which is the combined loss of water from the soil and plants through evaporation and transpiration. As evapotranspiration rates increase, more water is lost from the soil surface, leaving behind salts that are dissolved in the remaining soil moisture. This process of salt concentration is particularly acute in regions with limited rainfall, where there is insufficient water to leach salts out of the root zone. As a result, salts accumulate in the upper soil layers, creating conditions that are hostile to plant growth.

The effects of increased temperatures on soil salinity are particularly evident in regions such as the Mediterranean, southwestern United States, and parts of Australia, where rising temperatures, combined with low rainfall, have led to increased salinity levels in agricultural soils. In these regions, the interplay between higher temperatures, reduced precipitation, and increased irrigation has created a positive feedback loop, where salinity begets further water stress, which in turn exacerbates salinity.

Changes in Rainfall Distribution

Climate change has also altered global precipitation patterns, with some regions

experiencing more intense and frequent droughts, while others face increased rainfall and flooding. These shifts in rainfall distribution have significant implications for soil salinity, particularly in regions where agriculture is dependent on rainfall for irrigation.

In arid and semi-arid regions, where rainfall is already scarce, climate change-induced droughts exacerbate soil salinity by reducing the availability of water for leaching salts from the soil profile. In the absence of sufficient rainfall, salts that are naturally present in the soil or introduced through irrigation accumulate in the root zone, leading to increased soil salinity. For example, in the Middle East and North Africa, where rainfall has become increasingly erratic due to climate change, soil salinity has worsened in many agricultural areas, threatening food security in the region.

Conversely, increased rainfall and flooding in some regions can also contribute to soil salinity. In coastal areas, heavy rainfall can lead to waterlogging, which facilitates the upward movement of salts from deeper soil layers to the surface through capillary action. Additionally, flooding in coastal regions can carry saline water from the sea onto agricultural lands, depositing salts on the soil surface as the water recedes. This process is particularly concerning in deltaic regions, such as the Mekong Delta in Vietnam, where increased rainfall and rising sea levels have combined to exacerbate salinity issues in rice-growing areas.

Sea-Level Rise Leading to Saltwater Intrusion

Sea-level rise, driven by the melting of polar ice caps and the thermal expansion of seawater due to global warming, is one of the most significant climate change-induced factors contributing to soil salinity, particularly in coastal regions. The IPCC predicts that global mean sea levels could rise by up to 0.84 meters by 2100, with the potential for more significant increases if polar ice sheet melt accelerates (Bhushan & Sharma, 2022).

Sea-level rise exacerbates salinity through the process of saltwater intrusion, where saline water from the sea infiltrates freshwater aquifers and coastal agricultural lands. This process is particularly problematic in low-lying coastal regions, where the rising sea displaces freshwater, pushing it further inland and allowing saline water to penetrate deeper into the soil. Saltwater intrusion is a major concern in regions such as the Nile Delta, the Sundarbans in Bangladesh, and the Mekong Delta, where rising sea levels have led to the salinization of vast tracts of agricultural land.

The impacts of saltwater intrusion are not limited to the soil surface; as saline water infiltrates aquifers, it contaminates freshwater supplies that are critical for irrigation. This further exacerbates the salinity problem, as farmers are forced to use increasingly saline water for irrigation, compounding the accumulation of salts in the soil. In the case of the Nile Delta, for example, rising sea levels and saltwater intrusion have already rendered large areas of land unsuitable for agriculture, threatening the livelihoods of millions of farmers.

2.3 Soil Physicochemical Processes Salt Accumulation Dynamics

Salt accumulation in soils is a dynamic process that is influenced by both environmental conditions and human activities. The primary mechanism by which salts accumulate in the soil is through the evaporation of water from the soil surface, which leaves behind soluble salts that are present in the soil or introduced through irrigation. Over time, these salts build up in the root zone, where they can interfere with plant growth and reduce crop yields.

The rate of salt accumulation is influenced by several factors, including the type of irrigation water used, the soil's drainage capacity, and the climate of the region. In regions where groundwater is used for irrigation, the salinity of the water plays a critical role in determining the rate of salt accumulation. In areas where groundwater is naturally saline, such as in parts of India and Pakistan, the use

of this water for irrigation without proper drainage leads to the rapid accumulation of salts in the soil.

Soil texture and structure also play an important role in salt accumulation dynamics. In fine-textured soils, such as clay soils, water moves more slowly through the soil profile, leading to a higher concentration of salts near the surface (Huntley, 2023). In contrast, coarse-textured soils, such as sandy soils, allow water to percolate more easily through the soil profile, reducing the concentration of salts near the surface. However, in regions where rainfall is insufficient to leach salts from the root zone, even sandy soils can become saline over time.

Soil Structural Changes Due to Salinity

Soil salinity has profound effects on soil structure, which in turn affects the soil's ability to retain water and nutrients, as well as its suitability for supporting plant growth. High concentrations of sodium ions (Na^+) in saline soils can lead to the dispersion of soil particles, breaking down the aggregates that give soil its structure (Xie, et al., 2024). This process, known as sodification, reduces the porosity of the soil, making it more prone to compaction and waterlogging.

The breakdown of soil structure due to salinity also reduces the soil's ability to retain water, leading to increased runoff and erosion. In regions where salinity is a significant problem, such as the Indus Basin in Pakistan and the Murray-Darling Basin in Australia, the loss of soil structure has led to the degradation of large areas of agricultural land, reducing its productivity and increasing the risk of desertification.

In addition to the physical changes in soil structure, salinity also affects the chemical properties of the soil. High concentrations of salts in the soil solution reduce the availability of essential nutrients, such as potassium (K^+) and calcium (Ca^{2+}), which are displaced by sodium ions (Verma, et al., 2024). This nutrient imbalance further exacerbates the negative effects of salinity on plant growth, as plants

are unable to access the nutrients they need to sustain healthy growth.

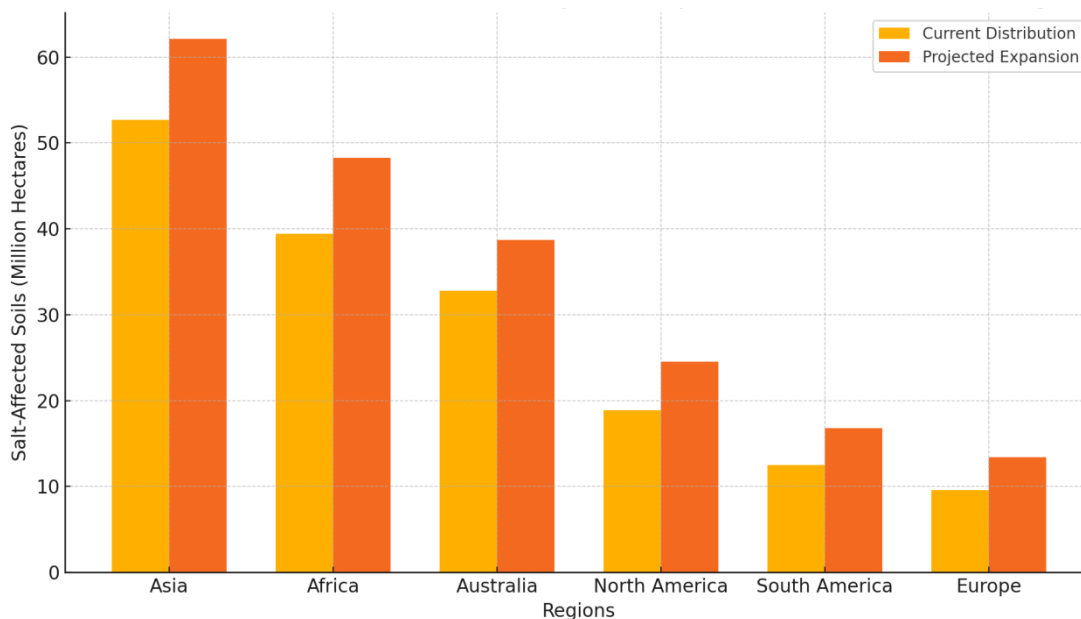


Fig 1: Global Distribution of Salt-Affected Soils and Projected Expansion under Climate Change Scenarios

The graph 1 compares the current distribution of salt-affected soils across various global regions with the projected expansion under climate change scenarios. Currently, Asia holds the largest area of salt-affected soils at 52.7 million hectares, followed by Africa with 39.4 million hectares, and Australia with 32.8 million hectares. Under climate change projections, all regions show a significant increase in salinized land, with Asia rising to

62.1 million hectares and Africa reaching 48.3 million hectares. This highlights the exacerbating effect of climate change on soil salinity, particularly in vulnerable regions, due to factors like rising temperatures, altered precipitation patterns, and sea-level rise. The data emphasizes the need for urgent mitigation strategies to preserve agricultural productivity in these affected areas.

Table 1: Classification of Salt-Affected Soils Based on Physicochemical Properties and Salinity Levels

Soil Type	pH Range	Electrical Conductivity (dS/m)	Exchangeable Sodium Percentage (ESP)	Dominant Salt Type	Impact on Agriculture
Saline Soil	< 8.5	> 4	< 15	NaCl, CaCl ₂ , MgSO ₄	Reduced crop yield, osmotic stress
Sodic Soil	> 8.5	< 4	> 15	Na ₂ CO ₃ , NaHCO ₃	Soil structure degradation, poor infiltration
Saline-Sodic Soil	< 8.5	> 4	> 15	NaCl, Na ₂ CO ₃	Toxic ion accumulation, poor drainage
Non-saline Sodic	> 8.5	< 4	> 15	NaHCO ₃ , Na ₂ SO ₄	Structural collapse, reduced fertility
Acidic Saline Soil	< 5.0	> 4	< 15	Fe, Al salts	Severe toxicity, impaired root growth

Table 1 provides a detailed classification of salt-affected soils based on their physicochemical properties, including pH range, electrical conductivity (EC), exchangeable sodium percentage (ESP), and dominant salt types. The table also highlights the specific impacts these soils have on agricultural productivity. For example, saline soils, characterized by an EC greater than 4 dS/m and pH below 8.5, primarily contain salts like NaCl and MgSO₄, which lead to osmotic stress, significantly reducing crop yields. In contrast, sodic soils, with high pH values above 8.5 and ESP exceeding 15%, are more prone to soil structure degradation, causing poor water infiltration and root penetration. Saline-sodic soils, with high salinity and sodium content, combine the detrimental effects of both salinity and sodicity, resulting in poor drainage and toxic ion accumulation. This table serves as an essential tool for understanding how various soil types affect agricultural systems and guides the selection of appropriate reclamation strategies.

3. Physiological and Biochemical Responses of Plants to Soil Salinity

3.1 Plant Stress Responses to Salinity

Soil salinity poses a multifaceted threat to plant growth and development, inducing both osmotic and ionic stress, which disrupt the physiological and metabolic balance of plants. Salinity stress primarily manifests through two stages: an initial osmotic stress that reduces the plant's ability to absorb water, followed by ionic stress, which leads to toxicity and nutrient imbalances.

Osmotic Stress Effects on Plant Water Uptake

The presence of excess salts in the soil solution causes a reduction in the water potential, leading to osmotic stress that limits water availability to plants. This decrease in water potential creates a gradient that makes it difficult for plants to absorb water from the soil, mimicking drought-like conditions even in the presence of ample water. As soil salinity increases, the external osmotic potential around plant roots drops

significantly, forcing the plant to expend more energy to take up water, which reduces the plant's overall energy reserves for growth and development. Osmotic stress also prompts stomatal closure in leaves to minimize water loss through transpiration, which, while conserving water, limits carbon dioxide uptake and thus affects photosynthesis (Memon, et al., 2024; Ullah, Qasim, Sikandar,, et al., 2024). Reduced photosynthetic activity leads to stunted growth and reduced biomass, which are among the early indicators of salinity stress in plants.

The impact of osmotic stress is particularly evident during the early stages of plant growth. Seedlings are highly susceptible to salinity as the limited root system struggles to cope with the lower availability of water. Reduced cell expansion in leaves and roots is also a direct consequence of osmotic stress, which ultimately hampers the overall development of the plant. This mechanism underscores the importance of understanding water potential changes in saline soils to develop strategies that enhance plant water use efficiency.

Ion Toxicity and Nutrient Imbalances

In addition to osmotic stress, salinity induces ionic stress in plants, primarily due to the excessive accumulation of toxic ions such as sodium (Na⁺) and chloride (Cl⁻). High concentrations of Na⁺ disrupt cellular homeostasis and interfere with essential physiological processes (Arif, et al., 2020). Na⁺ competes with potassium (K⁺) for uptake through the plant's potassium transporters, leading to a deficiency in K⁺, which is crucial for various metabolic functions, including enzyme activation, protein synthesis, and osmoregulation (Ullah, Qasim, Abaidullah,, et al., 2024).

Ion toxicity is exacerbated by the ability of Na⁺ and Cl⁻ to accumulate in the cytosol, where they disrupt enzymatic functions, cause oxidative damage, and lead to cell death. To mitigate this, plants activate mechanisms to compartmentalize these toxic ions in vacuoles, reducing their cytoplasmic concentrations. However, long-term exposure

to high salinity can overwhelm the plant's ability to sequester Na^+ and Cl^- , leading to damage at the cellular and tissue levels (Ebeed, et al., 2024).

In addition to ion toxicity, salinity-induced nutrient imbalances significantly affect plant nutrition. The excessive presence of Na^+ interferes with the uptake and transport of essential nutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg). Na^+ competes with K^+ for binding sites on membrane transport proteins, which reduces the plant's ability to absorb K^+ and other nutrients efficiently. This leads to deficiencies that further impair metabolic functions and growth (Khan, et al., 2024; Zumbal, et al.). For instance, reduced Ca^{++} uptake weakens cell wall integrity, affecting cell expansion and division, while Mg^{2+} deficiency hinders chlorophyll synthesis, reducing photosynthetic efficiency.

Together, osmotic stress and ionic toxicity disrupt plant-water relations, nutrient homeostasis, and metabolic functions, making salinity one of the most challenging abiotic stresses for agricultural productivity. Addressing these physiological challenges requires an integrated understanding of plant responses and the development of cultivars that can better manage water and ion uptake under saline conditions.

3.2 Biochemical Mechanisms of Salinity Tolerance

Plants have evolved various biochemical mechanisms to cope with salinity stress, including the accumulation of osmoprotectants, activation of antioxidant defense systems, and modification of metabolic pathways to mitigate damage caused by osmotic and ionic stress.

Osmolyte Accumulation (e.g., Proline, Glycine Betaine)

One of the key strategies employed by plants to combat osmotic stress is the synthesis and accumulation of compatible solutes, or osmolytes. These small, organic molecules, such as proline and glycine betaine, help stabilize cellular osmotic potential by

balancing the intracellular and extracellular water potential without disrupting normal cellular functions. Osmolytes act as osmoprotectants, stabilizing proteins and membranes, scavenging reactive oxygen species (ROS), and protecting cellular structures from damage due to dehydration (Fatima, et al., 2024; Rasheed, et al., 2024).

Proline, in particular, plays a multifaceted role in salinity tolerance. Apart from acting as an osmoprotectant, proline functions as an antioxidant and a signaling molecule that regulates gene expression under stress conditions. Its accumulation is often correlated with increased stress tolerance in plants, as it helps mitigate oxidative damage caused by excess Na^+ and Cl^- ions.

Glycine betaine is another important osmoprotectant that accumulates in response to salinity. It stabilizes the structure of proteins and membranes, protecting them from the destabilizing effects of salt stress. Glycine betaine also maintains enzyme activity and photosynthetic efficiency under high salinity conditions, making it a critical component of the plant's biochemical defense against osmotic stress (Hossain, et al., 2021; Waseem, et al., 2023).

The accumulation of osmolytes is a highly regulated process involving the upregulation of specific biosynthetic pathways under stress conditions. This regulation is often controlled by stress-responsive transcription factors that sense osmotic changes and activate genes responsible for osmolyte biosynthesis.

Antioxidant Enzyme Activation (e.g., SOD, CAT, POD)

Salinity stress leads to the overproduction of reactive oxygen species (ROS), including superoxide radicals (O_2^-), hydrogen peroxide (H_2O_2), and hydroxyl radicals (OH^-), which cause oxidative damage to lipids, proteins, and nucleic acids. To mitigate oxidative stress, plants activate their antioxidant defense systems, which include both enzymatic and non-enzymatic antioxidants.

The enzymatic antioxidants include superoxide dismutase (SOD), catalase (CAT),

and peroxidases (POD), which work together to neutralize ROS and protect cells from oxidative damage. SOD is responsible for converting superoxide radicals into hydrogen peroxide, which is then broken down into water and oxygen by CAT and POD (Jomova, et al., 2024; Mishra & Sharma, 2019). This enzymatic detoxification process is crucial for maintaining cellular redox balance under salinity stress.

The upregulation of antioxidant enzymes is often linked to the plant's ability to tolerate high salinity levels. Plants with enhanced SOD, CAT, and POD activities exhibit reduced oxidative damage and higher survival rates under salt stress. In addition to these enzymes, non-enzymatic antioxidants such as ascorbate and glutathione also play important roles in scavenging ROS and protecting plants from oxidative damage (Ali, et al.; Ullah, Ishaq, Ahmed, et al., 2024).

Salinity-induced ROS production not only causes direct damage to cellular components but also acts as a signaling molecule that triggers stress response pathways. The balance between ROS production and scavenging determines the extent of oxidative damage and the plant's ability to tolerate salinity.

3.3 Role of Phytohormones and Signaling Pathways

Phytohormones play a critical role in modulating plant responses to salinity stress by regulating growth, development, and stress adaptation. Among the key phytohormones involved in salinity tolerance are abscisic acid (ABA), ethylene, and salicylic acid (SA), each of which contributes to the plant's ability to cope with osmotic and ionic stress.

Abscisic Acid (ABA)

ABA is often referred to as the "stress hormone" due to its central role in mediating plant responses to abiotic stresses, including salinity. Under saline conditions, ABA levels in plants increase, leading to the closure of stomata to reduce water loss through transpiration (Huang, et al., 2024). This helps

conserve water but also limits carbon dioxide uptake, which can affect photosynthesis. ABA also regulates the expression of stress-responsive genes, including those involved in osmolyte biosynthesis, ion transport, and antioxidant defense.

In addition to its role in water conservation, ABA modulates ion transporters that control Na⁺ and K⁺ homeostasis in plant cells. By regulating the activity of specific ion channels, ABA helps prevent the excessive accumulation of Na⁺ in the cytosol, thereby reducing ionic toxicity.

Ethylene

Ethylene is another phytohormone that plays a complex role in salinity stress. While ethylene is primarily known for its role in fruit ripening and senescence, it also contributes to stress responses by regulating growth and development under adverse conditions. Ethylene production increases under salinity, and it interacts with other hormones like ABA and SA to modulate stress responses (Haidri, et al., 2024; Khan, et al., 2023).

Ethylene's role in salinity tolerance is multifaceted and can be either protective or detrimental, depending on the concentration and timing of its production. Low levels of ethylene may enhance stress tolerance by promoting antioxidant enzyme activity and reducing oxidative damage, whereas high levels of ethylene can inhibit root growth and exacerbate stress-induced damage.

Salicylic Acid (SA)

Salicylic acid (SA) plays a crucial role in modulating plant defense responses under various stress conditions, including salinity. SA is known for its role in systemic acquired resistance (SAR) and local defense responses against pathogens, but its involvement in abiotic stress tolerance, including salinity, has gained attention in recent years (Saleem, et al., 2021). Under salt stress, SA modulates plant physiological and metabolic processes by regulating ion transport, enhancing antioxidant activity, and interacting with

other hormones such as abscisic acid (ABA) and ethylene.

In plants experiencing salinity stress, SA can enhance the activities of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), which help to mitigate oxidative stress by neutralizing reactive oxygen species (ROS). By modulating the ROS-scavenging mechanisms, SA contributes to maintaining cellular redox homeostasis and preventing damage to vital cellular structures such as membranes and proteins.

Moreover, SA has been shown to regulate the uptake and transport of essential ions under salt stress. By influencing the activity of ion transporters and channels, SA helps to maintain ion balance, preventing the toxic accumulation of sodium (Na^+) and chloride (Cl^-) ions while ensuring adequate uptake of potassium (K^+) and other essential nutrients. This regulatory role is vital for mitigating ion toxicity and nutrient imbalances that typically occur in saline environments.

SA's crosstalk with other signaling molecules and phytohormones further amplifies its impact on plant responses to salinity. For instance, SA can modulate ABA and ethylene signaling pathways, fine-tuning the plant's response to osmotic and ionic stress. This intricate network of hormone interactions allows plants to adapt their growth and physiological processes in response to varying levels of salinity stress (Arif, *et al.*, 2020; Riyazuddin, *et al.*, 2020).

In summary, SA acts as a pivotal regulator of plant defense mechanisms against salinity by enhancing antioxidant defenses, maintaining ion homeostasis, and modulating crosstalk with other stress-responsive hormones.

Signal Transduction in Stress Adaptation

Signal transduction pathways are critical for plants to perceive and respond to salinity stress effectively. These pathways involve a series of molecular events triggered by the detection of external stress signals, leading to the activation of downstream stress-response genes and metabolic processes. In the context

of salinity, several key signaling pathways are involved in mediating plant responses to osmotic and ionic stress.

One of the primary signal transduction mechanisms activated under salinity stress is the salt overly sensitive (SOS) pathway. The SOS pathway plays a crucial role in regulating ion homeostasis, particularly the exclusion of excess Na^+ from plant cells. The SOS pathway is initiated when salinity-induced Na^+ accumulation triggers a calcium (Ca^{2+}) signal in the cytosol (Hussain, *et al.*, 2021). This calcium signal is perceived by the SOS3 protein, a calcium-binding sensor, which then interacts with the protein kinase SOS2. The SOS3-SOS2 complex phosphorylates and activates the Na^+/H^+ antiporter SOS1, which functions to extrude Na^+ from the cytoplasm, thereby reducing ionic toxicity.

In addition to the SOS pathway, mitogen-activated protein kinase (MAPK) cascades play a pivotal role in transducing salinity stress signals. MAPK cascades are involved in a wide range of stress responses, including the regulation of osmolyte biosynthesis, antioxidant enzyme activity, and ion transporter expression (Singh, *et al.*, 2024). When activated by stress, MAPK cascades amplify the initial stress signal and trigger the expression of stress-responsive genes that contribute to salinity tolerance.

Reactive oxygen species (ROS) also serve as important signaling molecules in plants under salt stress. While excessive ROS production can cause oxidative damage, controlled ROS levels function as secondary messengers in stress signaling pathways. ROS generated under salinity stress can activate transcription factors and other signaling molecules that regulate the expression of genes involved in ion transport, osmolyte accumulation, and antioxidant defense.

Another important signaling pathway in salinity stress adaptation involves abscisic acid (ABA), which not only regulates stomatal closure but also modulates gene expression through the ABA-responsive element (ABRE)-binding transcription factors. These

transcription factors activate the expression of genes involved in osmoprotectant synthesis, water transport, and ion homeostasis, further enhancing the plant's ability to cope with salinity.

Signal transduction pathways, therefore, play an essential role in orchestrating the complex

responses required for plant survival under salinity stress. By integrating environmental signals with physiological and biochemical processes, plants can modulate their growth, development, and metabolic functions to better withstand the challenges posed by saline soils.

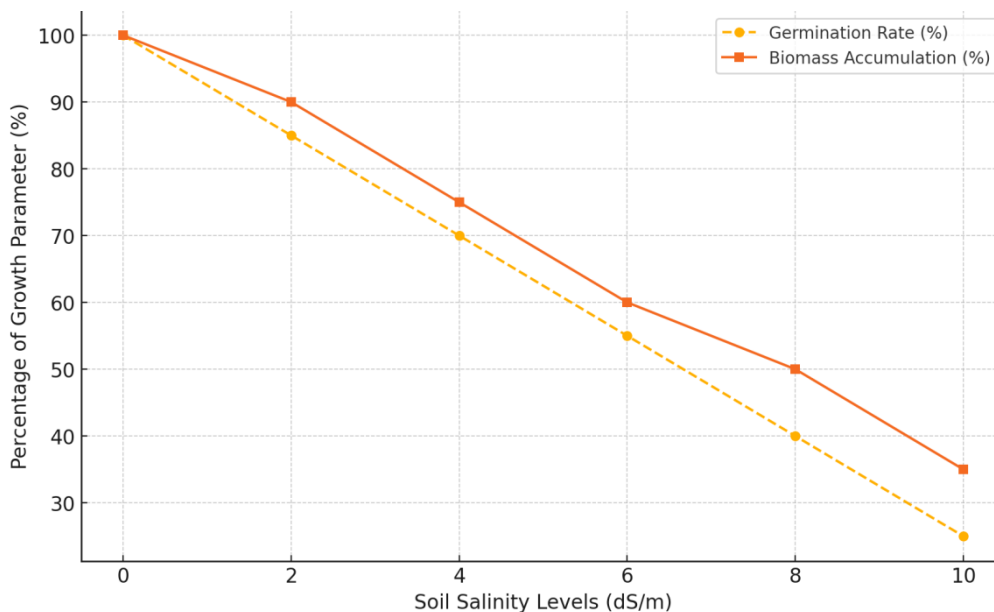


Fig 2: Effect of Soil Salinity on Plant Growth Parameters

The graph 2 presents the relationship between varying soil salinity levels and two critical plant growth parameters: germination rate and biomass accumulation. As salinity increases from 0 to 10 dS/m, both parameters exhibit a marked decline. At 0 dS/m (no salinity), the germination rate and biomass accumulation are at their highest, both at 100%. However, as salinity increases to 4 dS/m, the germination rate decreases to 70%, while biomass accumulation drops to 75%. By the time salinity reaches 10 dS/m, the

germination rate has plummeted to 25%, and biomass accumulation is down to 35%.

This comparison highlights the detrimental effect of increasing soil salinity on plant growth, where both germination success and the ability to accumulate biomass are progressively compromised. The graph emphasizes the need for effective salinity management to maintain crop viability and agricultural productivity.

Table 2: "Comparison of Physiological Traits among Crop Species under Saline Conditions"

Crop Species	Germination Rate (%)	Relative Water Content (%)	Proline Accumulation (µmol/g)	Chlorophyll Content (SPAD Units)	Na ⁺ /K ⁺ Ratio	Biomass Reduction (%)
Wheat	65	75	20	45	2.5	50
Rice	50	60	35	40	3.0	60
Barley	75	80	15	50	2.0	40
Tomato	45	55	50	35	4.0	65
Maize	55	65	30	42	2.8	55

This table compares various physiological traits of different crop species under saline conditions. The data shows that barley exhibits the highest germination rate (75%) and relative water content (80%), suggesting better tolerance to salinity stress compared to other crops like tomato, which shows a significantly lower germination rate (45%) and relative water content (55%). Proline accumulation, an indicator of stress response, is highest in tomato (50 μmol/g), reflecting its strong biochemical response to saline conditions, although this species also experiences the highest biomass reduction (65%). In contrast, barley, with lower proline

accumulation (15 μmol/g), shows the least biomass reduction (40%), indicating a different tolerance mechanism (Shah, et al., 2021).

The Na⁺/K⁺ ratio, a critical parameter for ion balance, is highest in tomato (4.0), suggesting severe ion toxicity, while barley maintains a lower ratio (2.0), and showing better ionic balance under salinity. This comparison highlights the variability in physiological responses among crops, with barley showing the most resilience and tomato the most sensitivity to saline stress.

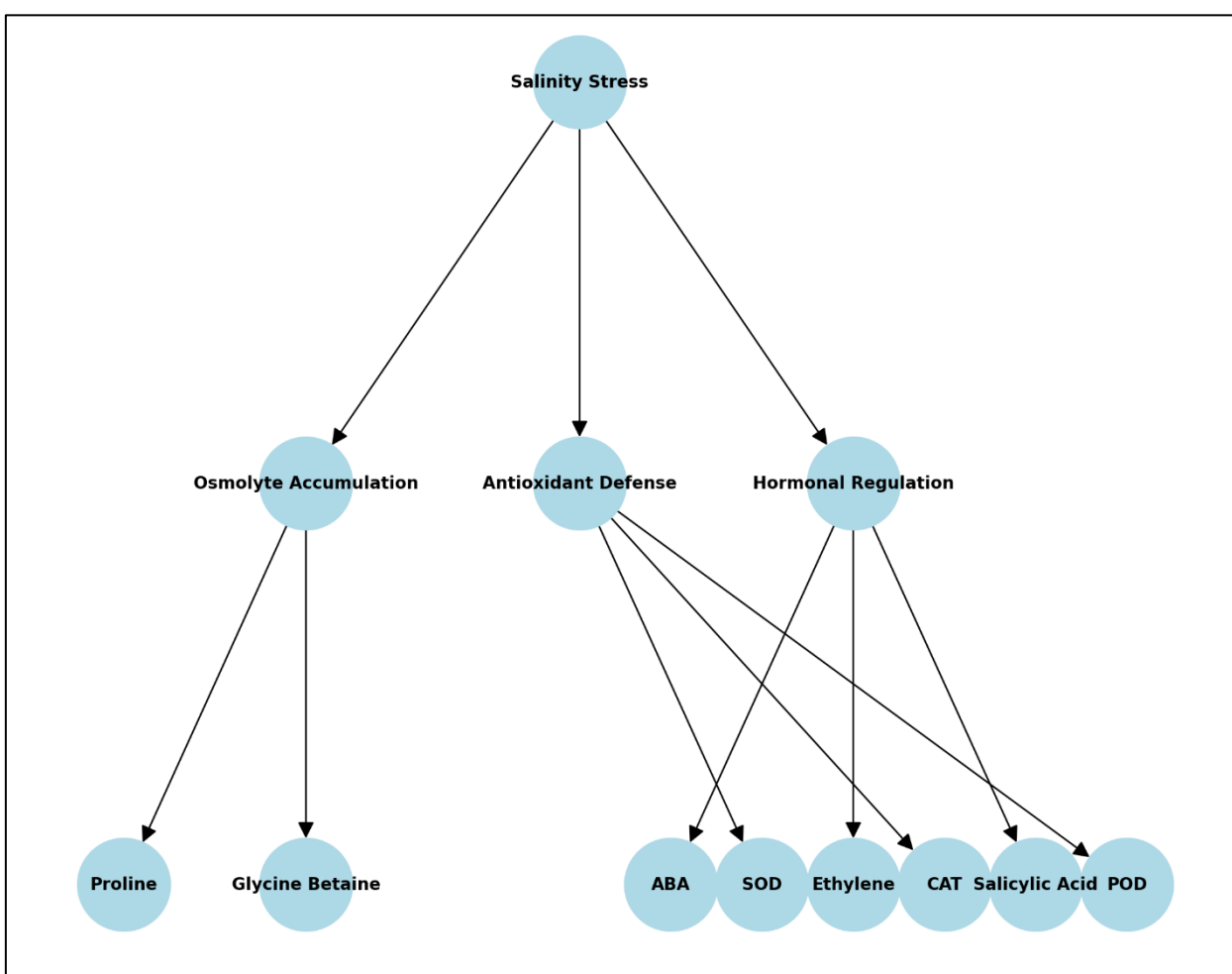


Fig 3: Biochemical Pathways Activated in Plants under Salinity Stress

This graph clearly depicts the intricate network of biochemical pathways activated in plants under salinity stress. The central node, "Salinity Stress," branches into three major adaptive mechanisms: osmolyte accumulation, antioxidant defense, and hormonal regulation. These mechanisms

work in tandem to mitigate the damage caused by salinity.

- **Osmolyte accumulation** includes the production of molecules like **proline** and **glycine betaine**, which help in maintaining osmotic balance.

- **Antioxidant defense** pathways are activated, with key enzymes like **SOD (superoxide dismutase)**, **CAT (catalase)**, and **POD (peroxidase)** neutralizing reactive oxygen species.
- **Hormonal regulation** involves stress-related hormones such as **ABA (abscisic acid)**, **ethylene**, and **salicylic acid**, which contribute to signal transduction and adaptation to stress conditions.

The graph visually compares the multiple biochemical routes plants employ to cope with salinity, highlighting the complexity of their defense mechanisms.

4. Agronomic Strategies for Managing Soil Salinity

Soil salinity is a significant agronomic challenge, particularly under the escalating impacts of climate change. Effective management strategies require integrating soil amendment practices and crop management techniques aimed at mitigating the detrimental effects of salinity on agricultural productivity. This section will explore the various soil amendments and crop management techniques, focusing on their scientific mechanisms, benefits, and practical applications in the field.

4.1 Soil Amendment Practices

The use of soil amendments such as gypsum, biochar, and organic matter has been widely recognized as a fundamental approach to managing soil salinity. These amendments improve soil structure, enhance water retention, and promote the leaching of excess salts, ultimately fostering healthier plant growth. Gypsum (calcium sulfate) is a prevalent amendment used to reduce soil sodicity by displacing sodium ions (Na⁺) from the soil exchange complex and replacing them with calcium ions (Ca²⁺) (Rai, *et al.*, 2021; Xu, *et al.*, 2023). The displaced sodium is then leached away through irrigation, which helps restore the soil's physical properties, improving porosity and water infiltration. This ameliorative effect of gypsum is particularly useful in saline-sodic soils where the high sodium content impairs soil structure and reduces hydraulic conductivity.

Biochar, a carbon-rich product derived from the pyrolysis of organic materials, has gained attention for its capacity to improve soil health under saline conditions. Biochar's high surface area and porous structure facilitate the retention of water and essential nutrients, which can counteract the water stress typically associated with salinity. Furthermore, biochar has been shown to enhance microbial activity in the rhizosphere, promoting the breakdown of organic matter and improving nutrient availability. This, in turn, fosters plant growth under saline conditions. Additionally, biochar's long-term stability in the soil makes it a sustainable option for soil amendment.

Organic matter, including composts and manures, serves as another crucial soil amendment for managing salinity. The decomposition of organic matter results in the release of humic substances, which enhance soil aggregation and improve water-holding capacity (Bashir, *et al.*, 2021). The increased organic carbon in the soil helps bind salts, preventing them from interfering with plant root function. Moreover, the microbial activity stimulated by organic matter application contributes to the biodegradation of saline compounds, facilitating the reclamation of salt-affected soils. Organic amendments are particularly advantageous in sandy soils, where the lack of structure exacerbates the effects of salinity.

Therefore, soil amendments such as gypsum, biochar, and organic matter function through various mechanisms, ranging from ion exchange to microbial stimulation—that collectively reduce soil salinity, improve soil structure, and enhance water retention. These practices play a critical role in mitigating the adverse effects of salinity and ensuring sustainable agricultural productivity.

4.2 Crop Management Techniques

Crop management techniques, including the selection and breeding of salt-tolerant varieties, as well as the implementation of crop rotation and intercropping systems, represent an essential component of soil

salinity management. The development of salt-tolerant crop varieties has been a focal point of agronomic research, driven by the need to sustain crop yields in saline environments. Salt tolerance in crops is a complex trait influenced by multiple genetic and physiological factors, including the ability to maintain osmotic balance, exclude toxic ions such as sodium (Na⁺) and chloride (Cl⁻), and enhance root water uptake (Arif, *et al.*, 2020; Ummer, *et al.*, 2023). Advances in molecular breeding and biotechnology have enabled the identification of salt tolerance genes, such as the HKT (High-affinity Potassium Transporter) gene family, which regulates ion transport and contributes to maintaining ion homeostasis under salt stress.

Breeding programs aimed at enhancing salt tolerance often employ marker-assisted selection (MAS) to accelerate the development of varieties with desirable traits. For example, salt-tolerant rice varieties such as IR29 and IR64 have been successfully developed and widely adopted in saline-prone regions of Asia (Hasan, *et al.*, 2021; Padmavathi, *et al.*, 2023). Similarly, salt-tolerant wheat varieties, such as KRL-210, have been introduced in parts of India, where saline soils pose a significant threat to agricultural productivity. In addition to conventional breeding methods, genetic engineering approaches have been utilized to introduce salt tolerance genes from halophytes (salt-tolerant plants) into glycophytes (salt-sensitive crops), further expanding the potential for cultivating crops in saline environments.

Crop rotation and intercropping systems also provide effective strategies for managing soil salinity. Crop rotation, the practice of alternating different crops in the same field across growing seasons, helps prevent the accumulation of salts in the soil. Certain crops, particularly deep-rooted species such as legumes, are capable of extracting water from deeper soil layers, thereby promoting the leaching of salts beyond the root zone (Lv, *et al.*, 2023; Paz, *et al.*, 2023). Moreover, legumes contribute to soil fertility by fixing atmospheric nitrogen through symbiotic

relationships with Rhizobium bacteria, enhancing soil quality and reducing the need for chemical fertilizers, which can exacerbate salinity issues.

Intercropping, the practice of growing two or more crops simultaneously in the same field, offers several benefits for managing soil salinity. This system promotes biodiversity and enhances soil structure, reducing the risk of salinity build-up. For example, intercropping salt-sensitive crops with salt-tolerant species can reduce salt concentrations in the rhizosphere of sensitive crops by altering the microenvironment and improving soil moisture retention. In saline soils, intercropping cereals with legumes has been shown to improve overall crop yields by optimizing resource use and reducing the negative effects of salinity on plant growth. Furthermore, intercropping can promote the growth of salt-tolerant root-associated microorganisms, which enhance nutrient availability and improve plant resilience to salt stress.

Overall, crop management techniques, including the development of salt-tolerant varieties and the implementation of rotation and intercropping systems, provide sustainable solutions for managing soil salinity. By optimizing crop selection and diversification, these practices can mitigate the detrimental effects of salinity on agricultural productivity and contribute to long-term soil health.

In conclusion, soil salinity poses a significant threat to global agricultural productivity, particularly under the increasing challenges presented by climate change (Mukhopadhyay, *et al.*, 2021; Singh, 2022). Effective management strategies, such as the use of soil amendments and crop management techniques, offer practical and sustainable solutions for mitigating the effects of salinity. Through a combination of gypsum, biochar, and organic matter amendments, alongside the selection of salt-tolerant crop varieties and the adoption of rotation and intercropping systems, farmers can enhance soil quality, reduce salinity

levels, and ensure the continued viability of agricultural systems in salt-affected regions. The integration of these strategies is essential for maintaining soil health and sustaining food security in the face of growing environmental pressures.

4.3 Advanced Irrigation Methods

The management of soil salinity through irrigation practices has long been a key focus in agronomic research, particularly under the stressors imposed by climate change. Advanced irrigation methods, such as drip irrigation and controlled irrigation scheduling, have emerged as effective solutions for mitigating the adverse effects of salinity on crop growth and productivity. Drip irrigation, also known as trickle irrigation, involves the precise delivery of water directly to the root zone of crops in small, controlled amounts (Ahmed, *et al.*, 2023). This method significantly reduces the risk of salt accumulation in the upper layers of the soil profile, as it minimizes surface evaporation—a major contributor to salt build-up. By ensuring a continuous and slow water flow, drip irrigation enhances the leaching of salts below the root zone, thereby maintaining soil salinity at levels conducive to plant growth. This method is particularly effective in arid and semi-arid regions, where water scarcity often exacerbates salinity issues.

Controlled irrigation scheduling complements the drip irrigation technique by optimizing the timing and volume of water applications based on crop needs and environmental conditions. Through the use of sensors and soil moisture monitoring technologies, irrigation schedules can be tailored to minimize water stress and reduce the risk of over-irrigation, which often leads to salt concentration in the root zone (Ahmed, *et al.*, 2023; Maurya, *et al.*, 2024). Controlled irrigation also prevents excessive leaching of nutrients and water, both of which can be detrimental to soil health and crop yield. In areas where saline water is used for irrigation, these advanced techniques are indispensable, as they mitigate the risk of salt accumulation

while ensuring the efficient use of available water resources.

The use of saline water for irrigation is becoming an increasingly necessary practice in regions facing freshwater shortages. However, the direct application of saline water without proper management can exacerbate soil salinization (Khondoker, *et al.*, 2023). To address this, researchers have developed irrigation management strategies that integrate the use of saline water with other water sources, such as freshwater or treated wastewater, in a controlled manner (Arslan Younas, *et al.*). This approach, known as conjunctive water use, allows for the dilution of saline water and reduces the overall salinity load on the soil. Additionally, techniques such as alternate furrow irrigation and cyclic irrigation, where saline water is alternated with freshwater during different growth stages, have been shown to minimize the negative impacts of salinity on crop performance (Minhas & Qadir, 2024). These methods not only help sustain agricultural productivity but also conserve freshwater resources, which are becoming increasingly scarce in many regions of the world.

4.4 Role of Microbial Inoculants and Biofertilizers

Microbial inoculants and biofertilizers play a pivotal role in enhancing plant tolerance to salinity stress by improving soil health and facilitating nutrient uptake. Among the most promising microbial inoculants are plant growth-promoting rhizobacteria (PGPR), which colonize the rhizosphere and exert beneficial effects on plant growth under saline conditions (Basu, *et al.*, 2021; Kumawat, *et al.*, 2021). PGPRs enhance salt tolerance through various mechanisms, including the production of phytohormones such as indole-3-acetic acid (IAA), which regulates root growth and improves water uptake. Additionally, PGPRs facilitate the accumulation of osmolytes, such as proline and glycine betaine, in plants, which help maintain cellular osmotic balance under salt stress (Baig, *et al.*, 2024; Ullah, Munir, *et al.*, 2024). These bacteria also improve nutrient acquisition by solubilizing essential nutrients

like phosphorus and potassium, which are often immobilized in saline soils due to high salt concentrations. The ability of PGPRs to modulate the expression of stress-responsive genes further contributes to their role in enhancing plant resilience to salinity.

One notable group of PGPRs are the halotolerant bacteria, which thrive in saline environments and are particularly effective in assisting plants to cope with high salt concentrations. These bacteria enhance soil aggregation and promote the formation of biofilms in the rhizosphere, which protect plant roots from the toxic effects of sodium and chloride ions (AbuQamar, *et al.*, 2024; Jha, *et al.*, 2022). Furthermore, some PGPR strains produce exopolysaccharides that bind to soil particles and improve soil structure, reducing the negative impact of salinity on water infiltration and root aeration. Studies have shown that the inoculation of crops with halotolerant PGPRs can significantly improve germination rates, root biomass, and overall crop yield in saline soils, making them a valuable tool in sustainable agricultural practices.

Mycorrhizal associations also play a crucial role in enhancing plant tolerance to salinity stress. Arbuscular mycorrhizal fungi (AMF) form symbiotic relationships with plant roots, facilitating the uptake of water and nutrients, particularly phosphorus, in exchange for photosynthetically derived carbon. Under saline conditions, mycorrhizal fungi enhance the hydraulic conductivity of plant roots, improving water uptake and reducing the osmotic stress induced by high salt concentrations (Pooja, *et al.*, 2024; Wahab, *et al.*, 2023). AMF also promote the accumulation of osmolytes and antioxidants in plants, which help mitigate the oxidative stress caused by salinity. Additionally, mycorrhizal

fungi improve soil structure by producing glomalin, a glycoprotein that binds soil particles together, enhancing soil aggregation and reducing the movement of salts within the soil profile.

The application of biofertilizers containing mycorrhizal fungi and PGPRs has proven to be an effective strategy for improving crop performance in saline environments. These biofertilizers not only enhance nutrient availability and water uptake but also promote the establishment of beneficial microbial communities in the soil, which contribute to long-term soil health and fertility. By improving the efficiency of nutrient use and reducing the reliance on chemical fertilizers, the use of biofertilizers aligns with sustainable agricultural practices aimed at mitigating the impacts of salinity on crop productivity (Baig, *et al.*, 2024; Ullah, Ishaq, Mumtaz,, *et al.*, 2024). Moreover, biofertilizers offer an environmentally friendly alternative to conventional agricultural inputs, as they reduce the accumulation of chemical residues in the soil and water bodies, contributing to the overall sustainability of agricultural ecosystems.

Therefore, advanced irrigation methods such as drip irrigation and controlled scheduling, along with the use of microbial inoculants and biofertilizers, represent promising strategies for managing soil salinity. These techniques not only mitigate the adverse effects of salinity on plant growth and soil health but also contribute to the sustainable use of water and nutrient resources in agriculture. The integration of these practices into broader salinity management frameworks is essential for ensuring the long-term viability of agricultural systems in saline-affected regions, particularly under the challenges posed by climate change.

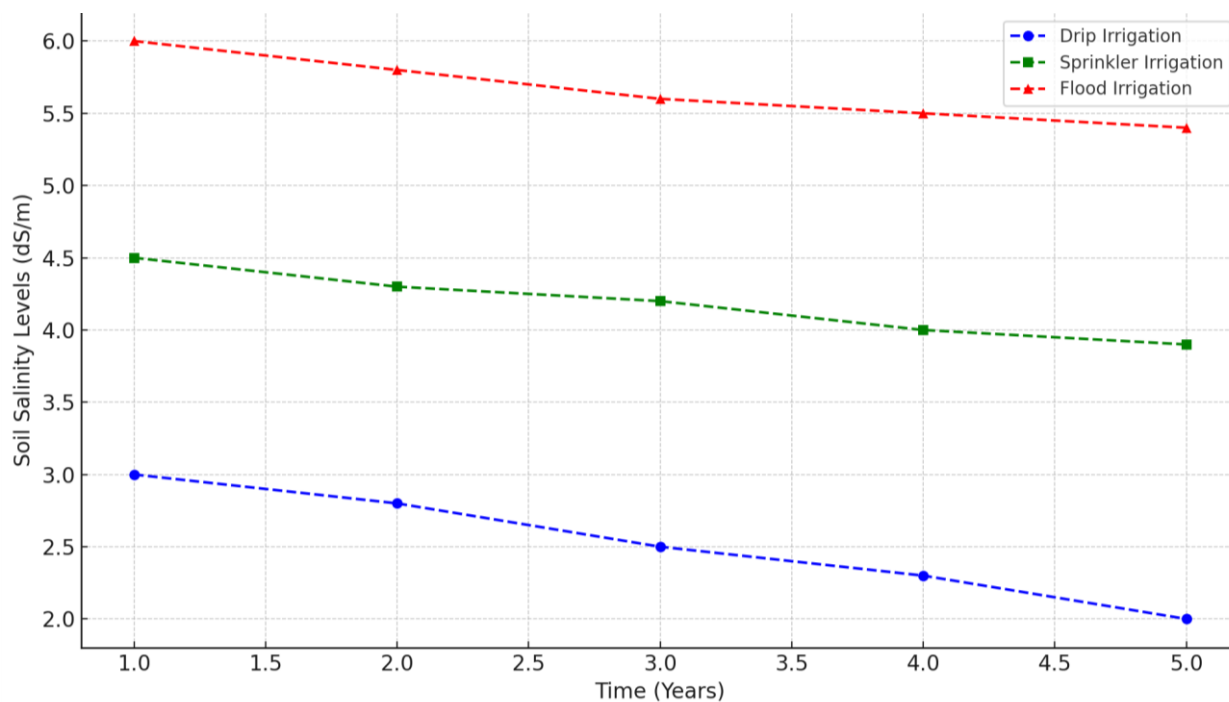


Fig 4: Impact of Different Irrigation Techniques on Soil Salinity Levels over Time

The graph 4 compares the effect of three irrigation techniques, drip irrigation, sprinkler irrigation, and flood irrigation, on soil salinity levels over a five-year period.

From the graph, it is evident that drip irrigation consistently maintains the lowest salinity levels, with a gradual decrease over time, reflecting its effectiveness in managing soil salinity. In contrast, flood irrigation shows the highest initial salinity levels, with

only a slight reduction over time. Sprinkler irrigation lies in the middle, with moderate salinity levels but a less pronounced reduction than drip irrigation.

This comparison highlights the superior efficacy of drip irrigation in reducing soil salinity over the years, making it an ideal technique for managing salinity in agriculture.

Table 3: Effectiveness of Various Soil Amendments in Salinity Reduction

Soil Amendment	Composition	Mechanism of Action	Reduction in Soil Salinity (%)	Improvement in Crop Yield (%)
Gypsum	Calcium sulfate	Displaces sodium ions, improves soil structure	40-60%	20-30%
Biochar	Organic carbon-rich material	Increases soil porosity, enhances water retention	30-50%	15-25%
Organic Matter	Manure, compost	Improves soil aggregation, promotes microbial activity	20-40%	10-20%
Sulfuric Acid	H ₂ SO ₄	Lowers soil pH, solubilizes salts	50-70%	25-35%
Polyacrylamides (PAMs)	Synthetic polymers	Reduces soil erosion, enhances water infiltration	30-45%	12-18%

This table compares the effectiveness of various soil amendments used to reduce salinity in agricultural soils. Gypsum, a commonly used amendment, shows a reduction in soil salinity by 40-60%, significantly improving crop yields by 20-30%. Biochar also proves effective by enhancing soil structure and water retention, contributing to a moderate salinity reduction (30-50%) and crop yield improvement (15-25%). Organic matter applications, such as manure or compost, improve microbial activity and soil aggregation, leading to a 20-40% reduction in salinity.

Sulfuric acid offers the highest salinity reduction (50-70%) by acidifying the soil and solubilizing salts, with a corresponding crop yield increase of 25-35%. Polyacrylamides (PAMs), while less widely used, still demonstrate effectiveness in reducing salinity by 30-45%, particularly by improving water infiltration and reducing soil erosion. The comparative analysis highlights that different soil amendments vary in effectiveness, depending on their composition and the specific mechanisms through which they act.

5. Sustainable Agricultural Management under Salinity and Climate Change

5.1 Integrated Salinity Management Approaches

The complexity of soil salinity and its exacerbation under climate change necessitates the integration of multiple strategies to ensure sustainable agricultural productivity. The adoption of integrated salinity management approaches that combine physiological, biochemical, and agronomic strategies offers a comprehensive solution to managing saline soils effectively. From a physiological perspective, understanding plant responses such as osmotic stress and ion toxicity allows for the development of salt-tolerant cultivars through selective breeding and biotechnological innovations (Qasim, Arif, et al., 2024; Qasim, Fatima, et al., 2024). Plants capable of minimizing sodium uptake, excluding harmful ions, or compartmentalizing them in

vacuoles can continue their normal physiological functions under saline conditions.

At the biochemical level, the accumulation of osmoprotectants like proline, glycine betaine, and trehalose, along with the activation of antioxidant defense systems, plays a crucial role in enhancing plant resilience against salt-induced oxidative stress. This biochemical framework, coupled with agronomic practices, creates a synergistic effect (Hossain, et al., 2021; Sani & Yong, 2021). Agronomic interventions, such as the use of soil amendments like gypsum, biochar, and organic matter, reduce the detrimental impact of salinity by improving soil structure, enhancing water retention, and displacing harmful ions like sodium. Crop management techniques, such as crop rotation, intercropping, and the adoption of salt-tolerant varieties, further complement these physiological and biochemical mechanisms. In combining these diverse approaches, integrated management of salinity not only preserves soil health but also maintains agricultural productivity in the face of climate change.

5.2 Policy and Socioeconomic Considerations

While the scientific and technical aspects of salinity management are crucial, the success of these strategies depends largely on the socio-economic context in which they are implemented. Effective salinity management requires substantial support from policymakers to ensure the adoption of sustainable practices by farmers, particularly in regions with high salinity levels and limited resources (Mazumder & Kabir, 2022). Policymakers must prioritize the development of frameworks that promote the dissemination of knowledge regarding sustainable salinity management practices. This could involve extension services, farmer training programs, and incentives for adopting environmentally friendly technologies.

The economic analysis of salinity management strategies is essential in

demonstrating the long-term benefits of investing in soil and water management. Short-term costs associated with the implementation of advanced irrigation systems, the application of soil amendments, or the breeding of salt-tolerant crops may deter some farmers, particularly in low-income regions. However, studies show that these initial investments yield significant long-term benefits, such as increased crop productivity, reduced water usage, and improved soil health, which ultimately contribute to food security and rural economic stability. Governments must also consider providing financial subsidies, tax relief, or credit access to encourage the adoption of salinity management technologies. Policymakers should also advocate for international cooperation, as salinity and climate change are global issues that require coordinated efforts across borders to ensure the sustainability of agriculture.

5.3 Future Directions and Research Needs

As climate change continues to alter environmental conditions, the development of new innovations and research in salinity management will be vital to sustaining agricultural productivity. One promising area of research is the application of advanced biotechnology for the development of highly salt-tolerant crops. Genetic engineering, CRISPR-based gene editing, and other molecular breeding technologies offer opportunities to improve the efficiency of plant responses to salinity stress. For instance, the identification and manipulation of genes responsible for salt tolerance, such as those encoding ion transporters (e.g., HKT1, SOS1) and osmolyte biosynthesis enzymes (e.g., P5CS), provide a targeted approach to improving salinity resilience in crops. These innovations have the potential to revolutionize agricultural practices in salt-affected regions by providing crops that can thrive even in harsh conditions.

Another critical research direction is the development of climate-resilient agricultural planning. As climate change intensifies, altering precipitation patterns, increasing temperatures, and raising sea levels, adaptive

agricultural strategies must be employed. Precision agriculture techniques, combined with climate-smart technologies, can optimize the use of water, fertilizers, and other inputs under salinity and climate stress. Integrating salinity management into broader climate adaptation plans at national and global levels is key to ensuring the future sustainability of food production systems. Moreover, research on the use of remote sensing technologies for real-time monitoring of salinity levels and the development of predictive models for salinity expansion can help inform agricultural practices and policy decisions.

5.4 Innovations in Biotechnology for Salinity Tolerance

In recent years, biotechnology has emerged as a promising tool for enhancing plant tolerance to salinity. The identification of genes involved in salinity tolerance has opened avenues for developing genetically engineered crops with enhanced abilities to withstand salt stress. Key innovations in biotechnology include the use of transgenic plants that express genes for ion homeostasis, osmolyte accumulation, and reactive oxygen species (ROS) scavenging. For instance, transgenic plants expressing vacuolar Na⁺/H⁺ antiporters show increased ability to sequester sodium ions in vacuoles, preventing their accumulation in the cytoplasm and thereby mitigating ion toxicity.

Another innovative approach is the use of CRISPR-Cas9 gene editing to precisely target and modify specific genes responsible for salinity tolerance. By editing genes that regulate stress-responsive pathways, scientists can enhance a plant's ability to cope with high salinity levels. Additionally, recent research on the epigenetic regulation of salinity stress responses suggests that manipulating epigenetic markers could offer another layer of resilience by enabling plants to "remember" previous exposure to salt stress and respond more effectively to subsequent stresses.

5.5 Climate-Resilient Agricultural Planning

To address the combined challenges of salinity and climate change, future

agricultural planning must prioritize climate resilience. Climate-resilient agriculture encompasses a wide range of practices designed to minimize the impacts of climate variability and salinity on crop production. Central to this approach is the development and promotion of climate-smart agricultural practices, such as conservation tillage, agroforestry, and integrated water management. Conservation tillage, for example, reduces soil disturbance, enhances soil organic matter content, and improves water retention, making soils more resilient to salinity and drought.

Agroforestry systems, where trees are integrated into agricultural landscapes, offer multiple benefits in salinity-affected regions. The deep root systems of trees can lower

water tables and prevent salt accumulation in the root zone of crops. Moreover, agroforestry systems improve biodiversity and provide additional sources of income for farmers through timber, fruit, and other tree-based products. Precision irrigation systems, such as drip irrigation, are another key component of climate-resilient agricultural planning. By delivering water directly to the root zone of crops, these systems minimize water wastage and reduce the risk of salt accumulation in the soil. Implementing these climate-smart strategies at scale will require collaboration between governments, researchers, and farmers, with a focus on ensuring the long-term sustainability of food production systems.

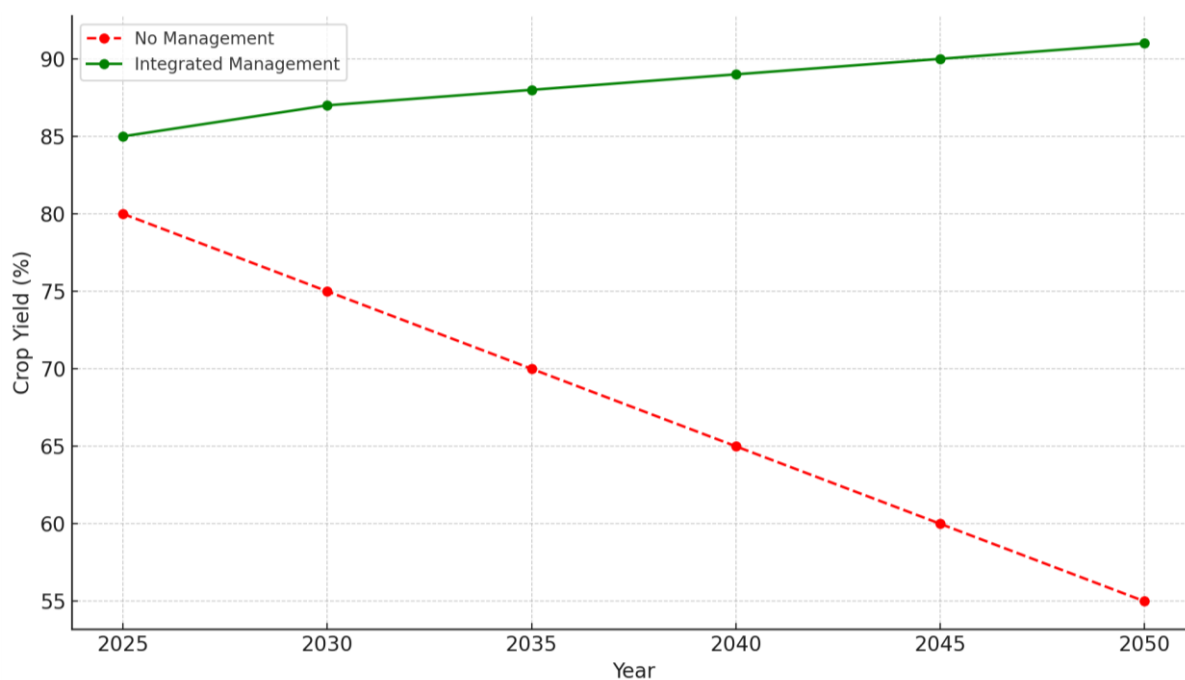


Fig 5: Projected Benefits of Integrated Salinity Management on Crop Yields Under Climate Change Scenarios

The graph 5 predicts the expected crop yield percentages from 2025 to 2050. It compares two scenarios: one without any salinity management strategies and the other with integrated salinity management practices in place.

Over time, crop yields without management decline steadily due to the exacerbating effects of climate change and increasing soil salinity. In contrast, the integrated salinity

management approach shows a gradual improvement in yields, demonstrating its effectiveness in mitigating the negative impacts of soil salinity. By 2050, yields with integrated management are projected to be significantly higher than those with no management, underscoring the importance of adopting sustainable practices to ensure agricultural productivity under changing environmental conditions.

Table 4: Summary of Sustainable Practices for Salinity Management and Their Outcomes

Sustainable Practice	Mechanism	Agronomic Outcome	Economic/Environmental Impact	Effectiveness
Gypsum Application	Calcium displaces sodium, improving soil structure	Enhanced soil permeability and water infiltration	Cost-effective, improves soil fertility	High
Biochar Addition	Increases water retention and nutrient availability	Improved plant growth and stress resilience	Carbon sequestration, enhances soil health	Moderate to High
Crop Rotation with Salt-Tolerant Crops	Reduces soil salinity accumulation and regenerates soil health	Increases crop diversity, reduces pest/disease incidences	Sustainable, cost-effective, enhances yield stability	High
Drip Irrigation	Precision water application reduces salt build-up in root zone	Optimizes water use, minimizes salinity stress on crops	Water-saving, reduces energy and labor costs	High
Plant Growth-Promoting Rhizobacteria (PGPR)	Enhances plant stress tolerance through symbiotic relationships	Increased root growth, better nutrient uptake	Environmentally friendly, reduces chemical inputs	Moderate to High
Mycorrhizal Inoculation	Facilitates nutrient uptake and improves plant salinity tolerance	Enhanced plant growth and yield under saline conditions	Environmentally friendly, improves soil biodiversity	High

The table provides a comprehensive summary of various sustainable salinity management practices and their corresponding outcomes. It lists each practice along with its underlying mechanism of action, the agronomic results observed in terms of plant growth or soil condition, and the economic or environmental impact associated with its use. The effectiveness of each method is also highlighted. Practices such as gypsum application, biochar addition, and drip irrigation show high effectiveness in improving soil quality and crop yield, while microbial solutions like PGPR and mycorrhizal inoculation contribute to sustainable, eco-friendly approaches with moderate to high effectiveness.

Conclusion

In summary, soil salinity remains a significant challenge for global agriculture, particularly under the intensifying effects of climate change. The mechanisms of salinization, driven by natural processes and exacerbated by human activities, lead to critical physiological, biochemical, and agronomic impacts on plant growth, reducing crop yields and threatening food security. Increased temperatures, altered rainfall patterns, and sea-level rise further accelerate salinity issues, particularly in coastal and arid regions. The review highlights that addressing soil salinity requires a multifaceted approach, integrating soil amendments, advanced irrigation techniques, salt-tolerant crop varieties, and

the use of biofertilizers and microbial inoculants. These combined agronomic, physiological, and biochemical strategies are essential for sustaining agricultural productivity in saline environments. Furthermore, the importance of interdisciplinary research and collaboration cannot be overstated, as continuous innovation in biotechnology, climate-resilient agriculture, and sustainable management practices are vital for effectively managing soil salinity. Governments, researchers, and agricultural stakeholders must work together to create sustainable solutions to mitigate the ongoing and future impacts of salinity, ensuring food security and environmental conservation in the face of climate change.

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