TRENDS IN ANIMAL AND PLANT SCIENCES
https://doi.org/10.62324/TAPS/2023.009
www.trendsaps.com; editor@trendsaps.com

REVIEW ARTICLE

Salinity Stress Effects on Nutrient Uptake in Plants and its Influence on Plant Growth Efficiency

Muhammad Awais[1], Zaid Rasheed[2] and Muhammad Tayyab Sadiq[1]

[1]Institute of Soil and Environmental Sciences, University of Agriculture Faisalabad, Pakistan
[2]Department of Plant Breeding and Genetics, University of Agriculture Faisalabad, Pakistan
***Corresponding author:** mawaisuaf12@gmail.com

Article History: 23-020 Received: 23-Feb-2023 Revised: 14-Apr-2023 Accepted: 25-Jun-2023

ABSTRACT

Salinity stress poses significant threats to global agriculture, affecting plant nutrient uptake and overall growth efficiency. This comprehensive review explores the underlying mechanisms of salinity-induced damage in plants, delving into the intricate physiological, biochemical, and genetic adaptations employed by plants in response to salinity stress. Salinity's impacts on nutrient availability in the soil and plant root nutrient absorption are highlighted, with particular emphasis on how these impacts ultimately affect plant growth and productivity. The review also examines the negative influence of salinity on photosynthesis and transpiration, further elucidating the complex relationship between salinity stress and plant growth efficiency. Furthermore, we discuss various strategies to mitigate salinity stress, ranging from traditional breeding and genetic engineering to the use of beneficial soil microorganisms and soil amendments. We emphasize the potential of these strategies in enhancing salt tolerance in crops and contributing to sustainable agricultural practices in saline-prone areas. Finally, we outline future research directions and potential applications, underscoring the need for a more profound understanding of plant-salinity interactions. The review suggests that integrating our current understanding with advanced technologies, such as high-throughput sequencing, functional genomics, and artificial intelligence, could accelerate the development of salt-tolerant crop varieties. Such advancements could greatly contribute to global food security amidst the escalating environmental challenges posed by climate change and soil salinization.

Key words: Salinity Stress, Plant Nutrient Uptake, Plant Growth Efficiency, Biochemical Responses, Genetic Adaptations, Salt Tolerance, Soil Microorganisms, Genetic Engineering.

INTRODUCTION

The ongoing pressures of climate change and human activities have resulted in increasing soil salinity, presenting an escalating challenge to agricultural productivity and food security across the globe (Razzaq et al., 2020). Salinity stress in plants, an adversarial circumstance instigated by excess salt content in soil, imposes a considerable constraint on the growth and yield of numerous crops. This review focuses on an intricate aspect of salinity stress - its influence on nutrient uptake in plants, and the subsequent impact on plant growth efficiency (Parihar et al., 2015).

Soil salinization is a key abiotic stressor that affects agricultural crops all over the world. The United Nations Food and Agriculture Organization estimates that salinity affects more than 800 million hectares of land worldwide. When the amount of total soluble salts or sodium ions in the root zone becomes too much, a plant experiences salinity stress, which inhibits its growth and output (Razzaq et al., 2020). Osmotic stress reduces the amount of water that is available to plants and is caused by the excess salts in the soil solution. When sodium and chloride ions are present in excess, they can also create ionic stress, which is damaging for several plant metabolic processes (Negro et al., 2017).

Plants are affected by salinity stress in a variety of ways, including physical and metabolic alterations. According to Khalid et al., excessive salt can physically inhibit plants from absorbing water, causing them to wilt and perhaps die from dehydration (Razzaq et al., 2021). Key physiological functions like photosynthesis, nutrient intake, and protein synthesis are biochemically hampered by salt stress. The main cause of this,

Cite This Article as: Awais M, Rasheed Z and Sadiq MT, 2023. Salinity stress effects on nutrient uptake in plants and its influence on plant growth efficiency. Trends in Animal and Plant Sciences 1: 64-72. https://doi.org/10.62324/TAPS/2023.009

according to Babar et al. (2023), is the excessive sodium concentration, which inhibits the absorption of crucial nutrients including potassium, calcium, and magnesium (Zafar et al., 2020; Zafar et al., 2022). Salinity stress can result in the production of reactive oxygen species in addition to oxidative damage to plant cells (Sairam & Tyagi, 2004).

The intake of nutrients is significantly impacted by salinity stress (Khalid & Amjad, 2018). The availability and absorption of nutrients are both impacted by salt stress, which alters the balance of nutrients in plants. For instance, increased salt levels in the root zone may prevent potassium, a mineral necessary for plant growth, from being absorbed. Similar to how too much chloride can prohibit plants from utilising nitrate-which is necessary for the creation of protein—properly (Ammar et al., 2022; Hamza et al., 2018). The capacity of plants to survive as a whole can be severely lowered by such nutritional imbalances (Carillo et al., 2011).

Objectives of the Review

The primary objective of this review is to provide an in-depth understanding of the effects of salinity stress on nutrient uptake in plants and its subsequent influence on plant growth efficiency. We aim to explore the physiological and biochemical responses of plants to salinity stress, particularly focusing on how high salt conditions affect the absorption and utilization of essential nutrients. Furthermore, this review intends to elucidate how these alterations in nutrient uptake under salt stress conditions impact the overall plant growth efficiency.

In addition, this review seeks to shed light on the adaptive mechanisms plants employ to counteract salinity stress, focusing on strategies related to nutrient uptake and usage. We also aim to discuss current approaches and future directions in mitigating the effects of salinity stress on plants, which may include genetic engineering, plant breeding, use of salt-tolerant crops, and soil management techniques.

Ultimately, the goal is to provide valuable insights to researchers, agronomists, and farmers, aiding in the development of effective strategies for crop management in saline soils. By addressing these aspects, we hope to contribute towards improving agricultural sustainability in areas affected by soil salinization, a pressing concern given the current global climate scenario.

Understanding Salinity Stress

To devise effective strategies for combating salinity stress, it is essential first to understand its nature, classification, and how it inflicts damage on plants. Salinity stress constitutes a formidable obstacle to agriculture, with its impact extending from the physiological level to the biochemical processes within plants. Comprehending these aspects can equip researchers and agricultural practitioners with insights to mitigate its effects, thereby enhancing crop productivity and resilience (Ahmad et al., 2013).

Definition and Classification of Salinity Stress

Salinity stress is a harmful condition that occurs when there is too much salt in the soil, most commonly due to high sodium chloride concentrations (Ashraf et al., 2022; Babar et al., 2023; BABAR et al., 2022). Soil salinity can be caused by natural processes such as mineral weathering and seawater intrusion, as well as human acts such as improper irrigation techniques. According to Khalid, Abdullah, et al. (2002), salt stress can slow plant development, diminish productivity, and even induce plant mortality in severe cases.

The two main parameters used to categorise salinity stress are the sodium adsorption ratio (SAR), which calculates the sodium content relative to calcium and magnesium, and the electrical conductivity of the soil water extract, which evaluates total soluble salts (Bano et al., 2023; BASHIR et al., 2023; Bhutta et al., 2023). Saline soils have a high electrical conductivity, but sodic soils have a high SAR. Sodic soils feature an excess of sodium ions, which can lead to soil structure collapse, whereas saline soils are distinguished by an abundance of soluble salts such as sodium chloride, magnesium sulphate, and calcium sulphate (Hussain et al., 2019).

Salinity stress can also be classified as light, moderate, or severe based on electrical conductivity values. Under minor salinity stress, sensitive plants may incur a modest growth loss, but most crops may face significant growth inhibition and, in the worst situations, plant mortality (Rasool et al., 2013).

Mechanisms of Salinity-Induced Damage in Plants

Salinity stress induces damage in plants through two main mechanisms: osmotic stress and ionic toxicity. Both these mechanisms are interrelated and can result in substantial inhibition of growth (Hasanuzzaman et al., 2013).

Osmotic stress occurs initially when excess salts in the soil solution reduce the osmotic potential, making it more difficult for plants to extract water. Drought conditions in the plant, inhibiting cell expansion and leading to stunted growth (Khalid, Abdullah, et al., 2021). The stress can also induce stomatal closure, which limits carbon dioxide uptake for photosynthesis, thereby affecting the plant's metabolic activity and productivity (Isayenkov & Maathuis, 2019).

Ionic toxicity, on the other hand, arises when the plant absorbs excessive sodium and chloride ions from the saline environment (Chaudhry et al., 2022; FATIMA, SAEED, KHALID, et al., 2022; Fatima, Saeed, Ullah, et al., 2022; Hassan et al., 2021). These ions can accumulate in plant tissues, disrupting biochemical and physiological processes. High sodium concentrations can interfere with potassium uptake, a nutrient crucial for various cellular activities including enzyme activation, protein synthesis, and stomatal movement. Similarly, elevated chloride levels can impede nitrate absorption and affect the nitrogen metabolism, hampering protein synthesis (Läuchli & Grattan, 2007).

Salinity stress can also provoke the production of ROS (Khalid et al.). Over time, the cumulative effect of these damages can lead to reduced plant growth, yield decline, and potentially plant death (Tanveer & Ahmed, 2020).

Moreover, salinity stress can have a significant impact on nutrient availability and uptake (Khalid, Amjad, et al., 2021). High salt conditions can alter the soil chemistry, which can influence the solubility and thus availability of certain nutrients. For instance, high sodium concentrations can lead to calcium deficiency in plants by replacing it in the soil solution (A. Hassan et al., 2022; M. Hassan et al., 2022; Imtiaz et al., 2022; IQBAL et al., 2023). Such disturbances in nutrient balance can further exacerbate the detrimental effects of salinity stress on plant growth and productivity (Yu et al., 2020).

Understanding these mechanisms provides a crucial foundation for research into effective salinity management strategies and the development of salt-tolerant crop varieties, ultimately contributing to the sustainability of agriculture in saline-affected areas (Khalid, Tahir, et al., 2021).

Plant Response to Salinity Stress

When exposed to salinity stress, plants employ a variety of responses to cope with the adverse conditions, facilitating their survival in high salt environments (Khan et al., 2023; Mehboob et al., 2020a, 2020b). These responses encompass biochemical adjustments as well as morphological and anatomical changes. Understanding these mechanisms not only aids in our comprehension of plant resilience to salinity stress, but also provides a basis for developing strategies to improve salt tolerance in crop plants (BABAR et al., 2022).

Biochemical Responses to Salinity Stress

Changes in biochemistry play a major role in how plants respond to salt stress. By enabling plants to preserve cellular functionality and encourage survival under saline conditions, these adaptations work to counteract the deleterious consequences of high salt concentrations. One of the main metabolic responses to salinity stress is the buildup of appropriate solutes, also referred to as osmolytes (Babar et al., 2023). Examples of them include proline, glycine betaine, and sugars. By preserving osmotic equilibrium inside cells, these substances support water absorption and retention under high salt circumstances (Arif et al., 2020).

An other significant metabolic response to salt stress is the activation of antioxidant systems. Oxidative stress is a result of an excess of reactive oxygen species (ROS), which can be brought on by high salt concentrations. Superoxide dismutase, catalase, and ascorbate peroxidase are a few examples of antioxidant enzymes that plants actively produce to combat this (Khalid, Abdullah, et al., 2021). By removing ROS from the environment, these enzymes limit oxidative damage and protect biological components. Stress from salinity has a comparable impact on plant hormone levels. For instance, in response to salt stress, levels of the stress hormone abscisic acid often increase, resulting in stomatal closure to stop water loss. Similar to auxins, gibberellins, and cytokinins, the balance of other hormones may change under salinity stress, affecting a variety of characteristics of plant growth and development (Basu et al., 2021).

Morphological and Anatomical Changes in Response to Salinity

In response to salinity stress, plants exhibit several morphological and anatomical modifications that serve as adaptive strategies to cope with the adverse conditions. These changes can help enhance water uptake, reduce transpiration, and improve overall plant water use efficiency. One common morphological change under salt stress is a reduction in plant size due to decreased cell expansion and division. This is often accompanied by a reduction in leaf area, which can help minimize water loss through transpiration (Hernández, 2019).

In terms of root architecture, plants often respond to salinity stress by increasing root-to-shoot ratios. By allocating more resources to root growth, plants enhance their ability to absorb water from saline soils. The roots may also undergo anatomical changes, such as the thickening of the cortex and epidermis, which can provide a barrier to the passive entry of toxic ions. In addition to these modifications, some plants may form salt glands or bladders, specialized structures that secrete excess salts. These adaptations, found in halophytes (salt-tolerant plants), enable these plants to tolerate high salt concentrations that would be detrimental to most other species. In summary, plants respond to salinity stress through a variety of biochemical, morphological, and anatomical changes. These adaptive strategies allow plants to cope with the challenging conditions imposed by salinity stress, promoting survival and growth in saline environments. Knowledge of these responses can be harnessed to improve salinity tolerance in crops, enhancing agricultural productivity in salt-affected regions (Läuchli & Grattan, 2007).

Impact of Salinity on Nutrient Uptake

One of the major effects of salinity stress in plants is the disruption of nutrient uptake and assimilation. Salinity can alter the physicochemical properties of the soil, influencing nutrient availability and affecting the ability of plant roots to absorb essential nutrients. This impact on nutrient dynamics can significantly affect plant growth and productivity, often resulting in nutrient deficiency symptoms even when the nutrients are present in the soil (Chakraborty et al., 2018).

Effects of Salinity on Nutrient Availability in Soil

Soil salinity directly influences nutrient availability by modifying the soil's chemical properties. The increase in the concentration of specific ions, particularly sodium, can lead to nutrient imbalances, resulting in decreased availability of essential nutrients for plant uptake (Mudasir et al., 2021; Nadeem et al., 2022; SHAFIQUE et al., 2023). For example, a high concentration of sodium ions in saline soil can displace calcium ions from the soil particles (Khalid, Abdullah, et al., 2021). This phenomenon, known as sodium-induced calcium deficiency, can lead to reduced calcium availability, despite the actual presence of this nutrient in the soil. Calcium is essential for maintaining the structural integrity of plant cell walls and for the normal functioning of cellular membranes. Thus, its deficiency can have detrimental effects on plant growth and development (Bidalia et al., 2019). Furthermore, salinity can also alter the soil pH, affecting the solubility of certain nutrients. For instance, high pH levels in sodic soils can reduce the solubility of micronutrients like iron, zinc, and manganese, making them less available for plant uptake (SHAH et al., 2023; Shahani et al., 2021; Zaghum et al., 2021).

Salinity's Influence on Plant Root Nutrient Absorption

Besides affecting nutrient availability in soil, salinity also impacts the ability of plant roots to absorb nutrients. The high concentration of salts in the soil solution can interfere with the nutrient absorption process, often leading to ion imbalances within the plant tissues. One of the primary ways salinity impacts nutrient absorption is through ion competition. High concentrations of sodium ions in saline soils can compete with the uptake of other positively charged ions, particularly potassium (Khalid, Amjad, et al., 2021). Given that sodium and potassium ions are similar in size and charge, the roots' ion transport systems may absorb sodium instead of potassium when sodium concentrations are high. Given the central role of potassium in various physiological processes, including enzyme activation, protein synthesis, and water regulation, its deficiency can substantially affect plant growth and productivity (Bidalia et al., 2019).

Moreover, the high chloride levels in saline soils can interfere with the uptake of nitrate, a key nutrient required for protein synthesis and other nitrogenous compounds. This interference can result in nitrogen deficiency, further hindering plant growth and development (Hamza et al., 2018; Kamal et al., 2019; Mustafa et al., 2022; Razzaq et al., 2020). Salinity stress can also affect the function and structure of plant roots, which can impair nutrient uptake. For instance, saline conditions can lead to reduced root growth and root hair development, decreasing the root surface area available for nutrient absorption (Puvanitha & Mahendran, 2017).

In summary, salinity has a profound impact on nutrient uptake in plants, primarily by affecting nutrient availability in the soil and the roots' ability to absorb nutrients. These changes can lead to nutrient deficiencies and imbalances, adversely affecting plant growth and productivity. Understanding these impacts is essential for developing effective strategies to manage salinity stress in agricultural systems, contributing to food security in regions affected by soil salinization.

Salinity and Plant Growth Efficiency

Salinity is a significant factor affecting plant growth efficiency, which encompasses the effectiveness of plants in using available resources for growth and biomass production (Grewal, 2010).

Salinity Impact on Photosynthesis and Transpiration

Photosynthesis is markedly affected by salinity. High salinity stress leads to a decrease in photosynthetic efficiency by impacting several aspects of the process. Firstly, it reduces the stomatal aperture, limiting the carbon dioxide intake necessary for photosynthesis. Secondly, it can cause damage to chloroplasts, thereby affecting the light-harvesting complex and the electron transport chain, both crucial components of the photosynthetic process. Moreover, salinity stress can also lead to nutrient deficiencies, particularly of elements like nitrogen and magnesium, which are vital for the synthesis and functioning of chlorophyll, the primary pigment involved in photosynthesis (Vasantha et al., 2010).

Transpiration, the process by which water is lost from plants through small openings called stomata, is also affected by salinity. Under saline conditions, the high salt concentration in the soil leads to lower soil water potential, making it more difficult for the plant to take up water. Consequently, plants close their stomata to limit water loss, indirectly affecting photosynthesis due to reduced carbon dioxide intake (Sharma et al., 2005).

Simultaneously, high salinity also disrupts the plant's water balance. It decreases the plant's water uptake capacity due to lower water potential in the soil and increases water loss by enhancing the plant's transpirational demand. This imbalance can result in plant dehydration, wilting, and, in severe cases, plant death, all contributing to reduced plant growth efficiency.

Effects of Salinity on Biomass Production

The adverse effects of salinity on photosynthesis and transpiration have a direct impact on plant biomass production. Reduced photosynthetic efficiency means that less carbohydrate – the primary source of energy for growth and development – is produced. Consequently, plant growth is stunted, resulting in lower biomass production (Liu & Yildiz, 2018).

Furthermore, salinity stress can also lead to a shift in resource allocation within the plant. Under stress conditions, plants often allocate more resources towards survival mechanisms, such as enhancing root growth for better water and nutrient uptake or producing more compatible solutes for osmotic balance.

While these responses aid in survival, they can divert resources away from growth and reproductive processes, thereby reducing overall biomass and yield (Parihar et al., 2015).

Additionally, salinity-induced changes in plant morphology, such as reduced leaf area and stunted growth, also contribute to lower biomass production. Reduced leaf area decreases the photosynthetic capacity of the plant, while stunted growth limits the overall size and productivity of the plant.

In conclusion, salinity has a substantial impact on plant growth efficiency, primarily through its effects on photosynthesis, transpiration, and biomass production. By limiting the plant's ability to take up water, reducing the effectiveness of photosynthesis, and redirecting resources away from growth processes, salinity stress can substantially reduce plant productivity. These insights underline the importance of developing and implementing strategies to mitigate the effects of salinity stress on plant growth, a vital consideration in ensuring agricultural productivity in salinized regions (Razzaq et al., 2021; Zafar et al., 2020; Zafar et al., 2022).

Adaptation Mechanisms and Tolerance Strategies

Plants have evolved a wide array of adaptation mechanisms and tolerance strategies to survive in saline environments. These adaptations encompass genetic changes, physiological adjustments, and morphological modifications that enhance salt tolerance and enable plants to maintain growth and productivity under salinity stress. Some of these strategies particularly focus on improving nutrient uptake under high salt conditions (Hernández, 2019).

Plant Genetic Adaptations to Salinity Stress

At the genetic level, plants employ various strategies to counteract the damaging effects of salinity stress. A key feature of these adaptations is the activation of stress-responsive genes that encode proteins involved in combating salinity stress. For instance, genes encoding transporters for the efficient sequestration or exclusion of sodium ions get activated under salinity stress. These transporters can prevent the buildup of toxic sodium levels within the cytoplasm, mitigating the damaging effects of high salt concentrations. Moreover, genes involved in the synthesis of compatible solutes or antioxidants, both crucial for mitigating the biochemical impacts of salinity, also get upregulated (abu Haraira et al., 2022; AFZAL et al., 2023; Alam et al., 2021; ALMAS et al., 2023). Overexpression of these genes helps to improve osmotic adjustment and scavenge reactive oxygen species, protecting cells from salt-induced damage. In addition to these, plants also possess genes associated with the regulation of stress-signaling hormones, like abscisic acid. These hormones play a pivotal role in triggering various defense mechanisms against salinity stress. By manipulating these genes, plants can fine-tune their responses to salt stress, enhancing their survival under adverse conditions (Botella et al., 2005).

Mechanisms of Nutrient Uptake Under Salinity Stress

Nutrient uptake under salinity stress is a complex process that involves several adaptive strategies. A primary mechanism is the selective uptake of essential ions, even in the presence of high concentrations of sodium ions. For instance, plants can preferentially uptake potassium over sodium by modulating the activity of high-affinity potassium transporters (Bano et al., 2023; BASHIR et al., 2023; Bhutta et al., 2023; Chaudhry et al., 2022; FATIMA, SAEED, KHALID, et al., 2022). This selective absorption helps maintain the cellular ion balance and mitigate the negative impacts of sodium toxicity. Another crucial adaptation strategy is the enhancement of root growth and development under salinity stress. By increasing root-to-shoot ratios, plants enhance their ability to absorb water and nutrients from saline soils. Some plants also form specialized structures, such as salt glands or bladders, to exclude excess salts, thereby reducing the negative impacts on nutrient uptake (Seleiman et al., 2022).

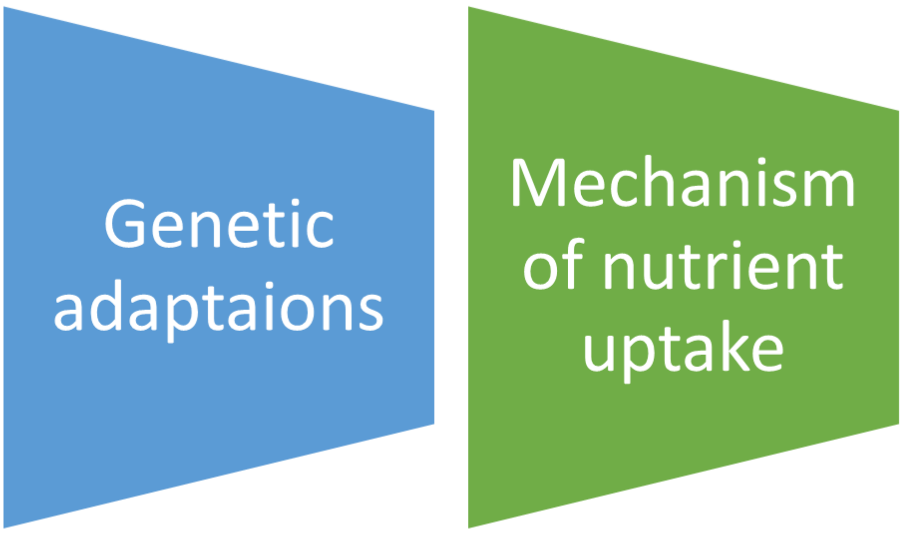

Fig. 1: Two different ttolerance sstrategies in plants.

Moreover, the regulation of membrane transport proteins plays a key role in nutrient uptake under salinity stress. For instance, upregulation of transporters involved in the uptake of nitrate or phosphate can help maintain the supply of these essential nutrients under saline conditions (Fatima, Saeed, Ullah, et al., 2022; Hassan et al., 2021; A. Hassan et al., 2022; M. Hassan et al., 2022; Imtiaz et al., 2022).

In conclusion, plants employ various genetic adaptations and physiological strategies to improve nutrient uptake and survival under salinity stress. These adaptations underscore the resilience of plants to adverse environmental conditions and provide insights for developing strategies to enhance salt tolerance in crop plants. Through the harnessing of these natural defense mechanisms, we can improve agricultural productivity in salt-affected regions, contributing to food security in an era of increasing environmental stress.

Approaches to Mitigate Salinity Stress in Plants

Breeding and Genetic Engineering for Salt Tolerance

Plants that perform well under salinity stress are chosen and crossed in salt tolerance breeding to develop improved cultivars. By harnessing genetic variety both within and between species, this age-old strategy has been utilised to improve the salt tolerance of numerous crops. Breeding attempts, however, can be challenging due to the complex structure of salt tolerance, which involves several genes and processes. As a remedy to these difficulties, genetic engineering techniques are increasingly being used to generate salt-tolerant crops. By properly modifying the genes involved in salinity tolerance, researchers can improve the plant's ability to withstand salinity stress (Turan et al., 2012).

Sodium transporter genes, for example, can be overexpressed to reduce their deleterious effects by enhancing the plant's ability to reject sodium or sequester it in the vacuole. Similarly, changing the genes that produce antioxidants or Osmo protectants can improve the plant's ability to survive the osmotic and oxidative stress caused by salt. Despite genetic engineering's potential, societal acceptance and regulatory constraints have limited its application. However, these technologies provide powerful tools for increasing agricultural plants' salt tolerance, boosting sustainable agriculture in saline-prone areas (Roy et al., 2014).

Use of Beneficial Soil Microorganisms and Amendments

Some soil microorganisms, such as certain bacteria and fungi, can enhance plant growth under salinity stress. These microorganisms can improve nutrient availability. Soil amendments, such as organic matter or gypsum, can also be used to mitigate salinity stress. Organic matter can improve soil structure and water-holding capacity, reducing the impacts of salinity on plant water status. Gypsum, on the other hand, can displace sodium ions from soil particles, reducing soil sodicity and improving soil structure. In conclusion, various approaches can be used to mitigate salinity stress in plants, ranging from breeding and genetic engineering to the use of beneficial soil microorganisms and amendments. By combining these strategies, we can develop holistic solutions to manage salinity stress in agricultural systems, enhancing productivity and sustainability in salt-affected areas (Bello et al., 2021).

Conclusion and Future Perspectives

As we delve deeper into understanding plant biology, the intricate dynamics between plants and their environments become more evident. Salinity stress stands as a significant environmental challenge influencing the global agricultural landscape. This review paper has encapsulated key aspects of salinity stress effects on nutrient uptake in plants, its influence on plant growth efficiency, and mitigation strategies.

Future Research Directions and Applications

Despite our current knowledge, more extensive research is needed to better understand the mechanistic aspects of plant responses to salinity stress. It is essential to investigate in greater detail the genetic mechanisms of salt tolerance and how these mechanisms can be effectively exploited in crop improvement programs.

High-throughput sequencing technologies and functional genomics offer immense possibilities to identify and functionally characterize genes related to salt tolerance. These technologies can be harnessed to create comprehensive genetic resources for salt tolerance that can guide breeding and genetic engineering efforts.

Moreover, the use of beneficial soil microorganisms and soil amendments warrants more attention. Understanding the intricate relationships between plants and these beneficial microorganisms under salt stress could open up novel avenues for enhancing salt tolerance. Similarly, research on soil amendments can provide sustainable and cost-effective strategies to manage soil salinity.

The application of machine learning and artificial intelligence in understanding plant responses to salinity stress is an emerging field. These computational approaches can help process complex datasets and identify patterns that can guide future research and applications.

As climate change intensifies, and soil salinization becomes more prevalent, the quest for salt-tolerant crop varieties becomes ever more urgent. Combining our understanding of plant responses to salinity stress with advanced tools and technologies can catalyse the development of innovative strategies to enhance crop productivity in saline-prone areas. By bridging the gap between fundamental research and practical applications, we can contribute to achieving global food security in the face of escalating environmental challenges.

REFERENCES

abu Haraira, A., Ahmad, A., Khalid, M. N., Tariq, M., Nazir, S., & Habib, I. (2022). Enhancing health benefits of tomato by increasing its antioxidant contents through different techniques: A review. Advancements in Life Sciences, 9(2), 131-142.

Afzal, M., Khalid, M., Imtiaz, M., Nasir, B., Shah, S., Nawaz, M., Nayab, S., Malik, S., Majeed, T., & Maqbool, R. (2023). Selection of drought tolerant wheat genotypes based on mean performance and biplot analysis. Biological and Clinical Sciences Research Journal, 2023(1), 188-188.

Ahmad, P., Azooz, M. M., & Prasad, M. N. V. (2013). *Ecophysiology and responses of plants under salt stress*. Springer.

Alam, S., Khalid, M. N., Ijaz, M., Akram, M. S., Irfan, M., & Hassan, M. (2021). Rearing of Maize Stem Borer, Chilo partellus (Lepidoptera: Crambidae) under Laboratory Conditions.

Almas, M., Sami, A., Shafiq, M., Bhatti, M., Haider, M., Hashmi, M., & Khalid, M. (2023). Sale price comparison of saggian flower market: a case study. Bulletin of Biological and Allied Sciences Research, 2023(1), 39-39.

Ammar, A., Ghafoor, S., Akram, A., Ashraf, W., Akhtar, S., Nawaz, M., Zaghum, M., Khan, M., Aas, M., & Shaheen, A. (2022). Genetic evaluation of indigenous and exotic wheat germplasm based on yield related attributes. Biological and Clinical Sciences Research Journal, 2022(1).

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.

Ashraf, A., Amhed, N., Shahid, M., Zahra, T., Ali, Z., Hassan, A., Awan, A., Batool, S., Raza, M., & Irfan, U. (2022). effect of different media compositions of 2, 4-d, dicamba, and picloram on callus induction in wheat (Triticum aestivum L.). Biological and Clinical Sciences Research Journal, 2022(1).

Babar, M., Khalid, M. N., Haq, M. W. U., Hanif, M., Ali, Z., Awais, M., Rasheed, Z., Ali, M. F., Iftikhar, I., & Saleem, S. (2023). 12. A comprehensive review on drought stress response in cotton at physiological, biochemical and molecular level. *Pure and Applied Biology (PAB)*, *12*(1), 610-622.

Babar, M., Khalid, M. N., Haq, M. W. U., Hanif, M., Ali, Z., Awais, M., Rasheed, Z., Ali, M. F., Iftikhar, I., & Saleem, S. (2023). 12. A comprehensive review on drought stress response in cotton at physiological, biochemical and molecular level. Pure and Applied Biology (PAB), 12(1), 610-622.

BABAR, M., NAWAZ, M., SHAHANI, A., KHALID, M., LATIF, A., KANWAL, K., IJAZ, M., MAQSOOD, Z., AMJAD, I., & KHAN, A. (2022). GENOMIC ASSISTED CROP BREEDING APPROACHES FOR DESIGNING FUTURE CROPS TO COMBAT FOOD PRODUCTION CHALLENGES. *Biological and Clinical Sciences Research Journal*, *2022*(1).

BABAR, M., NAWAZ, M., SHAHANI, A., KHALID, M., LATIF, A., KANWAL, K., IJAZ, M., MAQSOOD, Z., AMJAD, I., & KHAN, A. (2022). GENOMIC ASSISTED CROP BREEDING APPROACHES FOR DESIGNING FUTURE CROPS TO COMBAT FOOD PRODUCTION CHALLENGES. Biological and Clinical Sciences Research Journal, 2022(1).

Bano, M., Shakeel, A., Khalid, M. N., Ahmad, N. H., Sharif, M. S., Kanwal, S., Bhutta, M. A., Bibi, A., & Amjad, I. (2023). Estimation of Combining Ability for Within-Boll Yield Components in Upland Cotton (Gossypium hirsutum). Sarhad Journal of Agriculture, 39(1).

BASHIR, H., ZAFAR, S., REHMAN, R., HUSSAIN, M., HARIS, M., KHALID, M., AWAIS, M., SADIQ, M., & AMJAD, I. (2023). IMPACT OF POTENTIALLY SOIL MINERALIZABLE NITROGEN (PMN) ON SOIL HEALTH AND CROP PRODUCTION. Biological and Agricultural Sciences Research Journal, 2023(1).

Basu, S., Kumar, A., Benazir, I., & Kumar, G. (2021). Reassessing the role of ion homeostasis for improving salinity tolerance in crop plants. *Physiologia Plantarum*, *171*(4), 502-519.

Bello, S. K., Alayafi, A. H., Al-Solaimani, S. G., & Abo-Elyousr, K. A. (2021). Mitigating soil salinity stress with gypsum and bio-organic amendments: A review. *Agronomy*, *11*(9), 1735.

Bhutta, M. A., Bibi, A., Ahmad, N. H., Kanwal, S., Amjad, Z., Farooq, U., Khalid, M. N., & Nayab, S. F. (2023). Molecular Mechanisms of Photoinhibition in Plants: A Review. Sarhad Journal of Agriculture, 39(230).

Bidalia, A., Vikram, K., Yamal, G., & Rao, K. (2019). Effect of salinity on soil nutrients and plant health. *Salt Stress, Microbes, and Plant Interactions: Causes and Solution: Volume 1*, 273-297.

Botella, M. A., Rosado, A., Bressan, R. A., & Hasegawa, P. M. (2005). Plant adaptive responses to salinity stress. *Plant abiotic stress*, 37-70.

Carillo, P., Annunziata, M. G., Pontecorvo, G., Fuggi, A., & Woodrow, P. (2011). Salinity stress and salt tolerance. *Abiotic stress in plants-mechanisms and adaptations*, *1*, 21-38.

Chakraborty, K., Basak, N., Bhaduri, D., Ray, S., Vijayan, J., Chattopadhyay, K., & Sarkar, R. K. (2018). Ionic basis of salt tolerance in plants: nutrient homeostasis and oxidative stress tolerance. *Plant nutrients and abiotic stress tolerance*, 325-362.

Chaudhry, U. F., Khalid, M. N., Aziz, S., Amjad, I., Khalid, A., Noor, H., & Sajid, H. B. (2022). Genetic studies in different F2 segregating population for yield and fiber quality traits in cotton (Gossypium hirsutum L.). Journal of Current Opinion in Crop Science, 3(3), 135-151.

FATIMA, A., SAEED, A., KHALID, M., IMAM, M., RAFIQUE, M., SHARIF, M., IQBAL, N., TIPU, A., & AMJAD, I. (2022). GENETIC STUDIES OF F2 POPULATION FOR FIBER AND YIELD RELATED ATTRIBUTES IN GOSSYPIUM HIRSUTUM. Biological and Clinical Sciences Research Journal, 2022(1).

Fatima, A., Saeed, A., Ullah, M., Shah, S., Ijaz, M., Anwar, M., Khaliq, A., Chohan, S., Khalid, M., & Khan, A. (2022). Estimation of gene action for the selection of superior parents and their cross combinations for yield and fiber associated attributes in american cotton (Gossypium hirsutum L.). Biological and Clinical Sciences Research Journal, 2022(1).

Grewal, H. S. (2010). Water uptake, water use efficiency, plant growth and ionic balance of wheat, barley, canola and chickpea plants on a sodic vertosol with variable subsoil NaCl salinity. *Agricultural Water Management*, *97*(1), 148-156.

Hamza, M., Tahir, M. N., Mustafa, R., Kamal, H., Khan, M. Z., Mansoor, S., Briddon, R. W., & Amin, I. (2018). Identification of a dicot infecting mastrevirus along with alpha-and betasatellite associated with leaf curl disease of spinach (Spinacia oleracea) in Pakistan. Virus Research, 256, 174-182.

Hasanuzzaman, M., Nahar, K., & Fujita, M. (2013). Plant response to salt stress and role of exogenous protectants to mitigate salt-induced damages. *Ecophysiology and responses of plants under salt stress*, 25-87.

Hassan, A., Khalid, M. N., Rehman, Z. U., Amjad, I., Mudasir, M., Rasheed, Z., & Chaudhry, U. F. (2021). Hormones Performs a Crucial Role in the Regulation of Cotton Fiber Synthesis.

Hassan, A., Naseer, A., Shahani, A., Aziz, S., Khalid, M., Mushtaq, N., & Munir, M. (2022). Assessment of fiber and yield related traits in mutant population of cotton. Int. J. Agri. Biosci, 11(8).

Hassan, M., Sarwar, S., Shahzad, S., Zafar, S. A., Bilal, A., Akhter, S., Qamar, H., Asghar, S., Altaf, M., & Saleem, S. (2022). Screening of bread wheat genotypes for heat tolerance using artificial and natural environment.

Hernández, J. A. (2019). Salinity tolerance in plants: Trends and perspectives. *International Journal of Molecular Sciences*, *20*(10), 2408.

Hussain, S., Shaukat, M., Ashraf, M., Zhu, C., Jin, Q., & Zhang, J. (2019). Salinity stress in arid and semi-arid climates: Effects and management in field crops. *Climate change and agriculture*, *13*, 201-226.

Imtiaz, M., Shakeel, A., Nasir, B., Khalid, M., & Amjad, I. (2022). HETEROTIC POTENTIAL OF UPLAND COTTON HYBRIDS FOR EARLINESS AND YIELD RELATED ATTRIBUTES. Biological and Clinical Sciences Research Journal, 2022(1).

IQBAL, J., KHALID, M., RIAZ, S., RAZAQ, A., SHAKOOR, A., KARIM, A., RAZZAQ, B., GOHAR, M., AQEEL, M., & MAJEED, T. (2023). DISSECTION OF YIELD AND FIBER QUALITY TRAITS UNDER DROUGHT CONDITION IN GOSSYPIUM HIRSUTUM L. Biological and Clinical Sciences Research Journal, 2023(1), 330-330.

Isayenkov, S. V., & Maathuis, F. J. (2019). Plant salinity stress: many unanswered questions remain. *Frontiers in Plant Science*, *10*, 80.

Kamal, H., Minhas, F.-u.-A. A., Farooq, M., Tripathi, D., Hamza, M., Mustafa, R., Khan, M. Z., Mansoor, S., Pappu, H. R., & Amin, I. (2019). In silico prediction and validations of domains involved in Gossypium hirsutum SnRK1 protein interaction with cotton leaf curl Multan betasatellite encoded βC1. Frontiers in Plant Science, 10, 656.

Khalid, M. N., Abdullah, A., Ijaz, Z., Naheed, N., Hamad, A., Sheir, M. A., Shabir, F., Parveen, K., & Khan, M. D. (2021). Application and Potential Use of Advanced Bioinformatics Techniques in Agriculture and Animal Sciences. *Ind. J. Pure App. Biosci*, *9*(3), 237-246.

Khalid, M. N., Ajmal, H. M. N., Rasheed, Z., Mujtaba, H., Shah, S. A. H., Chohan, S. M., Majeed, T., Sattar, A., Asif, M., & Aas, M. I. A. A comprehensive review on salinity effects, mechanism of tolerance and its management strategies in cotton.

Khalid, M. N., Amjad, I., Hassan, A., Ajmal, U., Ammar, A., Rasheed, Z., & Qasim, M. (2021). Genetics of Inter Cropping for Crop Productivity Enhancement.

Khalid, M. N., Tahir, M. H., Murtaza, A., Murad, M., Abdullah, A., Hundal, S. D., Zahid, M. K., & Saleem, F. (2021). Application and Potential Use of Advanced Biotechnology Techniques in Agriculture and Zoology. *Ind. J. Pure App. Biosci*, *9*(2), 284-296.

Khalid, M., & Amjad, I. (2018). The application of mutagenesis in plant breeding under climate change. *Bulletin of Biological and Allied Sciences Research*, *2018*(1), 15-15.

Khan, R., Ghayas, M., Khalid, M., & Amjad, I. (2023). Transgenic strategies for enhancing cotton disease resistance: current status and future directions. Agrobiological Records 13: 82-91. In.

Läuchli, A., & Grattan, S. (2007). Plant growth and development under salinity stress. *Advances in molecular breeding toward drought and salt tolerant crops*, 1-32.

Liu, Y., & Yildiz, I. (2018). The effect of salinity concentration on algal biomass production and nutrient removal from municipal wastewater by Dunaliella salina. *International Journal of Energy Research*, *42*(9), 2997-3006.

Mehboob, S., Kashif, M., KHALID, M., & Amjad, I. (2020a). ASSOCIATION STUDY OF ASSORTEDYIELD LINKED COMPONENTS IN WHEAT CROSSES BY INVOLVING EXOTIC GENOTYPES. Bulletin of Biological and Allied Sciences Research, 2020(1), 18-18.

Mehboob, S., Kashif, M., Khalid, M., & Amjad, I. (2020b). Genetic diversity assay of the local wheat varieties and chinese crosses for yield linked attributes under local conditions. Bulletin of Biological and Allied Sciences Research, 2020(1), 19-19.

Mudasir, M., Noman, M., Zafar, A., Khalid, M. N., Amjad, I., & Hassan, A. (2021). Genetic Evaluation of Gossypium hirsutum L. for Yield and Fiber Contributing Attributes in Segregating Population. Int. J. Rec. Biotech9, 1-9.

Mustafa, R., Hamza, M., Rehman, A. U., Kamal, H., Tahir, M. N., Mansoor, S., Scheffler, B. E., Briddon, R. W., & Amin, I. (2022). Asymptomatic populus alba: a tree serving as a reservoir of begomoviruses and associated satellites. Australasian Plant Pathology, 51(6), 577-586.

Nadeem, A., Shakeel, A., IMTIAZ, M., Nasir, B., Khalid, M., & Amjad, I. (2022). GENETIC VARIABILITY STUDIES FOR YIELD AND WITHIN BOLL YIELD COMPONENTS IN COTTON (GOSSYPIUM HIRSUTUM L.). Biological and Clinical Sciences Research Journal, 2022(1).

Negrão, S., Schmöckel, S., & Tester, M. (2017). Evaluating physiological responses of plants to salinity stress. *Annals of botany*, *119*(1), 1-11.

Parihar, P., Singh, S., Singh, R., Singh, V. P., & Prasad, S. M. (2015). Effect of salinity stress on plants and its tolerance strategies: a review. *Environmental Science and Pollution Research*, *22*, 4056-4075.

Puvanitha, S., & Mahendran, S. (2017). Effect of salinity on plant height, shoot and root dry weight of selected rice cultivars. *Scholars Journal of Agriculture and Veterinary Sciences*, *4*(4), 126-131.

Rasool, S., Hameed, A., Azooz, M., Siddiqi, T., & Ahmad, P. (2013). Salt stress: causes, types and responses of plants. *Ecophysiology and responses of plants under salt stress*, 1-24.

Razzaq, A., Ali, A., Safdar, L. B., Zafar, M. M., Rui, Y., Shakeel, A., Shaukat, A., Ashraf, M., Gong, W., & Yuan, Y. (2020). Salt stress induces physiochemical alterations in rice grain composition and quality. Journal of food science, 85(1), 14-20.

Razzaq, A., Ali, A., Zafar, M. M., Nawaz, A., Xiaoying, D., Pengtao, L., Qun, G., Ashraf, M., Ren, M., & Gong, W. (2021). Pyramiding of cry toxins and methanol producing genes to increase insect resistance in cotton. GM crops & food, 12(1), 382-395.

Roy, S. J., Negrão, S., & Tester, M. (2014). Salt resistant crop plants. *Current opinion in Biotechnology*, *26*, 115-124.

Sairam, R., & Tyagi, A. (2004). Physiology and molecular biology of salinity stress tolerance in plants. *Current science*, 407-421.

Seleiman, M. F., Aslam, M. T., Alhammad, B. A., Hassan, M. U., Maqbool, R., Chattha, M. U., Khan, I., Gitari, H. I., Uslu, O. S., & Roy, R. (2022). Salinity stress in wheat: effects, mechanisms and management strategies. *Phyton (0031-9457)*, *91*(4).

SHAFIQUE, M., BANO, M., KHALID, M., RAZA, A., SHAHID, M., HUSSNAIN, H., IQBAL, M., HUSSAIN, M., ABBAS, Q., & IQBAL, M. (2023). GERMPLASM POTENTIAL FOR DIFFERENT ADVANCE LINES OF GOSSYPIUM HIRSUTUM FOR WITHIN BOLL YIELD COMPONENTS. Biological and Clinical Sciences Research Journal, 2023(1), 297-297.

SHAH, J., RAMZAN, U., NASEER, S., KHALID, M., AMJAD, I., MAJEED, T., SABIR, W., SHAHEEN, M., ALI, B., & SHAHMIM, F. (2023). CHEMICAL CONTROL OF SOUTHERN LEAF BLIGHT OF MAIZE CAUSED BY HELMINTHOSPORIUM MAYDIS. Biological and Clinical Sciences Research Journal, 2023(1), 225-225.

Shahani, A. A. A., Yeboah, E. O., Nadeem, M., Amjad, I., Ammar, A., Rehman, A. U., Awais, M., & Khalid, M. N. (2021). Cytogenetics, Types and its Application in Crop Improvement. Int. J. Rec. Biotech, 9(1), 9-14.

Sharma, N., Gupta, N., Gupta, S., & Hasegawa, H. (2005). Effect of NaCl salinity on photosynthetic rate, transpiration rate, and oxidative stress tolerance in contrasting wheat genotypes. *Photosynthetica*, *43*, 609-613.

Tanveer, M., & Ahmed, H. A. I. (2020). ROS signalling in modulating salinity stress tolerance in plants. *Salt and Drought Stress Tolerance in Plants: Signaling Networks and Adaptive Mechanisms*, 299-314.

Turan, S., Cornish, K., & Kumar, S. (2012). Salinity tolerance in plants: breeding and genetic engineering. *Australian Journal of Crop Science*, *6*(9), 1337-1348.

Vasantha, S., Venkataramana, S., Gururaja Rao, P., & Gomathi, R. (2010). Long term salinity effect on growth, photosynthesis and osmotic characteristics in sugarcane. *Sugar tech*, *12*, 5-8.

Yu, B., Yang, J., Niu, J., & Wang, G. (2020). Antioxidant responses to hyperosmolarity stress in the intertidal Pyropia yezoensis (Bangiales, Rhodophyta). *Algal Research*, *48*, 101930.

Zafar, M. M., Razzaq, A., Farooq, M. A., Rehman, A., Firdous, H., Shakeel, A., Mo, H., & Ren, M. (2020). Insect resistance management in Bacillus thuringiensis cotton by MGPS (multiple genes pyramiding and silencing). Journal of Cotton Research, 3(1), 1-13.

Zafar, M. M., Rehman, A., Razzaq, A., Parvaiz, A., Mustafa, G., Sharif, F., Mo, H., Youlu, Y., Shakeel, A., & Ren, M. (2022). Genome-wide characterization and expression analysis of Erf gene family in cotton. BMC Plant Biology, 22(1), 134.

Zaghum, M., Khalid, M., Zia, M., Gul, M., Amjad, I., & Irfan, M. (2021). Molecular Regulation in Seed Development Influencing the Fiber Growth in Gossypium hirsutum L. Acta scientific agriculture, 5, 15-23.