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Impact of Soil Salinity on Wheat Growth and Yield: Challenges, Mechanisms, and Management Strategies

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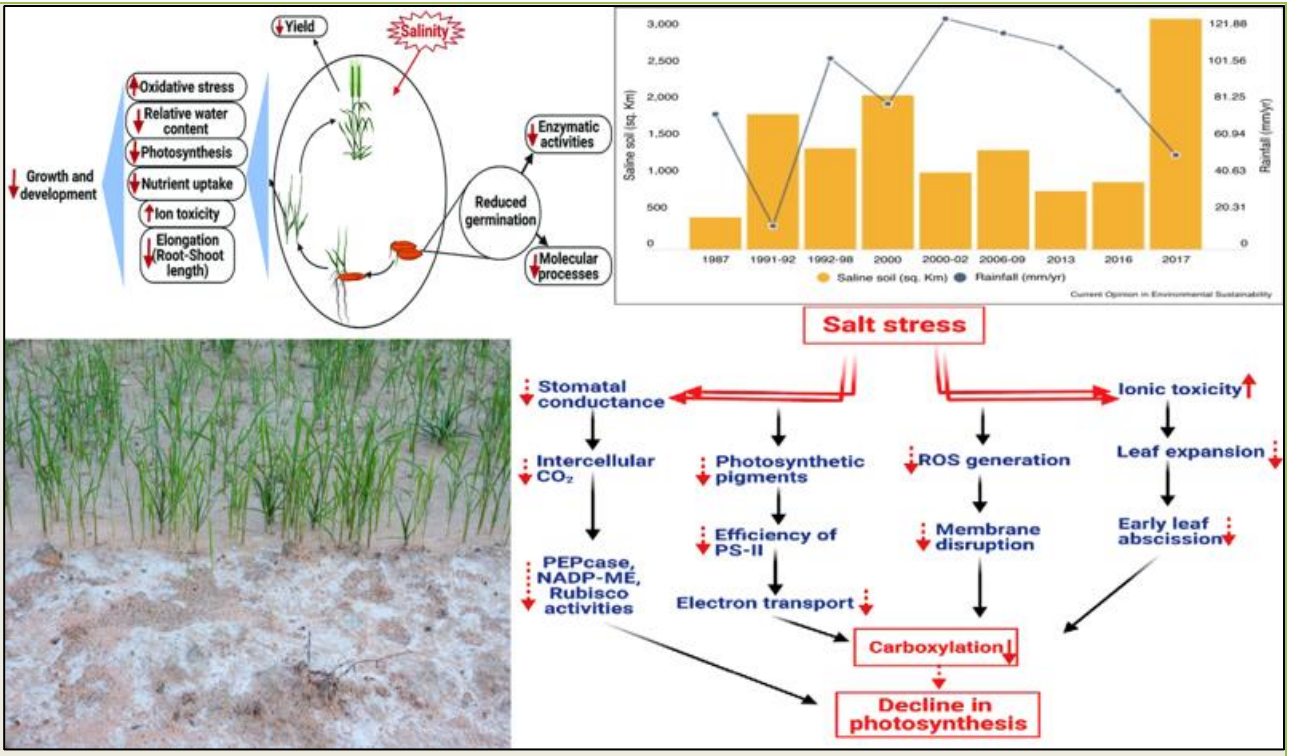
Abstract

Review Article



Graphical Abstract

The development and productivity of wheat (Triticum aestivum) are severely hampered by soil salinity, a key abiotic stressor that poses a significant threat to world food security. Osmotic stress, ionic toxicity, and oxidative damage in wheat plants are caused by excessive salt buildup in the soil, which also interferes with water absorption, ion homeostasis, and nutrient balance. Grain yield, photosynthetic efficiency, root and shoot growth, and germination are all hampered by these stresses. Developing successful management techniques for wheat requires understanding the physiological, pharmacological, and molecular factors behind salt tolerance. To lessen salinity-induced stress's effects, plants use various adaptive responses, including ion compartmentalization, antioxidant defense mechanisms, osmoprotectant accumulation, and hormone modulation. Breeding and biotechnological developments, including genome editing, transgenics, and marker-assisted selection, have demonstrated promise in enhancing wheat's resistance to salt. Furthermore, reducing the negative impacts of salinity requires using agronomic treatments such as soil amendments, biofertilizers, and adequate irrigation techniques. The role of precision farming, an innovative solution

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that enhances wheat's resistance to salty conditions, is not just a solution but an inspiring example of how technological advancements can revolutionize agriculture. This paper thoroughly examines the difficulties caused by soil salinity, clarifies the fundamental principles of tolerance, and investigates creative management techniques to maintain wheat yields in the face of salt stress.

Keywords: Soil salinity, Wheat growth, Wheat yield, Salinity stress, Antioxidant defense, Osmoprotectants, Hormonal regulation, Salinity-induced oxidative stress, Nutrient imbalance, Soil amendments, Salinity mitigation strategies, Salt-tolerant wheat varieties, Biotechnological approaches, Genetic modification, Plant-microbe interactions, Rhizosphere management.

INTRODUCTION

An alternative viewpoint views soil salinity as an evolutionary constraint that drives wheat adaptability and resistance, even though it is frequently seen as a significant abiotic stressor limiting agricultural yield (Gonzalez Guzman *et al.*, 2022). Saline conditions that wheat (Triticum spp.) has experienced over time have served as selection factors, encouraging the survival and spread of genotypes that are tolerant of salt. Ion homeostasis, osmotic adjustment, and stress-responsive gene expression are only a few of the physiological and molecular strategies that natural populations of wheat and its wild cousins, such as Triticum monococcum and Aegilops species, have developed to deal with excessive salinity (Pour-Aboughadareh *et al.*, 2021). Modern breeding methods use the genetic variety in salt tolerance features created by this evolutionary drive to create hardy cultivars. To lessen the negative consequences of salt stress, wheat, for example, has evolved the capacity to improve potassium absorption, compartmentalize harmful sodium ions in vacuoles, and control stress-related hormones like (ABA) abscisic acid (Quamruzzaman *et al.*, 2022). Moreover, epigenetic changes like DNA methylation and histone modifications may have facilitated the heritable control of salt tolerance genes, progressively allowing wheat to adapt to saline soils throughout several generations. Strategies to increase wheat resilience in the face of climate change and soil degradation can be informed by knowing salinity as an evolutionary driver rather than just a stressor (Hossain *et al.*, 2021). Future studies should investigate salt tolerance's genetic and epigenetic underpinnings to improve breeding efforts, utilizing landraces and ancient wheat cultivars. Scientists and agronomists may use natural adaptation processes to create sustainable wheat production systems in increasingly salty environments by changing the narrative from one that views salinity as a limitation to one that views it as an evolutionary force (Mujeeb-Kazi *et al.*, 2019).

Due to soil salinization, which impacts about 20% of irrigated fields globally, increased concerns about cultivating wheat under saline circumstances have been raised (Singh *et al.*, 2022). South Asia, the Middle East, North Africa, Australia, and portions of China and the US are among the world's hotspots for growing wheat in salty conditions. Large areas of the Indo-Gangetic Plain in South Asia, especially in India and Pakistan, suffer from saline problems due to excessive irrigation and inadequate drainage, making the creation of salt-tolerant wheat cultivars necessary (Chatrath *et al.*, 2007). Similarly, dry climates and a reliance on saline irrigation water from rivers like the Nile and the Tigris-Euphrates system cause nations like Egypt, Iran, and Iraq in the Middle East and North Africa (MENA) area to suffer from soil salinity. In order to maintain yields, wheat breeding initiatives in Australia, one of the top exporters of wheat, concentrate on improving salt tolerance in the country's large saline-prone regions of Western Australia, South Australia, and New South Wales. Secondary salinization from extensive farming and seawater intrusion affects China's North China Plain and coastal areas like the Yellow River Delta (Gaydon *et al.*, 2017). Saline soils are another problem in the United States, especially in the Central Valley of California and portions of Texas, where wheat production is impacted by irrigation-induced salinity. Global research projects aim to address these issues by developing salt-tolerant wheat cultivars, using biotechnological strategies like CRISPR and marker-assisted selection, and implementing sustainable farming methods like better drainage systems, salt leaching methods, and halophytic companion crops (Tarolli *et al.*, 2024). These initiatives are essential for reducing the negative impacts of climate change on wheat production and guaranteeing food security in areas prone to salinity. As agricultural scientists, researchers, and policymakers, your role in these initiatives is crucial. Your contributions can make a significant difference in addressing this global challenge, and your expertise and dedication are key to the success of these efforts (Saleem *et al.*, 2024).

In areas where agriculture is essential to national stability and global food security, soil salinity poses significant economic and geopolitical concerns (Basset *et al.*, 2024). Salinity makes countries more dependent on food imports by lowering crop yields and depleting soil fertility, exacerbating trade imbalances and increasing reliance on large agricultural exporters. As seen by the conflicts over the Tigris-Euphrates and Indus River basins, this reliance may exacerbate geopolitical tensions, particularly in areas with limited water resources where transboundary water management becomes a divisive topic. The financial impact of soil salinity goes beyond decreased agricultural productivity since impacted nations must pay more for desalination, alternative irrigation techniques, and land rehabilitation (Qadir *et al.*, 2014). Smallholder farmers in poor countries are especially at risk because they frequently lack the funds necessary to put in place salinity-resistant practices, resulting in a rise in social instability, migration, and rural poverty. Moreover, the phenomena exacerbate global geopolitical rivalry by encouraging countries to engage in overseas strategic land purchases, commonly known as "land grabbing," contributing to desertification and land degradation (Zimerman *et al.*, 2024). Climate change worsens These problems, making long-term agricultural planning more uncertain by accelerating salinization in desert and coastal regions due to increasing sea levels and unpredictable weather patterns. As countries look for long-term solutions to preserve food sovereignty and economic stability, soil salinity is becoming more than simply an agricultural issue; it plays a significant role in determining economic policies, international trade agreements, and geopolitical agendas (Boyer *et al.*, 2010).

Multidimensional Understanding of Soil Salinity

Beyond its traditional association with sodium chloride (NaCl), soil salinity is a multifaceted and complex phenomenon that includes a range of salts, including magnesium sulfate ($MgSO_4$), calcium chloride ($CaCl_2$), and sodium sulfate (Na_2SO_4), each of which has unique physicochemical and biological effects on soil health and plant productivity (Zinck *et al.*, 2009). Although the main issue is frequently NaCl-induced salinity, Na_2SO_4 also has a negative impact by generating soil dispersion and osmotic stress, which hinder root water absorption. Similarly, $CaCl_2$, despite its potential to ameliorate sodium-induced soil structure deterioration by increasing flocculation, adds to salt stress by changing ionic balances and reducing plant nutrient absorption. Magnesium sulfate ($MgSO_4$) further exacerbates salinization by disrupting magnesium-calcium ratios, leading to soil compaction and reduced microbial diversity. Beyond surface-level salinity, hidden subsurface salinity poses a significant challenge, particularly for deep-rooted crops like wheat, where salt accumulation in deeper soil layers restricts root elongation, alters rhizosphere microbiota, and impairs water and nutrient absorption, ultimately reducing grain yield. This hidden salinity can remain undetected by traditional soil sampling methods, necessitating advanced real-time monitoring techniques (Wang *et al.*, 2024). Integrating artificial intelligence (AI) and remote sensing technologies has revolutionized soil salinity assessment, enabling precise, large-scale monitoring through hyperspectral imaging, drone-based sensing, and machine learning algorithms that accurately predict salinity variations. These technologies facilitate proactive salinity management by identifying problem areas before visible crop damage occurs, allowing for targeted soil amendments, optimized irrigation strategies, and precision farming interventions. Therefore, a comprehensive approach to soil salinity management must consider the diverse salt contributors, subsurface salinity dynamics, and the application of cutting-edge AI-driven monitoring techniques to ensure sustainable agricultural productivity in saline-prone regions (Reza *et al.*, 2025).

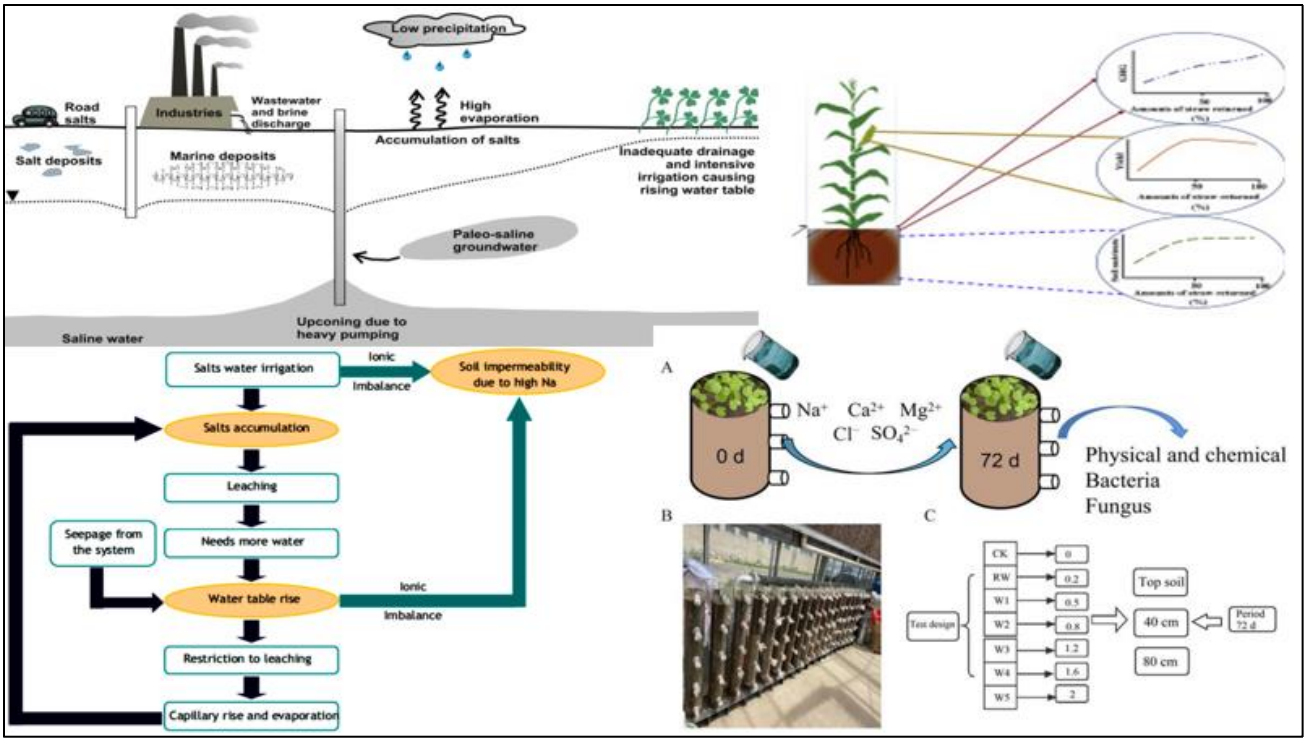

Fig 1: Multidimensional Understanding of Soil Salinity

Impact of Soil Salinity on Wheat Growth and Yield: A Systems Approach

A key abiotic stressor that substantially affects wheat development and production is soil salinity, which alters several physiological, molecular, and biochemical processes (El Sabagh *et al.*, 2021). Wheat adaptability is influenced by metabolic changes, plant genetics, soil microbiome dynamics, and epigenetic alterations, all of which are included in a systems approach to understanding salt stress. Osmotic stress, ionic toxicity (mainly from the buildup of Na+ and Cl-), and oxidative damage, which interferes with nutrient absorption, photosynthesis, and root architecture, are all consequences of high salt levels in the soil. Furthermore, the rhizosphere microbiome is changed by salt stress, which influences root-microbe interactions by lowering beneficial plant-growth-promoting bacteria (PGPB) and encouraging halotolerant species in the microbial community. Wheat stress is exacerbated by this disturbance, which also impacts hormone signaling, nitrogen solubilization, and general soil health. At the molecular level, epigenetic changes facilitate stress memory, including DNA methylation, histone modifications, and non-coding RNAs, enabling wheat to maintain adaptive responses throughout successive generations (Jin *et al.*, 2024). According to omics technologies such as transcriptomics, proteomics, and metabolomics, salinity causes metabolic rewiring that results in changes in energy metabolism to lessen stress-induced damage, increased antioxidant activity, and modified synthesis of osmoprotectants (such as proline and glycine betaine). Different stages of wheat growth are more or less susceptible to salt; the most important windows for intervention are during germination, early seedling establishment, and reproductive phases. Early growth abnormalities in root development brought on by salinity hinder water absorption and nutrients, and reproductive stage stress results in pollen sterility, decreased grain filling, and lower yield. Strategies for mitigating salinity stress include breeding salt-tolerant genotypes, employing microbial inoculants to enhance soil microbial resilience, and utilizing epigenetic priming to improve long-term stress tolerance. A holistic systems approach integrating plant genetics, microbiome engineering, and metabolic adaptation provides a promising framework for enhancing wheat resilience in saline environments (Iqbal *et al.*, 2023).

Table 1: Impact of Soil Salinity on Wheat Growth and Yield, A Multidimensional

Factor	**Impact on Wheat Growth**	**Mechanisms Affected**	**Intervention Strategies**	**Reference**
Osmotic Stress	Reduced seed germination, impaired root and shoot growth	Water potential imbalance, stomatal closure, reduced cell expansion	Use of osmoprotectants, hydropriming, and seed coating	Pratap *et al.*, 2010
Ionic Toxicity (Na+, Cl-)	Nutrient imbalance, chlorosis, reduced biomass	In competition (K+/Na+ imbalance), enzyme inhibition, oxidative stress	Breeding for Na+ exclusion, rootstock grafting, and ion transporters	Evelin *et al.*, 2012
Oxidative Stress	Lipid peroxidation, protein oxidation, DNA damage	Reactive oxygen species (ROS) accumulation, reduced photosynthesis efficiency	Application of antioxidants (ascorbate, glutathione), exogenous phytohormones	Ma *et al.*, 2013
Microbiome Shift	Loss of beneficial microbes, dominance of halotolerant species	Altered nutrient cycling, reduced plant growth-promoting rhizobacteria (PGPR)	Microbial inoculants, biofertilizers, and soil amendments	Singh *et al.*, 2024
Epigenetic Modifications	Stress memory, altered gene expression	DNA methylation, histone acetylation, small RNAs	Epigenetic priming, biostimulants, and chemical modulators	Kim *et al.*, 2017
Metabolic Rewiring	Accumulation of osmolytes altered primary and secondary metabolism	Proline synthesis, carbohydrate metabolism shift, polyamine production	Omics-driven metabolic engineering, targeted metabolite supplementation	Xu *et al.*, 2022
Growth Stage Sensitivity	Germination, seedling establishment, and flowering are the most vulnerable.	Reduced germination rate, root elongation inhibition, pollen sterility	Timed irrigation, controlled environment cultivation, foliar nutrient application	Bhattacharya *et al.*, 2022
Yield Reduction	Reduced grain size, lower seed set, decreased harvest index	Impaired carbohydrate translocation, lower photosynthetic efficiency	Genomic selection, transgenic approaches, precision agriculture	Sehgal *et al.*, 2018
Soil Amendments	Altered soil structure, improved water retention	Organic matter addition, gypsum application, biochar incorporation	Soil conditioning, mulching, controlled drainage systems	Fang *et al.*, 2021
Genetic Breeding Approaches	Development of salt-tolerant wheat varieties	Marker-assisted selection, gene editing (CRISPR), transgenic modifications	Deployment of salt-tolerant cultivars, hybrid wheat programs	Ashraf *et al.*, 2022

Mechanistic Insights into Salinity Tolerance in Wheat

In wheat, salinity tolerance is a complicated characteristic controlled by several physiological, biochemical, and molecular processes that allow the plant to recognize, react to, and lessen the harmful effects of elevated salt concentrations (El Sabagh *et al.*, 2021). Ion transporters, changes in membrane potential, and signaling cascades that identify ionic and osmotic stress are the main electrophysiological components of wheat cells' detection of salt stress. In order to preserve ionic homeostasis, wheat roots quickly detect sodium (Na^+) inflow through plasma membrane depolarization, which activates sodium exclusion mechanisms (SOS1 antiporters) and high-affinity potassium (K^+) transporters (HKT1). Furthermore, reactive oxygen species (ROS) modulate Ca2+ channels, further controlling downstream adaptive responses and acting as secondary messengers in stress signaling. In addition to controlling ion flow, non-coding RNAs (ncRNAs), such as long non-coding RNAs (lncRNAs) and microRNAs (miRNAs), play important roles in the post-transcriptional control of wheat genes linked to tolerance to salt. Specific lncRNAs alter chromatin remodeling and transcription factor activity to improve stress resistance, whereas miRNAs like miR528 and miR398 control ROS detoxification and antioxidant defense pathways (Begum *et al.*, 2022). The complex interaction of hormonal signals or the wheat hormone further determines the plant's ability to adjust to salt stress. In order to prevent excessive sodium buildup, abscisic acid (ABA) functions as a crucial regulator by inducing stomatal closure, initiating stress-responsive genes, and modifying ion transport proteins. Under saline stress, the interaction of ABA, auxins, and cytokinins is essential for preserving root development and architecture. Cytokinins counteract the effects of ABA by encouraging cell proliferation and postponing leaf senescence, whilst auxins affect root elongation and lateral root development to maximize water absorption. This complex hormonal interaction guarantees wheat's resistance to salt, demonstrating possible targets for genetic and biotechnological treatments to improve wheat salinity tolerance through coordinated physiological and molecular responses (Ullah *et al.*, 2024).

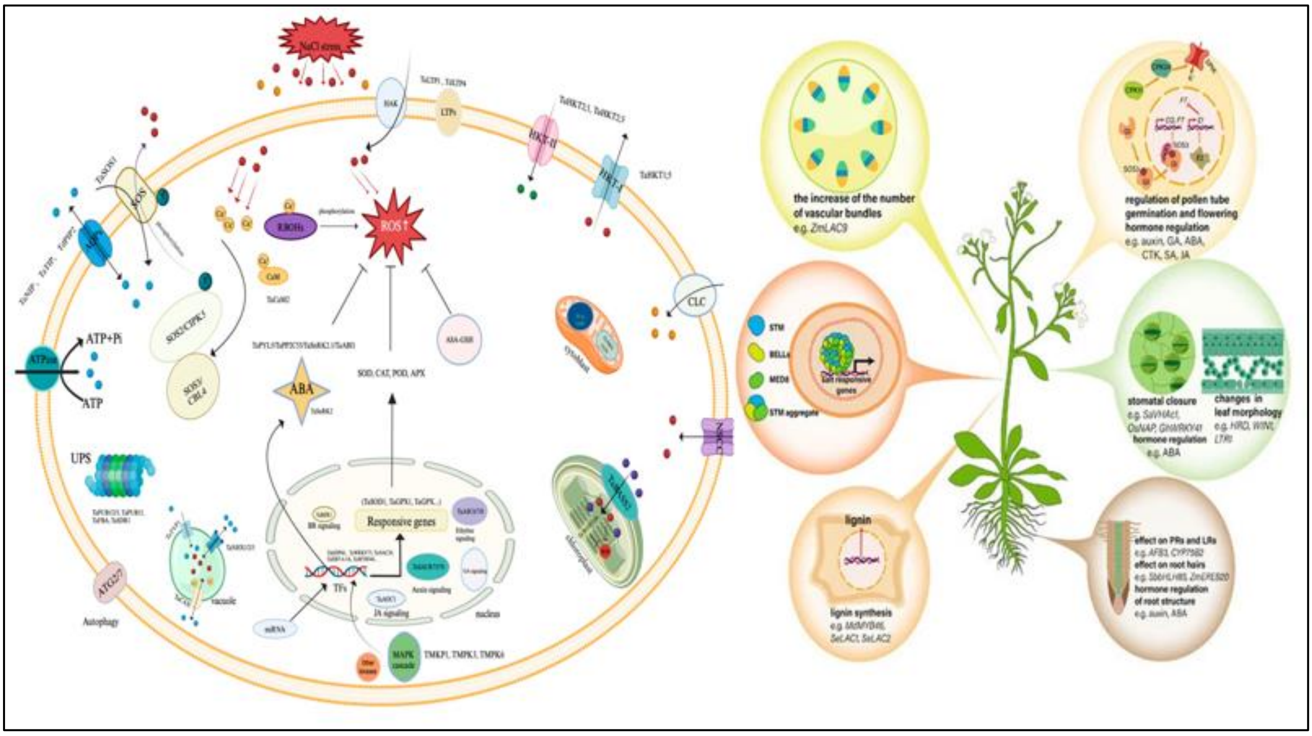

Fig 2: Mechanistic Insights into Salinity Tolerance in Wheat

Integrative Genetic and Molecular Strategies for Salinity Tolerance

Enhancing crop resistance to salinity requires integrative genetic and molecular approaches, especially for wheat, a key food crop extremely vulnerable to salt stress (Jha *et al.*, 2019). Genome-wide association studies (GWAS), which make it possible to identify genetic loci linked to salt tolerance, are one of the main techniques used in this endeavor. Researchers can identify important genes or regulatory networks that resist high salinity and reveal the intricate genomic architecture underpinning salt tolerance by mapping these loci. Food security in regions impacted by soil salinization depends on producing salinity-tolerant wheat cultivars with increased yield under saline circumstances, which has already been made possible using GWAS. In addition to GWAS, synthetic biology presents encouraging opportunities to increase tolerance to salt. Scientists can use synthetic biology to build new metabolic pathways, change ion transporters, or tweak signaling networks that control stress responses to increase a plant's tolerance to saltwater conditions. Developing transgenic wheat cultivars with improved salt tolerance features is one example of this strategy enabling precise and focused treatments. Proteomics, metabolomics, and epigenomics are examples of multi-omics techniques proving to be very helpful in comprehending the molecular pathways behind salinity stress (Ullah *et al.*, 2022). By identifying proteins that are either activated or inhibited in response to salt stress, proteomics provides insight into the cellular adaptive responses of plants. Metabolomics provides Potential stress tolerance indicators, illuminating how metabolites and secondary chemicals alter in response to salt. Contrarily, epigenomics studies alterations in DNA methylation, histone modifications, and non-coding RNA expression, frequently implicated in controlling genes that respond to stress. Combining this multi-omics data, a thorough knowledge of how wheat and other crops respond to salt stress is attained, which helps direct the creation of genetically modified cultivars more suited to flourish in saline conditions. In order to breed more robust crops and support agricultural sustainability in the face of climate change and the rising salinization of arable land, these integrative solutions are essential (Hussain *et al.*, 2020).

Innovative Agronomic and Soil Management Strategies

Innovative agronomic and soil management techniques are revolutionizing agricultural methods, especially when tackling soil salinity, which hinders crop growth (Tarolli *et al.*, 2024). The creation of nano-fertilizers, nano-biochar, and nano-based desalination techniques has made nanotechnology a game-changer in the fight against salinity. While nano-biochar functions as a soil amendment that increases water retention, soil structure, and microbial activity, helping to lessen the negative impacts of salinity, nano-fertilizers improve nutrient delivery to plants, increasing efficiency and lowering nutrient leaching. Furthermore, desalination technologies based on nanotechnology provide creative ways to eliminate excess salts from soil or irrigation water, improving farming sustainability in areas prone to salinity. The application of Soil Electrical Conductivity (EC) mapping, which allows farmers to track and evaluate soil salinity, advances precision agriculture (Corwin *et al.*, 2005). This method enables focused interventions by identifying high-salinity zones and maximizing fertilizer and water usage. Another potential approach is the use of bacteria that produce exopolysaccharides (EPS), which are known to lower soil salinity through various processes, including forming biofilms that improve soil structure and help retain moisture. Biosaline agriculture, which combines biological and technical solutions, is becoming more popular. It focuses on integrating halophyte plants that can withstand salt into intercropping or crop rotation systems, especially in wheat cultivation. In addition to aiding in managing salty soils, this strategy increases agricultural systems' resilience and biodiversity. Combined, these tactics offer a comprehensive and long-term method of enhancing crop yields and soil health in salt-affected regions, opening the door to more resilient farming (Faisal *et al.*, 2024).

Emerging Biotechnological Frontiers in Salinity Management

The increasing challenge of salinity-induced stress on crops, especially wheat, has prompted research into cutting-edge biotechnological strategies to increase crop resilience (Prakash *et al.*, 2025). CRISPR-Cas9 and epigenome editing technologies have become transformative tools for precise genetic modifications, allowing the development of wheat varieties that can withstand salinity stress. In parallel, CRISPR-Cas9 allows gene expression manipulation without changing the underlying DNA sequence, offering a more flexible approach to improving salinity tolerance by activating or silencing specific gene loci. Using engineered microbial consortia to reduce salinity is another interesting approach. In order to lessen the impacts of salt, these consortia cultivate helpful microorganisms, such as fungi and bacteria, that may be applied to wheat fields (Khan *et al.*, 2022). Improved plant development can result from these bacteria' ability to increase soil quality, encourage nutrient absorption, and create compounds that counteract salt stress. Furthermore, artificial root microbiomes provide yet another cutting-edge tactic for enhancing tolerance to salt. These artificial microbiomes can improve stress tolerance, increase water and nutrient availability, and even activate plant defense systems by creating and manipulating microbial communities inside the plant's root zone. Combined, these biotechnology advancements give optimism for raising agricultural production in saline-prone areas by representing state-of-the-art salt control in wheat farming (Thabet *et al.*, 2024).

Table 2: Emerging Biotechnological Frontiers in Salinity Management for Wheat Resilience

Technology /Approach	Description	Mechanism of Action	Benefits	Challenges	Applications in Wheat Cultivation
CRISPR-Cas9 Gene Editing	A genome-editing technology that allows precise modifications to the wheat genome to enhance salinity tolerance.	Targeted modification of genes related to ion transport, osmotic regulation, and stress response pathways.	Enables the creation of salt-tolerant wheat varieties with precise genetic traits.	Ethical concerns, off-target effects, regulatory approval challenges.	Development of salt-tolerant wheat varieties for saline soils.

Epigenome Editing	A technique that modifies gene expression without altering the DNA sequence, allowing the activation or silencing of key genes involved in stress responses.	Modifying epigenetic marks like DNA methylation and histone modification to regulate the expression of genes linked to salt tolerance.	It offers a reversible and potentially safer alternative to genetic modification, allowing for flexible management of stress responses.	Limited understanding of the long-term effects, difficulty in controlling epigenetic changes	Use in breeding programs to enhance wheat resilience without altering the underlying DNA sequence.
Engineered Microbial Consortia	Beneficial microorganisms, such as bacteria and fungi, are introduced into soil to enhance salinity tolerance by promoting plant growth and soil health.	Microbes can improve nutrient uptake, degrade harmful salts, and produce bioactive compounds that alleviate stress.	It enhances soil health, reduces the impact of salinity on plant growth, and improves overall crop yield.	Difficulties in ensuring microbial stability and consistency in different environmental conditions.	The application of microbial consortia is to increase wheat yield in saline-prone areas by improving soil and root health.
Synthetic Root Microbiomes	Custom-designed microbial communities are introduced to plants' root zones to improve nutrient uptake, water availability, and stress resistance.	Microbial communities are engineered to support the plant's stress response and improve salt tolerance by modulating plant-pathogen interactions and nutrient absorption.	It enhances root function, improves stress tolerance, and boosts nutrient uptake in saline soils.	Complexity in designing and maintaining stable synthetic microbiomes across different environments.	Use in wheat fields to optimize root microbiota for salinity tolerance and better resource utilization.
Gene-Stress Pathway Integration	Integrating multiple salinity-resilience genes into wheat via biotechnological approaches creates a comprehensive stress response.	Co-expression of multiple genes related to salt stress tolerance, enhancing the overall plant resilience against salt-induced damage.	A holistic approach to salinity stress improves wheat yield in highly saline soils.	Genetic interactions, regulatory hurdles, and difficulty in optimizing multiple gene integrations.	Development of high-yield, salinity-tolerant wheat varieties with integrated stress-resilience mechanisms.
Plant-Microbe Symbiosis	Enhancing the natural symbiotic relationship between plants and beneficial microorganisms to help wheat plants better tolerate saline environments.	Beneficial microbes form associations with plant roots, improving nutrient uptake, enhancing salt tolerance, and promoting plant growth under saline conditions.	Improved plant-microbe interactions boost wheat growth and resilience to salinity without extensive genetic modification.	Ensuring long-term stability of symbiotic relationships and dealing with environmental variability.	Application of microbial inoculants in saline agricultural systems to improve plant health and crop productivity.
Salt-Responsive Gene Activation Systems	Advanced systems to activate salt-responsive genes in response to environmental stress using external stimuli or environmental signals.	When environmental salinity levels are detected, salt-specific promoters drive the activation of salt tolerance-related genes in wheat.	Adaptive response to salinity stress, providing controlled gene activation based on external conditions.	Difficulty in fine-tuning gene activation and response to variable environmental conditions.	Application in precision farming to control wheat’s response to salinity stress in real-time.
Transgenic Wheat Varieties for Salt Tolerance	Development of genetically modified wheat that expresses specific traits to enhance tolerance to high-salinity conditions.	Incorporating salt-tolerant genes from other plants or organisms (e.g., halophytes) to improve wheat’s ability to withstand saline environments.	Provides a direct solution for salinity stress, ensuring stable crop yield in affected regions.	Public perception issues, regulatory hurdles, and market acceptance of genetically modified crops.	Deployment of transgenic wheat to maintain yield stability in saline-prone agricultural zones.

Socioeconomic, Environmental, and Policy Considerations

In order to comprehend the broader effects of salt on agricultural systems, it is essential to consider the social, environmental, and policy aspects of wheat agriculture that are impacted by salinity (Hopmans *et al.*, 2021). Wheat production is severely hampered by economic losses brought on by salinized soil because salinity lowers crop yields, restricts the amount of arable area, and raises the price of inputs like fertilizer and water. Wheat is a key crop in salty regions, where farmers frequently face financial difficulties due to the trade-offs between sustaining output and coping with declining yields. In addition to contributing to soil deterioration, salinity gradually lowers soil fertility, making it more challenging to maintain successful wheat production without large expenditures on irrigation or soil amendments. Salinization worsens the deterioration of natural habitats, reducing biodiversity and impacting the environment (Ondrasek *et al.*, 2021). However, in many areas, farmer-led innovations in salinity control have emerged as a crucial component of adaptive tactics. Using salt-tolerant crop varieties, better irrigation techniques, and soil amendments like gypsum or organic matter are just a few examples of the low-cost, successful methods that local farmers have developed to manage salinity. Case studies from saline regions worldwide, such as the Indus Valley in Pakistan and coastal regions of Australia, demonstrate this. These developments offer important insights for policy frameworks that promote sustainable agriculture in saline areas and lessen salt's adverse effects on wheat production. Long-term resilience in these regions depends on policies that support soil and water management financially, invest in farmer education and training, and promote research into saline-tolerant crop growth. Furthermore, as climate change, significantly rising temperatures, and sea levels can worsen soil salinization, salinity management and climate resilience are intimately related. Agroforestry and soil carbon management are two examples of carbon sequestration techniques that may be integrated into salty lands to help reduce climate change and promote the production of climate-resilient wheat. These methods enhance soil structure and water retention in addition to aiding in carbon sequestration, which benefits long-term agricultural production in salty areas (Nair *et al.*, 2015).

Future Roadmap and Research Horizons

In order to improve crop resilience and sustainable farming methods, the future roadmap for combating salinity stress in agriculture is set to use artificial intelligence, quantum technologies, and holistic environmental strategies (Zhang *et al.*, 2024). Utilizing quantum mechanics, quantum sensing, and quantum agriculture are ground-breaking innovations that increase the accuracy of crop salinity stress detection. Researchers may identify early metabolic changes in plants exposed to salt conditions using quantum dots, entanglement-based sensors, and nanoscale imaging. This enables real-time monitoring and action. By providing very sensitive detection techniques that surpass conventional soil and plant analysis methods, these technologies have the potential to improve precision agriculture significantly. At the same time, artificial intelligence (AI)-driven prediction models for managing salinity in wheat crops are being created to detect stress situations, optimize irrigation schedules, and suggest adaptive tactics catered to particular genotypes and environmental circumstances. With previously unheard-of accuracy, machine learning algorithms can forecast production losses and recommend mitigation techniques after training on enormous datasets, including soil characteristics, meteorological variables, and genetic elements. By integrating AI-powered precision farming technologies, farmers can make data-driven decisions that maximize resource utilization while preserving production (Titirmare *et al.*, 2024). Long-term agricultural viability, however, depends on an integrated response to salinity and drought stress in a changing climate; therefore, treating salinity stress cannot be seen in a vacuum. A combined approach that combines soil microbiome optimization, water-efficient irrigation systems, genetic engineering for stress-tolerant crops, and climate-responsive policies is required to ensure food security in light of the growing frequency of extreme weather events and rising global temperatures. In order to create next-generation strategies for reducing drought stress and salinity in the face of changing climatic patterns, future research should concentrate on multidisciplinary partnerships that span agronomy, biotechnology, quantum physics, and artificial intelligence. The agricultural industry may transition to a more robust and adaptable future by utilizing these cutting-edge technologies and integrated frameworks, guaranteeing that food production worldwide continues to be sustainable in the face of environmental uncertainty (Louta *et al.*, 2024).

CONCLUSION

A new rethinking of wheat farming is required in light of the rising problem of soil salinization, combining scientific discoveries with practical agricultural methods. Maintaining global wheat production depends on closing the gap between basic research and field applications as climate change worsens and arable land disappears owing to increasing soil salinity. Precision farming, microbial-assisted soil amendments, and plant genetics advancements offer encouraging avenues for creating salt-tolerant wheat cultivars and enhancing soil health. These technologies must be successfully transferred from controlled laboratory settings to various agricultural environments to ensure their sustainability, scalability, and economic viability for farmers globally. A comprehensive strategy incorporating agronomic techniques, policy interventions, and farmer education is necessary to adopt salinity-resilient wheat farming effectively. In order to speed up information sharing, pool resources, and create flexible frameworks that address region-specific salinity issues, a worldwide cooperative effort is also necessary. Governments, academic institutions, and agricultural stakeholders must collaborate to encourage sustainable solutions, create climate-resilient crop policies, and assist farmers in implementing cutting-edge practices. In a period of increasing environmental stress, the agricultural sector can protect food security, minimize the negative impacts of soil salinization, and guarantee the long-term sustainability of wheat production by promoting multidisciplinary research and cross-border collaboration.

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