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Response, Adaptation and Mechanism of Wheat Plants to Salinity Stress

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Abstract. Soil salinity has emerged as a major constraint to global food production, with its severity continuously escalating due to anthropogenic activities such as excessive irrigation, land degradation, and climate change. Wheat (*Triticum aestivum L.*), a staple crop and primary source of carbohydrates and energy for much of the global population, is particularly sensitive to salinity stress. High salt concentrations adversely affect the plant's physiological and biochemical processes, including inhibited seed germination, stunted vegetative growth, disrupted reproductive development, reduced enzymatic activity, and impaired photosynthesis. Salinity stress also causes hormonal imbalances, induces oxidative stress through the accumulation of reactive oxygen species (ROS), and ultimately leads to significant yield losses. A comprehensive understanding of wheat's responses to salinity stress is essential for developing effective mitigation strategies. Efforts to enhance salinity tolerance have included the selection of tolerant genotypes, conventional breeding programs, and molecular approaches such as genetic engineering. While promising, these methods are often time-consuming, costly, and labor-intensive. As a complementary solution, agronomic management practices have gained attention for their practical application in improving wheat performance under saline conditions. Techniques such as the use of arbuscular mycorrhizal fungi, plant growth-promoting rhizobacteria (PGPR), exogenous phytohormone application, seed priming, and proper nutrient management have shown effectiveness in enhancing plant resilience and productivity in saline soils. This paper reviews the physiological impacts of salinity on wheat, explores potential adaptive mechanisms, and discusses practical management strategies aimed at improving wheat performance under salt stress conditions.

Keywords: Abiotic Stress, Plant Physiology, Salinity Stress, Salt Tolerance, Wheat

1 Introduction

Wheat (*Triticum aestivum L.*) stands as one of the most vital cereal crops globally, serving as a major staple and primary protein source for humans. Besides its high carbohydrate content, wheat is rich in essential nutrients such as B and E vitamins, magnesium, phosphorus, dietary fiber, and other bioactive compounds beneficial to human health (Ma et al., 2016). Globally, wheat ranks first among cereal crops in terms of grain production and is a dietary staple for over 36% of the world's population, contributing approximately 20% of total caloric intake and 55% of carbohydrate consumption. Furthermore, wheat plays a crucial role in providing both micronutrients and macronutrients necessary for human well-being.

Salinity is an increasingly significant abiotic stress that threatens agricultural productivity worldwide. More than 20% of arable land is affected by salt, with the impacted area expanding due to human activities and climate change (Arora, 2019). Abiotic stresses are responsible for nearly 50% of crop yield losses (Acquaah, 2007). In the context of a rapidly growing global population, food production must rise by 70% by 2050 to ensure food security (FAO, 2009). Wheat, rice, and maize are the world's major staples, yet wheat holds the top position in terms of global cultivation and consumption (Iqbal et al., 2021), dominating approximately 38.8% of fertile agricultural land and offering a higher grain protein content (12–15%) than other cereals (FAO, 2016). However, productivity remains vulnerable to climate-induced stresses, with models projecting up to a 6% decline in wheat yields under stressful environmental conditions (Asseng et al., 2015).

Salinity stress significantly impacts wheat productivity, with yield losses beginning at salinity levels of 6–8 dS m^{-1}. The FAO reports that 397 million hectares of wheat farmland are severely affected by salinity, posing a

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substantial threat to global food security. Salt stress disrupts critical physiological processes in plants, primarily through ionic toxicity and nutrient imbalances. These disruptions lead to reduced seed germination, stunted growth, altered reproductive development, and significant yield reduction (Royo and Abió, 2003). Additionally, salt stress impairs enzymatic activities, photosynthesis, membrane stability, hormonal regulation, water uptake, and nutrient absorption, while also triggering oxidative stress.

Initially, salinity imposes osmotic stress, reducing the plant's ability to absorb water from the soil and accelerating leaf water loss. Over time, ionic stress follows as toxic ions like Na^+ and Cl^- accumulate in plant tissues, further impairing growth and cellular function. This dual-phase stress response—osmotic followed by ionic—adversely affects membrane integrity, nutrient balance, reactive oxygen species (ROS) detoxification, antioxidant enzyme activity, photosynthesis, and stomatal conductance. As such, salinity is often categorized as both hyperosmotic and hyperionic stress.

The high concentration of salts surrounding plant roots restricts water extraction, leading to water stress, while elevated salt levels within cells induce ionic toxicity (Munns and Tester, 2008). Na^+ and Cl^- accumulation in plant tissues exposed to high soil NaCl concentrations severely disrupt ionic equilibrium. Excessive Na^+ interferes with K^+ uptake, a vital element for plant growth and metabolism, potentially leading to reduced productivity or plant death (Arif et al., 2020). Salinity stress can thus impair the uptake and translocation of essential nutrients, altering cellular homeostasis and metabolic pathways critical for plant survival.

As a response to salinity stress, plants increase ROS production, including singlet oxygen, superoxide radicals, hydroxyl radicals, and hydrogen peroxide. These ROS can cause oxidative damage to key cellular components such as proteins, lipids, and DNA, disrupting vital cellular processes. Overall, the complex physiological and biochemical disruptions caused by salinity highlight the urgent need for integrated strategies to enhance wheat tolerance to salt stress and maintain global food security under changing environmental conditions.

Ear filling is a critical phase in corn plant growth that is very sensitive to water availability. Several studies have shown that drought stress during the grain filling phase significantly reduces the weight of 100 seeds and yield per ear. Research by Alam et al. (2021) showed that corn plants that experienced drought during the ear filling phase experienced a decrease in yield of up to 30–50% compared to plants that received optimal rainfall. Meanwhile, research by Sari and Widodo (2022) also stated that uneven distribution of rainfall can cause physiological disorders in plants, such as decreased photosynthetic activity and impaired seed formation.

On the other hand, excessive rainfall also has a negative impact, especially on land with poor drainage. Intensive rain during the cob filling period causes water saturation in the soil which inhibits root respiration and nutrient absorption, and increases the potential for disease attacks. Rachmawati et al. (2020) reported that corn planted in the rainy season with high intensity experienced decreased seed formation due to root and stem rot.

Given that the ear filling phase determines the quantity and quality of the final maize crop, a thorough understanding of the relationship between rainfall and this phase is essential. This literature review aims to review the results of the last four years of research to understand the impact of rainfall variation on ear filling in maize and its implications for sustainable cultivation strategies.

2 Research Methodology

The writing of this journal employs literature study or by reviewing five international journals as data sources, which examine the impact of salinity stress on wheat plants.

3 Results and Discussion

3.1 The Impact of Salinity Stress on Wheat Seed Germination

Germination is a critical and dynamic phase in the plant life cycle that determines a plant's ability to grow and develop optimally. Physiologically, germination comprises three major phases: the first phase involves imbibition, or the absorption of water by the dry seed; the second phase includes the activation of key enzymes and the initiation of metabolic processes; and the third is the post-germination phase, characterized by the rupture of the endosperm and the elongation of the radicle, followed by the emergence of the seedling's initial shoots (radicle and plumule) (Bewley et al., 2013).

However, this vital process is highly vulnerable to environmental stress, particularly salinity stress. Saline conditions lower the osmotic potential of the germination medium, thereby hindering water uptake by the seed. This, in turn, disrupts enzyme activation required for protein metabolism, impairs the mobilization of food reserves stored in the seed, and ultimately interferes with the overall germination process. These disturbances directly suppress cell division and elongation rates, negatively affecting early seedling vigor and leading to reduced grain yield (Zhu, 2001; Ashraf & Foolad, 2005).

In addition to osmotic stress, various internal and external factors influence the success of seed germination. These include seed dormancy, seed coat hardness, seed viability and vigor, ambient temperature, humidity levels,

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and light intensity. Previous studies have shown that the accumulation of compounds such as mucilage, callose, lignin, and suberin on the seed coat can intensify dormancy by limiting oxygen diffusion and water permeability, thereby delaying or even inhibiting germination (Nonogaki, 2006).

In wheat, a significant reduction in both germination rate and percentage has been reported under high salinity conditions, particularly at salinity levels of 12.5 dS m^{-1} (Ali et al., 2019). The plant's response to salinity is also highly dependent on the wheat variety. For example, the Kharchia 65 variety has demonstrated higher salt tolerance than KRL 1–9, due to its ability to maintain higher chlorophyll content, cell membrane stability, and relative water content (Munns & Tester, 2008). Furthermore, research by Charushahi et al. (2020) reported that under extremely high salinity, germination could be completely inhibited due to limited water imbibition. In contrast, varieties like Al-Hussein exhibit strong salt tolerance during the early growth stages, as indicated by high tolerance indices and greater chlorophyll stability under varying salt concentrations.

3.2 Effects of Salinity Stress on Wheat Growth

Wheat growth, both during the vegetative and reproductive phases, is highly susceptible to the detrimental effects of salinity stress. This abiotic stress significantly impairs the plant's physiological activities, particularly during the early seedling stage. Initial symptoms often include chlorosis (leaf yellowing due to chlorophyll degradation), necrosis (tissue death), and in severe cases, seedling mortality (Munns & Tester, 2008; Shrivastava & Kumar, 2015).

Salinity-induced early senescence limits shoot elongation, reduces leaf expansion, and decreases overall plant height (Parihar et al., 2015). Additionally, it adversely affects several key growth parameters, such as leaf size, number of leaves, leaf area, root colonization, and shoot dry matter accumulation (Kaya et al., 2010; Hussain et al., 2018).

Roots, being the primary organ for water and nutrient uptake, are among the first to be impacted by saline conditions. Salinity interferes with root development, leading to reduced root length, root diameter, root volume, and both fresh and dry root weights (Maas & Hoffman, 1977; Ozturk et al., 2021). It also impairs coleoptile elongation and disrupts seedling establishment.

Otu et al. (2020) observed that increasing salt concentrations in the growth medium caused a marked decline in root and shoot lengths, fresh root weight, and elongation rates. These reductions clearly indicate impaired physiological processes under saline stress. Furthermore, the relative growth rate (RGR) of both roots and leaves significantly decreases under saline conditions when compared to normal environments.

Numerous studies have reported a general reduction in growth parameters—including seedling length, shoot and root length, leaf area, fresh and dry biomass, plant height, and tillering ability—across varying salinity levels (Ashraf et al., 2010; Ahmad et al., 2021). These findings highlight that salinity stress not only restricts physical growth but also negatively affects the overall productivity of wheat.

3.3 The Effects of Salinity Stress on Photosynthesis in Wheat Plants

Salinity stress negatively affects a range of vital physiological processes in plants, including respiration, membrane stability, ion toxicity, and most notably, photosynthesis. The photosynthetic process involves several components, such as Photosystem I (PS-I), Photosystem II (PS-II), the electron transport chain, and the carbon dioxide reduction pathway. Disruption at any stage of these processes can significantly reduce the photosynthetic efficiency of crop plants.

Exposure to salinity leads to a considerable decline in the levels of photosynthetic pigments—particularly chlorophyll a and b—with more pronounced reductions observed in salt-sensitive genotypes than in salt-tolerant ones. This decrease in pigment content may be attributed to the accumulation of toxic ions within chloroplasts and the enhanced activity of chlorophyllase, an enzyme that degrades chlorophyll. During the vegetative stage, salt stress also impairs carbohydrate synthesis and its subsequent translocation to the grains during the grain-filling phase (Munns & Tester, 2008).

Sodium chloride (NaCl) treatments reduce stomatal conductance, limiting CO_2 uptake necessary for carboxylation reactions and the activity of the enzyme ribulose-1,5-bisphosphate carboxylase/oxygenase (RUBISCO), ultimately lowering the photosynthetic efficiency. Kafi (2009) observed that the photosynthetic responses of wheat genotypes varied depending on the growth stage, salt concentration, and duration of exposure. Reduced stomatal conductance and a decline in the variable to maximum fluorescence ratio (Fv/Fm) have been identified as primary limiting factors affecting photosynthesis under salinity stress.

Toxic levels of Na^+ and Cl^- ions in the leaves also disrupt chlorophyll structure and PS-II functionality, further inhibiting the rate of photosynthesis. Moreover, reduced stomatal conductance negatively impacts the efficiency of the electron transport chain, leading to decreased production of ATP (adenosine triphosphate) and NADPH

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(nicotinamide adenine dinucleotide phosphate), which are essential for the Calvin cycle. As a result, the quantum yield of PS-II declines significantly, especially in salt-sensitive genotypes (Zhu, 2001).

All physiological and biochemical processes in plants are highly dependent on water availability. High salt concentrations induce both osmotic and ionic stress, which decrease the plant's water potential and impede water uptake by the roots. This leads to a reduction in the plant's relative water content (RWC). For example, after six days of salt exposure, RWC dropped by 3.5% in salt-tolerant wheat genotypes and by as much as 6.7% in sensitive ones, resulting in a significant decline in water use efficiency (Ashraf & Foolad, 2005).

Generally, water stress during the flowering stage and post-anthesis period has a profound impact on wheat productivity. The salt-sensitive wheat variety HD 2687 exhibited greater reductions in chlorophyll content, membrane stability, and RWC under stress conditions compared to the salt-tolerant variety Kharchia 65, which naturally possesses better adaptability to saline environments.

3.4 The Effects of Salinity Stress on Photosynthesis in Wheat Plants

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The plant’s response to salinity varies depending on genotype and seasonal growth habit. Studies have shown that winter wheat cultivars tend to accumulate higher Na^+ concentrations compared to spring wheat types, reflecting physiological and genetic differences in ion exclusion capabilities (Ashraf & Harris, 2004). Salt-tolerant genotypes generally possess more effective mechanisms to retain higher potassium levels and favorable K^+/Na^+ ratios in leaf tissues. These mechanisms include Na^+ exclusion at the root level, sequestration of toxic ions into vacuoles, and maintenance of ion homeostasis at the cellular level (Zhu, 2003).

The ability to sustain nutrient balance under salinity stress is a key indicator in selecting wheat varieties with salt tolerance. Therefore, a comprehensive understanding of mineral uptake dynamics under saline conditions is vital for improving crop performance on salt-affected soils

3.5 Grain Yield

Grain yield in wheat is influenced by several agronomic and physiological traits, including tiller number, spike length and size, grain number and weight, root and shoot growth, chlorophyll content, membrane stability, and stomatal conductance. Any reduction in these traits due to salt stress can directly affect the final grain yield. The extent of yield reduction depends largely on the salinity level and the tolerance capacity of the wheat genotype (Hussain et al., 2017).

A study involving 40 wheat genotypes under salt stress reported significant variability in their responses. Salt-sensitive genotypes showed greater yield losses compared to tolerant ones, mainly due to decreased tiller number, spike size, and grain weight (Hussain et al., 2017).

Salt stress has been shown to reduce the thousand-kernel weight by up to 20% and starch content by 6% compared to control conditions. Exposure to high salinity levels (10 dS m^{-1}) significantly decreased spike length by 24%, number of spikelets by 21%, thousand-kernel weight by 70%, straw yield by 20%, and total grain yield by 67% (Ashraf & Foolad, 2005; Munns & Tester, 2008).

Numerous previous studies have also reported a marked decline in wheat grain yield with increasing salinity levels. This reduction is largely attributed to lower germination percentages and negative effects on leaf anatomy, particularly the number and size of medium and small veins that are critical for photosynthate transport (Zhu, 2001; Ali et al., 2019).

4 Conclusion

Wheat plants exhibit a range of morphological, physiological, and molecular responses when exposed to salinity stress. Among these, physiological and molecular mechanisms play a crucial role, as they provide a foundation for breeders to develop salt-tolerant wheat varieties. While considerable progress has been made in understanding how wheat copes with salinity, several areas still require deeper investigation. One of these is the physiological basis of assimilate partitioning—from source tissues like leaves to sink organs—under saline conditions. Another key area that remains underexplored is the root's response to salt stress, particularly how root–shoot signaling operates and how it affects nutrient and water uptake. In this context, genetic manipulation of salt tolerance traits offers a promising strategy to enhance wheat’s resilience in saline environments.

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