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Exploring the Resilience of Wheat to Salinity

Understanding Mechanisms and Sources of Salt Tolerance

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Abstract

A soil is considered saline, when the electrical conductivity of the saturated paste extract exceeds 4 dS m^{-1}, (equivalent to about 40mM NaCl). According to the Food and Agriculture Organization (FAO, 2018), salt affected 45 million hectares (Mha^{-1}) of irrigated land (19.5%), and 32 million hectares (2.1%) of dry land agriculture. Several wheat genetic stocks have been developed over the last few decades that exhibit all three types of tolerance mechanisms, namely tissue tolerance, osmotic tolerance, and ion (Na+) exclusion. We now have, new and improved genotyping assays in the form of SNP arrays and next-generation sequencing to facilitate gene discovery, new generation turn-over methods to get five to six generations per year by "speed breeding," facilitating gene deployment, gene-editing tools to precisely manipulate the effects of causal genes, and new phenomic platforms for capturing salinity effects in field. All of these technologies working together will aid in understanding the complex genetic architecture of wheat adaptability in saline soils.

Keywords: *Wheat, Saline, Soil, Tolerance, Agriculture*.

1. Introduction

In the realm of agricultural sciences, addressing the challenge of salinity stress on crop plants has become imperative for sustaining global food security. Among staple crops, wheat (*Triticum aestivum*) stands as a primary focus due to its widespread cultivation and significance in human nutrition. The detrimental effects of soil salinity on wheat yield necessitate a comprehensive exploration of the mechanisms and sources underlying salt tolerance in this crucial cereal. This endeavor seeks to unravel the intricate interplay of physiological, biochemical, and molecular processes that empower wheat to withstand salinity stress. By delving into the underlying mechanisms, we aim to decipher the complex adaptive strategies employed by wheat plants to thrive in saline environments. Furthermore, understanding the diverse sources contributing to salt tolerance in wheat will shed light on potential avenues for crop improvement, offering sustainable solutions to enhance resilience in the face of escalating salinity challenges. This exploration into the resilience of wheat to salinity is not only a scientific pursuit but a practical necessity in the pursuit of ensuring food security in the face of evolving environmental conditions. As we embark on this journey, the insights gained have the potential to inform targeted interventions and innovative agricultural practices, fostering a more robust and sustainable future for wheat cultivation in saline-prone regions.

Wheat production plays a pivotal role in global food security and must increase to meet the demands of the growing world population. Soil salinity, coupled with water scarcity and nutrient deficiency, stands as the most significant global constraint to wheat production. Soil salinity arises from the accumulation of soluble salts, primarily sodium chloride (NaCl), in the soil. High salt concentrations create osmotic stress and ion toxicity, disrupting normal plant physiological processes such as water uptake, nutrient absorption, and photosynthesis. Consequently, wheat plants exposed to salt stress experience reduced growth, yield losses, and, in severe cases, complete crop failure. According to the Food and Agriculture Organization (FAO, 2018), salt affects 45 million hectares of irrigated land (19.5%) and 32 million hectares (2.1%) of dry land agriculture. Efforts to enhance salt tolerance in wheat involve a multidisciplinary approach encompassing plant genetics, physiology, and molecular biology. Researchers are diligently working to unravel the intricate mechanisms underlying wheat's response to salt stress, including the identification of key genes and pathways involved in salt tolerance. Genetic modification and breeding strategies are being explored to develop salt-tolerant wheat varieties capable of thriving in saline soils while maintaining optimal growth and yield under challenging conditions.

2. Mechanisms for salt tolerance in plants

Low rates of salt transport to shoots, tolerance of high leaf salt concentrations via efficient sequestration within cell vacuoles, and osmotic adjustments are the three main mechanisms for salt tolerance in plants (Munns *et al.*, 2016).

2.1 Tissue tolerance of high leaf salt concentrations: Plant cell osmotic adjustment is critical for plant growth and survival in salt stress conditions. Tissue tolerance is the ability of cells or tissues to function in the presence of high internal Na^+ or Cl^- concentrations, greater than those known to be toxic to enzymes. The strategy of sequestering Na^+ and Cl^- in vacuoles while keeping cytoplasm concentrations low is the cornerstone of "tissue tolerance".

2.2 Na^+ exclusion: The exclusion of Na^+ from the leaves ensures that Na^+ does not accumulate to toxic levels. In most plants, the main site of Na^+ toxicity is the leaf blade, where Na^+ accumulates after being deposited in the transpiration stream rather than the roots. Plants transpire 50 times more water than they retain in their leaves, so keeping Na^+ out of the xylem sap that supplies water to the leaf blades is critical. The processes determining Na^+ accumulation in the shoot are primarily the processes controlling the net delivery of Na^+ in the root xylem. The net delivery of Na^+ to the xylem has four distinct components: (1) Influx into the root, (2) Efflux back out from the epidermal cells to the soil, (3) Efflux from cells in the stele into the xylem, and (4) Retrieval from the xylem before transpiration stream delivers Na^+ to the leaf blade.

2.3 Osmotic adjustment: The ion-specific phase of plant response to salinity begins when salt accumulates to toxic levels in old leaves, causing them to die prematurely. If the rate at which old leaves die exceeds the rate at which new leaves form, the supply of photosynthetic assimilate will deplete and the plant will no longer be able to grow. The "cost" of this osmotic adjustment is reduced yield in saline soils despite lower leaf Na+ concentration. While the introduction of Nax2 (Na+-excluding gene, TmHKT1; 5-A) into durum wheat increased yield by 25% in saline soil, yield remained lower than in non-saline soil (Negrao *et al.*, 2017).

3. Indicators for salinity tolerance selection:

On the basis of years of comprehensive research a number of indicators have been identified which are as follows:

3.1 Morphological traits:

- Total dry matter accumulation during the early stages of wheat growth has been widely used to distinguish tolerant and sensitive germplasm (Mahmood, 2009).
- The proportion of biomass subjected to salt treatment/control is used to calculate the salt tolerance index, which is used to assess salinity tolerance
- A positive relationship between dry matter and plant height at early seedling stages may be a reliable trait for screening wheat genotypes under salt stress (Ashraf *et al*, 2006).
- Root biomass maintenance and changes in root system architecture are important traits for saline soil growth.

3.2 Germination and early seedling traits:

- Seeds can germinate at very high salinity levels (>300mM NaCl or 30 dSm1), but the developing radicle cannot grow further.
- High salinity inhibits germination and seedling emergence, affecting stand establishment (Ashraf and Foolad, 2005).
- Seedling emergence from the soil may be more important than germination, especially if the soil surface is sodic and hard, because the coleoptile and roots must grow vigorously.

3.3 Cell or tissue damage related traits:

- Injury-based germplasm classification is difficult because it is difficult to pinpoint the source of injury, which could be due to osmotic stress, Na+ or Cl- accumulation in the leaf, or Ca2+ and K+ deficiency.
- Membrane stability is a powerful selection criterion for distinguishing salt tolerant and sensitive genotypes.
- Membrane integrity is compromised by reactive oxygen species (ROS)-induced lipid per oxidation, which results in the formation of malondialdehyde (MDA) when oxidize.
- In general, salt sensitive genotypes are more susceptible to lipid per oxidation in membranes than tolerant ones (Demiral and Turkan, 2005).

3.4 Physiological traits:

- Physiological disturbances caused by salinity include changes in gas exchange (photosynthetic rate, transpiration rate, and stomatal conductance), water relations, and pigment composition changes.
- Because of the osmotic stress caused by the salt around the roots, salinity has a rapid effect on stomatal conductance and plant growth.
- Under salt stress, there is a positive relationship between stomatal conductance and relative growth rate.
- Salinity stress also has an impact on plant water relations: lower soil water potential reduces plant water potential, and unless plants adjust osmotically, turgor may be lost.
- Plants that are subjected to salt stress accumulate high concentrations of inorganic ions or desynthesise low molecular weight organic solutes in order to perform osmotic adjustments (Singh *et al.*, 2010).

3.5 Ionic traits:

- Plants require some Na+ and Cl^- for osmotic adjustment, but excessive amounts can cause mineral toxicity or nutritional imbalance.

- Potassium (K+) is a major inorganic osmoticum of plant cells that is needed for many physiological processes as well as the activation of key enzymes. As a result, rather than Na+ concentration alone, the K+/Na+ ratio is considered very important for genotype selection and has been used as an index of salinity tolerance in bread wheat (Houshmand *et al.*, 2005).

4. Sources of salinity tolerance

4.1 Bread wheat cultivars and landraces:

Among hexaploid wheat landraces, Kharchia-65, HD-2009, Kalyansona, Raj-1114, Raj-821, and Raj-911 were rated as highly salt tolerant accessions 135 in consecutive order. S24 and S36 are two advanced derivatives of Kharchia-65 and bread wheat cultivar LU26S that have exceptionally high salinity tolerance. Jimai32 is a drought and salt tolerant cultivar that was developed in China in 1992 by crossing high yielding accessions Nongda311 and Kefan68. Jimai32 was improved further, resulting in another variety, Cang6001, with high tolerance to salt and drought stress, which was released in 1998, and H6756, which was released in Shandong province in 2004. Furthermore, three Chinese bread wheat varieties (Xumai 30, Yang 10-13, and Yang 11-10) and three Sudanese bread wheat varieties (Argine, Buahin, and Elnilein) were evaluated under varying saline conditions and cv. Elnilein was found to be the most salt tolerant (Ibrahim *et al.*, 2016).

4.2 Salinity tolerance in Aegilops tauschii and synthetic hexaploid wheat:

Many reports on screening A. tauschii accessions revealed significant genetic variation for salt tolerance, with much lower Na+ concentrations and higher K+/Na+ ratios in leaves compared to durum wheat. Synthetic hexaploid wheats could benefit from the diploid A. tasuchii's high salinity tolerance (SHWs) (Schachtman *et al.*, 1991).

4.3 Durum wheat and salt tolerance investigations:

Durum wheat (T. turgidum ssp. durum Desf.) is a tetraploid species with A and B genomes but no D genome, which confers many of the baking qualities and abiotic stress tolerance genes to bread wheat. Soil salinity has a greater impact on durum wheat yield than on bread wheat yield. When compared to bread wheat cultivars, durum cultivars are less tolerant of saline and sodic soils. Dry matter should be shot. Salinity has a greater impact on durum wheat production than it does on bread wheat. Supplemental irrigation is required to achieve high yields, and a large portion of the soil in these areas is saline. Agriculture is forced to use low-quality water, exposing soils to progressive salinization. Similarly, overuse of aquifers, particularly in coastal areas, may result in salt or brackish water intrusion, reducing its use for irrigation and domestic consumption (Araus, 2004).

4.4 Transgenic wheat for salinity tolerance:

Advances in molecular biology, cell and tissue culture have resulted in the development of improved transgenic approaches as a second method of developing tolerant wheat cultivars. Unlike traditional breeding, transgenic breeding is faster and allows for the pyramiding of multiple genes into a desired genotype. Furthermore, it is a precise method of gene transfer because it avoids linkage drag, which is commonly associated with the introgression of larger alien chromatin in traditional breeding. The Na+/H+ antiporter gene AtNHX1 (from Arabidopsis), which is thought to be responsible for Na+ sequestration in the vacuole, was genetically engineered into a wheat cultivar and resulted in improved growth, including germination, plant biomass, and yield under salt stress. The use of genetic engineering to manipulate genes encoding enzymes required for the biosynthesis of various osmoprotectants or loci directly involved in detoxification enzymes or sodium exclusion provides a foundation for the development of salt tolerant transgenic crops (Miller *et al.*, 2010).

5. Breeding and genetics for salinity tolerance

Although there are several agronomic and engineering strategies for increasing wheat production in salt-affected areas (such as leaching and drainage), genetic approaches such as breeding more tolerant varieties are a way of ensuring sustainable production in such areas or mitigating the impact of salinity on wheat productivity. However, developing a breeding programme for improved salinity tolerance necessitates (i) optimization of improved and high-throughput screening protocols for the selection and evaluation of salinity tolerance, knowledge of the genetic and physiological basis of salinity tolerance, identification of adequate genetic diversity and reliable selection criteria coupled with most appropriate breeding strategies for introgression of trait(s) into improved genetic backgrounds (Ashraf and Foolad, 2013). There are two main approaches under this mechanism;

a. Molecular markers and QTL linked to salt tolerance in wheat: To improve salinity tolerance in wheat, molecular markers have been widely used for gene mapping and gene introgression via marker-assisted selection (MAS).

b. Deployment of salinity tolerant genes in breeding germplasm: One of the most promising approaches is the transfer of the Kna1 locus via homologous recombination to improve the K+/Na+ ratio and thus the salt tolerance of durum.

Summary

Salinity is a complex abiotic stress that affects both irrigated and rainfed agriculture. Over the last few decades, significant research and breeding efforts have been made to improve salinity tolerance in cultivated wheat, frequently involving investigations to measure and identify single traits and underlying genes as surrogates for salinity tolerance under field conditions. Despite extensive QTL studies in wheat for salinity tolerance, progress toward candidate and functional gene discovery is slow, and our knowledge is limited to a few functional genes. The aforementioned technological advancements in all genetics and breeding disciplines are likely to influence the pace of future salinity tolerance research and, as a result, the availability of improved higher yielding salinity tolerant wheat cultivars for farmers. The primary sources of salinity tolerance in rare variants (such as highly tolerant landraces and Triticeae species) are critical targets for discovering and deploying genes that provide yield advantages in saline conditions. We believe that breeding/selection strategies similar to those used for drought tolerance targets, where advancing filial generations are alternated between irrigated and drought regimes should be used to improve recovery of salinity tolerant derivatives. Because salinity tolerance is a complex and polygenic trait, we recommend that genetic resources be used wisely, with a focus on whole plant response, particularly improved yield performance under field-based screening. Breeding wheat solely for improved salinity tolerance at the expense of significant yield loss in non-saline soils is no longer a viable option for farmers. As a result, when breeding wheat for stress conditions in the future, breeders must develop cultivars with high yield potential under both stress and non-stress conditions. The potential benefits of combining advances in rapid generation, such as doubled haploid, with increasing knowledge of tools to manipulate chromosome pairing and recombination, as well as advances in gene editing, merit consideration.

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