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Abiotic stress responses in wheat: Conventional, molecular, and biotechnological approaches

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Abstract

Global warming is gradually affecting the environmental factors involved in the growth of crops, with wheat, one of the world's most important commercial cereals, among those adversely affected by the changing environmental conditions. Increased climate change has resulted in increased abiotic stress factors like heat, drought, water stress, soil salinity, and pre-harvest sprouting, which have made wheat production highly stressful. Breeding wheat cultivars resilient to these complex stresses has emerged as a significant challenge facing the global scientific community. Although conventional breeding techniques lay the foundation for all plant improvement practices, they alone have been found to be inadequate in meeting the ever-growing production needs, necessitating the search for new ways and means of overcoming such stress. A lot of advancement has already been made using the combined knowledge of the disciplines of plant physiology, genetics, and breeding. Identification of the key traits involved in phenotyping, along with the genes responsible for stress resilience, is crucial in mitigating stress. It has been established time and again through research that the tolerance to stress in plants is a quantitative, multigenic characteristic, and unravelling the gene network regulation behind it is imperative for its specific manipulation. Genetic manipulation through molecular and genetic approaches is the way ahead for enhancing the performance of plants in stress conditions.

Keywords: Abiotic stresses, morphological, physiological, tolerance, management, strategies

Introduction

Triticum aestivum L. Thell, popularly known as wheat, stands as the second most critical food staple in India and one of the most widely cultivated cereal crops on a global scale, being highly significant in the global production and trading of cereals ^[1]. Recent studies show that wheat production globally in the year 2023 was around 785.1 million tons cultivated on around 220 million hectares of land globally ^[2]. The country of India holds the record as the world's second highest producer of wheat, producing around 109.52 million tons annually - around 13% of global production ^[3]. While the cultivation of wheat across the globe has increased significantly in terms of area, total production, and yield over the last four decades, the national wheat improvement program in India faces various problems in this duration ^[4]. Fulfilling the food needs of a predicted population of around 9.8 billion people by 2050 would mean producing 198 million tons of wheat every year ^[5]. These goals face challenges due to various biotic stresses that affect the production of wheat on a global scale ^[6].

The production of global wheat has experienced a steady decline due to the impact of both abiotic and biotic stresses ^[7]. Abiotic stresses such as temperature, water, salinity, and heavy metals caused by climate change affect the growth of wheat, lower its yields, and negatively impact the quality of the produce ^[8]. The biotic stress agents, which include fungal and viral diseases that affect plants, make matters even worse through wheat infections ^[7]. These forms of stress are significant threats to not only agriculture but also the environment, as they cause massive loss of wheat yield and decreased photosynthesis ability ^[9].

Of all the abiotic stresses, water stress emerges as the dominant reason for limiting the yield potential of wheat ^[10]. Erratic rainfall distribution in India has been shown to cause losses from lodging in wheat crops in the range of 12% to 66% ^[11]. Water stress in wheat occurs mainly in two types: drought stress and waterlogging stress ^[10, 29]. Out of the two types, drought stress

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exerts higher effects on yield than waterlogging stress and occurs almost anytime throughout the growing period ^[10]. Drought during the heading period affects wheat yield negatively, but the highest yield losses are observed during the reproductive phase ^[12]. In early-growth stages, drought stress at the seedling stage limits seedling emergence and tillering, whereas late-stage drought stress that takes place after flowering until physiological maturity enhances tissue oxidative damage ^[13]. These physiological stress events adversely impact wheat yield by inhibiting photosynthesis and limiting pollen fertility ^[12].

The yield loss due to water stress in various wheat cultivars in Central India varies from 11.6% to 43.6% ^[10].

Water logging occurs when water saturates the soil and stands stagnant for extended periods, or when there is an accumulation of soil moisture above FC more than 20% ^[14]. Such an excess soil moisture level causes a decline in the productivity of cultivated crops across over 4.5 million hectares of irrigated lands in the Indo-Gangetic Plains ^[11]. Sodic soils that possess high water tables are vulnerable to water logging, a phenomenon that is becoming more prevalent because of the rising incidences of storms and excessive precipitation as a result of global warming ^[14]. Wheat needs temperatures ranging from 14-15 °C to enable proper development of grains before harvesting ^[15]. Temperatures higher than 25 °C lead to a reduction in grain weight, whereas temperatures above 35-40 °C are detrimental to grain fill process ^[15]. Yield loss can also be observed due to variations in diurnal temperature levels resulting from climatic changes ^[8]. Temperatures exceeding critical threshold levels affect yield parameters such as number of grains per spike, grain initiation, and grain filling process ^[16].

Soil salinity is yet another important abiotic stress that has been shown to have significant negative effects on yield and the quality of wheat grains ^[17]. The impact of soil salinity on wheat yield is characterized by the reduction in the values of some of the important factors affecting yield like grain weight, spike length, spikelet number, and overall yield of the grains ^[18]. It is estimated that around 6% of the earth's surface, which translates to roughly 800 million hectares of land, are subjected to soil salinity, thus making it difficult to maintain wheat yield across the globe ^[17]. In India, about 6.73 million hectares of land suffer from the problem of soil salinity, with 2.96 million hectares of saline soils and 3.77 million hectares of sodic soils ^[11]. Simultaneously, the increasing usage of organic fertilizers that might contain heavy metals as contaminants has led to the emergence of another objective of this paper is to evaluate the main abiotic stresses that affect wheat yield in view of changing climatic conditions around the globe, and to review different strategies that could be used to enhance productivity ^[6, 7, 9] in view of changing climatic conditions around the globe.

Impact of abiotic stresses on wheat

Climate change and global warming have put tremendous pressure on the agricultural lands of tropic and sub-tropic regions, leading to a gradual decrease in crop production in the past few decades ^[6]. Some common abiotic stresses that threaten agricultural systems include heat, drought, imbalanced moisture levels, contamination from heavy metals, and soil salinity ^[7]. All these stresses interfere with the gene regulation network and metabolic activities, reducing the global crop production process significantly, especially in staple crops like rice and wheat ^[9]. The impact of abiotic stresses on agricultural crop production worldwide is such that it is estimated to cause more than half of the crop yield losses ^[20]. To meet the food demand of an

expected world population of almost 10 billion people in 2050, it will be necessary to increase food production by approximately 70% ^[5, 6]. Food production will become increasingly difficult in every nation, including the top wheat-producing countries of China, the United States of America, Australia, Russia, and Pakistan, where wheat is experiencing yield limitations due to abiotic stresses ^[1, 4]. Figure 1 presents the main abiotic stresses experienced in wheat.

High Temperature / Heat stress

Heat stress is one of the several physiological phases that are especially sensitive in different stages of wheat growth ^[21, 22]. Heat stress is considered as an extended condition in which the air temperature increases beyond a critical point resulting in severe damage and loss in growth and development of crops, thus restricting world wheat production ^[22]. Studies have shown that for every 1 °C increase in air temperature, wheat yields decline from about 4.1% to 6% ^[23, 24]. By 2050, it is estimated that wheat production will decline significantly by 50% in South Asia due to changes in rainfall distribution and higher temperatures caused by climate uncertainties ^[16]. On the world level, for every 1°C increase in temperature, the crop yield declines by about 7.4% ^[24]. For India and Russia, it causes a decrease in wheat yields by 9.1% and 7.8%, respectively ^[16, 23]. Heat stress occurring in 2021-2022 in India during the period of wheat grain filling results in a 3.0% decline in yield.

Heat stress, at a cellular level, causes irreversible damage to the thylakoid membrane, causing a breakdown in chlorophyll pigments and disrupting the functionality of PSII in wheat plants ^[26]. Furthermore, the reproductive capacity of the plant is affected, as pollen sterility, CO₂ fixation, and photorespiration levels are increased due to heat stress ^[27]. The growth and production capability of the wheat plants are adversely affected due to the negative impact of heat stress on the process of photosynthesis ^[22, 26]. Apart from photosynthesis, there are numerous ways by which heat stress impacts the agricultural productivity of wheat crops. For instance, heat stress may cause germination failure, low seedling growth rate, early leaf senescence, pollen sterility, and ultimately lead to decreased tiller number, lower panicle grain number, small grain size, and reduced total productivity ^[21, 27]. Chloroplast structure damage, chlorophyll content reduction, and enzyme inhibition are some additional repercussions of heat stress ^[26]. Globally, an estimated 36 million hectares (40% of temperate wheat habitats) face terminal heat stress, whereas another 7 million hectares suffer from sustained heat stress with a minimum daily temperature greater than 17.5 °C throughout the coldest period of the crop year ^[28].

Drought stress: Drought refers to the situation whereby there is a deficit in the availability of water compared to the requirements for evaporation and transpiration, thus making drought one of the major abiotic stresses restricting world-wide crop production ^[29]. Drought is considered as the main restriction to crop production in the rainfed agricultural systems. Drought imposes a major constraint to wheat production ^[10, 29]. Previous studies have revealed that drought may cause an estimated 9-10% loss of wheat yield on average, with some extreme drought instances resulting in up to 21% loss in yield ^[12, 30]. In case of severe osmotic stress due to drought, up to 90% of the yield could be lost depending on the genotype, developmental stages of the plant, and the period of water stress ^[31]. The amount of yield reduction is determined by the growth stage where stress happens; each growth stage is uniquely

vulnerable^[13]. Drought stress causes photosynthetic inhibition, thus reducing grain yields up to 45%^[32]. Drought yield reductions have been mainly associated with morphological, physiological, and biochemical processes of plants^[30, 33]. The quality of grains is affected when drought stress is experienced during flowering and grain filling^[12, 30].

Drought negatively affects tiller development, root size, dry mass content of roots and shoots, and total grain yield in wheat^[33]. Drought leads to decreased photosynthetic capacity through reductions in leaf area index and assimilation rates^[32, 35]. Drought reduces the grain number per ear by affecting critical physiological processes such as leaf photosynthesis, translocation of carbohydrates to ears, pollen fertility, and seed setting^[34]. The mechanism behind decreased grain numbers is due to meristem dysfunction, aborted florets, and male sterility caused by drought stress^[34]. On the leaf surface, drought-stressed plants show a significant decrease in net photosynthetic rate, stomatal conductance, and mesophyll conductance due to stomatal closure and changes in thylakoid structure^[35].

Salinity stress: Soil salinity represents a significant abiotic factor limiting wheat cultivation^[17, 18]. At present, more than 20% of the world's soils exhibit the salinization effect, and this figure keeps growing due to the negative impact of climate change and unsustainable agricultural activity^[36, 43]. Along with other factors, salinity is considered to be responsible for more than 50% of crop production losses^[20]. Every year, about 1.5 million hectares of lands become infertile as a result of salt content in soils, with predictions indicating that the amount could increase up to 50% of all arable lands until 2050^[37]. Salt-affected farmlands are predominantly located in semi-arid and arid areas, where crops suffer from different intensities of salinity^[38, 45]. Xerothermic conditions, which are represented by high air temperature and low precipitation rates, also enhance damages that plants sustain from salty soils^[38]. Among various field crops, wheat can be considered quite sensitive to salinity and fails to grow normally under increased soil salinity^[17, 45]. The weight of grain, the length of the spike, the number of spikelets, and the grain yield are all adversely affected by salt stress^[18]. Seedling plants have been identified as being particularly susceptible to salt stress, leading to high rates of seedling deaths^[39]. Extreme weather events, such as storms and floods, also pose additional threats to wheat growth in salty environments^[9].

Salt stress results in broad changes within the physiological and biochemical activities of wheat^[40, 42]. Productivity losses caused by salt stress are related to inhibited enzyme function, photosynthesis activity, and the ability for seed germination and seedling emergence^[36, 39]. Suppression of the rate of photosynthesis in conditions of salt stress occurs due to stomata closure and inhibition of electron transport chains during photosynthesis^[41]. Increased concentrations of ions Na⁺ and Cl⁻ in the region of stomata cause stomata closure; consequently, CO₂ intake decreases, and an overproduction of reactive oxygen species takes place leading to cellular dysfunction and death^[41, 42]. Metabolic activity suppression, damage to organellar structure, and changes in metabolites and photosynthetic pigments concentration occur under conditions of salt stress^[42]. Yield losses with economic significance occur when salt concentrations are higher than 6-8 dS m⁻¹, indicating wheat sensitivity to salinity^[36]. According to the FAO estimation, 397 million hectares of wheat-producing lands suffer from severe salinity problems, which become one of the challenges for world food security^[37]. Both ionic toxicity and

nutrient imbalance under conditions of salt stress negatively affect physiological functions and significantly lower yield rate^[43, 44].

Salt stress adaptation in plants is commonly classified into two stages^[44]. In the first stage, a fast response to osmotic stress occurs in reaction to a decrease in soil water potential, thereby restricting water absorption by the roots^[44]. In the second stage, which develops gradually over a period of days or even weeks in response to the severity of the salt concentration in the soil, an accumulation of toxic Na⁺ ions in the plant tissue takes place, leading to low crop yields and eventual plant death^[44]. Salinity initially hinders seed germination and later impairs vegetative growth and reproduction, thus contributing to reduced yield production^[39, 45]. Several physiological processes are affected by salt stress, such as enzyme activity, photosynthesis, cell membrane structure, hormonal balance, water and nutrient uptake, as well as oxidative stress^[42, 46]. Salt tolerance is a complex trait controlled by many genes through gene expression^[45]. Major adaptive strategies for salt stress tolerance include Na⁺ exclusion, maintaining optimal K⁺/Na⁺ ratios, osmoregulation, and antioxidant protection^[46]. Imbalances in ions hinder the absorption and transportation of other mineral nutrients, which adds to the problems of physiology^[43, 44]. In general, salinity is a limiting factor for seed germination, plant growth, reproductive function, and crop production^[40, 43].

Heavy Metal (Metalloids) Toxicity

One of the sources of HMs that have contributed to soil contamination is the application of organic fertilizers in agriculture due to the toxicity of heavy metals in such soils which restrict the growth and productivity of crops^[19, 47]. Some common HMs detected in polluted agricultural lands include Pb, Sn, Cr, As, Zn, Cd, Cu, Hg, and Ni^[47]. Toxicity of HMs present in the edible parts of wheat plants poses serious threats to human health via soil to plant transfer^[48, 50]. Plant root absorption of HMs occurs followed by their transportation into aerial parts via xylem loading using apoplastic and symplastic transport^[49]. HMs accumulation in plants causes growth inhibition through the reduction of chlorophyll synthesis and photosynthesis inhibition^[50, 51]. The growth of wheat plants in HM-polluted soils results in metabolic disorders, growth inhibition, decreased biomass, and increased oxidative stress^[51]. One of the most alarming properties of HMs includes their ability to enter the human food chain and accumulate in body tissues and organs leading to suppressed immunity, lung dysfunction, and organ failure^[47, 48].

Strategies to Mitigate Abiotic Stresses

In order to reduce the risks associated with the abiotic stress factors mentioned above, different techniques have been employed by scientists and plant breeders, including traditional and contemporary methods, which are explained in detail below:

Conventional Breeding: Plant breeding through conventional means involves the systematic utilization of natural genetic variability and reproductive systems for the creation of superior varieties of crops^[52, 53]. This includes the development and management of genetic variability, selection of plants with superior agronomic characters, and the assessment and release of new varieties^[53]. Breeding techniques vary depending on the type of reproductive system of the crop being bred, and in the case of self-pollinated crops like wheat, conventional methods continue to be common practice^[52, 53]. The ultimate objective of such breeding programs is the development of genetically

uniform varieties that have high yields and perform consistently under different conditions ^[52]. Pre-breeding procedures, which entail the transfer of favorable alleles from wild or unadapted relatives into an advanced genetic background, are very important in increasing genetic variability ^[52].

One of the critical aspects in breeding wheat based on the principles of stress resistance entails the inclusion of genotypes or landraces that demonstrate enhanced levels of tolerance to environmental stresses such as drought, extreme temperatures, and soil salinity ^[52]. Potential genotypes can be drawn from germplasm collections with the objective of identifying traits targeted for development ^[52]. These genotypes are then incorporated in breeding efforts using any of the approaches that have been developed to achieve this end ^[53]. One of the common techniques is the use of the pedigree breeding procedure, which entailed the successive crossing of selected plants from previous generations by selfing them until the desired phenotypes become homozygous and fixed ^[53]. The use of modified bulk pedigree procedure presents a modification of the traditional technique by avoiding selective crosses during early generations and allowing greater retention of diversity within the plant population ^[53]. Backcross breeding helps transfer desirable characteristics of plants from the donor parent into elite genetic backgrounds through multiple backcrosses ^[54]. Recurrent Selection involves a process whereby individuals with superior performance in a segregating population are mated together from one generation to another until there is an increase in the frequency of alleles that control polygenic traits like stress tolerance ^[53]. The technique of mutation breeding makes use of physical and chemical mutagens to induce mutations in wheat with the aim of identifying stress-tolerant strains ^[55]. These traditional methods when used independently or in conjunction play a critical role in breeding wheat varieties that have environmental resistance qualities ^[6].

Molecular breeding approaches

Marker Assisted Selection: In relation to molecular breeding and genomics techniques, there have been several advances that have improved the ability of researchers to create plants that are tolerant to various types of abiotic stresses in wheat ^[56, 57]. The marker-assisted selection (MAS) technique is a precise method of plant breeding that involves the use of molecular markers that are associated with particular traits like tolerance to heat, salinity, and drought ^[57]. It is able to speed up the process of breeding by allowing early generation selection of specific allele combinations, while avoiding reliance on extensive field phenotypic evaluation ^[56, 57]. MAS has been extensively used in breeding efforts involving wheat to improve its tolerance to various stresses ^[56]. An example was the use of MAS to transfer a QTL for drought resistance from a synthetic type of wheat into superior breeding germplasm ^[58]. Another example of the usefulness of MAS in wheat breeding was its application to identify heat tolerance QTLs ^[59].

Genomic Selection (GS): Genomic selection (GS) refers to a statistical method where genomics marker information is combined with the phenotypic performance to determine the genetic merit of individual plants ^[60]. GS is useful in the rapid discovery of lines with the potential to withstand environmental stressors without performing extensive phenotypic tests in various environments, hence enhancing the creation of climate-resistant wheat strains ^[60, 61]. GS has been used successfully to predict the yield of wheat in situations with thermal and drought stresses as well as enhance salt tolerance traits in wheat

seedlings ^[61]. Genome editing technologies, especially CRISPR/Cas9, can be effectively employed to achieve precise and accurate gene manipulation within the genomes that regulate the ability to withstand abiotic stresses in wheat ^[62, 63]. Genetic mapping followed by QTL analysis serves as an effective tool for identifying genomic regions with specific genes responsible for abiotic stress resistance ^[59, 64]. The use of high-density genetic maps has significantly increased the accuracy of QTL detection and helped to detect genomic regions linked with heat, salt, and drought tolerance in wheat ^[59, 64]. The identified QTLs can be effectively utilized in MAS breeding pipelines and molecular breeding schemes ^[56, 57]. The combination of genetic mapping, quantitative trait loci (QTL) identification, and marker-assisted selection is a robust approach to creating wheat varieties with resilient resistance to multiple stresses, which would contribute to sustainable food production under changing climatic conditions ^[56, 57]. The incorporation of these methods into the breeding process can facilitate the creation of wheat varieties that have improved resistance to multiple stresses, thus ensuring sustainable food production under changing environmental conditions ^[56, 57].

Biotechnological approaches

Indeed, genetic engineering and transgenic methods have demonstrated their power as breakthrough technologies when it comes to improving the inherent stress response capabilities of the crop in question, mainly by using transgenes encoding transcription factors, ion transporters, and Osmo protectant-producing enzymes ^[65, 72]. Successful efforts made with regard to improving tolerance to heat and drought stress by upregulation of TaDREB3 gene expression, along with successful production of transgenic lines that were salt tolerant thanks to the introduction of NHX1 and HKT1 ion transporter genes into their genome, can be considered as evidence ^[65]. Additionally, metabolic engineering, which involves modification of biosynthesis pathways of compatible solutes like trehalose, glycine betaine, or proline to increase tolerance to both drought and salt stress, proved efficient as well ^[66]. Moreover, increasing antioxidative defense mechanisms, i.e., by overexpression of SOD and APX enzymes, resulted in developing transgenic lines exhibiting improved tolerance to various abiotic stresses ^[67]. Among others, transcription factors belonging to DREB, MYB, WRKY, and NAC families played a significant role as a target for wheat transformation experiments due to their regulatory functions ^[65, 68].

The use of transcriptomics has brought about a significant change in the way in which the molecular responses of wheat to abiotic stresses can be studied ^[68, 69]. RNA sequencing permits global expression analysis of transcripts under stress conditions, making it possible to identify DEGs responsible for stress tolerance in wheat ^[68]. In addition, microarray techniques provide a way of performing accurate quantification of gene expression among a number of stress-responsive transcripts, thus facilitating the identification of promising gene targets for functional analysis ^[69]. RT-qPCR represents the gold standard technique in terms of the confirmation and measurement of expression levels of individual targets obtained through transcriptome screening ^[68, 69].

Research into proteomes has helped add a new dimension in the understanding of the stress response pathways within wheat plants; indeed, such research has provided new findings about the changes in proteins induced by stress that cannot be easily determined by transcriptomic studies ^[70, 71]. One of the key techniques used in this regard has been two-dimensional gel

electrophoresis, which allows for the separation of various proteins in terms of their molecular weight and isoelectric point, providing information on the abundance differences in various proteins under stress conditions [70]. Mass spectrometry technology, and especially LC-MS/MS technology, has revolutionized the field of proteomics by allowing for the detailed analysis of proteins associated with stress response, as well as providing information on post-translational modifications in functional proteins [71]. Metabolomics has helped to diversify the field even more by analyzing changes in the pool of metabolites under stress and integrating with information obtained through other omics sciences [9, 68]. Together, these fields provide information necessary to understand the networks underlying the regulation and metabolism associated with stress response in wheat, which in turn can be used to develop stress-resistant varieties [9, 72].

The total economic effect of abiotic stress on the world's agricultural sector is immense, given the continuous yield losses that pose significant risks to food security and the well-being of farming communities around the globe [20]. For many years now, plant breeding through traditional methods, coupled with proper agronomic practices, has remained a fundamental pillar in enhancing crop stress performance [52, 53]. However, considering the polygenic inheritance of stress tolerance, whereby multiple genes and gene products act in unison to confer a certain level of stress resistance, there exist limitations in terms of what can be accomplished through conventional breeding techniques alone, thus necessitating the incorporation of modern biotechnologies [65, 72]. In this regard, genetic transformation emerges as an innovative technology that allows for the introduction of functional genes from various biological sources into superior wheat lines, and it has been extensively explored for developing stress tolerance in crops [72]. Unfortunately, its widespread application has been thwarted by challenges such as gene silencing, uneven transgene expression, and poor transformation efficiency [72]. The use of plant tissue culture has become an additional and increasingly preferred method, providing an *in vitro* environment for selection and multiplication of stress

tolerant varieties of plants [73]. Minimal physical space and short periods of experimental time are required to implement this technology [73]. Somaclonal variation selection using plant tissue cultures under stress conditions has proven to be one of the most economically sound approaches to selecting stress resistant plant varieties [73].

Future Prospects: Looking to the future, there are expectations that abiotic stresses like drought, high temperatures, and salinity are likely to increase due to climate change, thus affecting the productivity of wheat not only directly but also indirectly due to cascaded effects from other environmental factors [6, 7]. The yield penalties caused by these stress factors vary depending on the stage of growth when they occur, the intensity of the stresses, and their duration [9, 20]. The resistance of each stress tolerance gene may be influenced by the environment in which it operates, highlighting the dynamic nature of the interaction between genes and the environment [8, 45]. This will call for an approach that is integrative and takes into consideration the different aspects of plant physiology, molecular biology, functional genomics, and genetic engineering that would help understand the multigenic pathways controlling stress adaptation [56, 64]. Fortunately, the sequencing of the wheat genome has been completed, creating opportunities for identifying candidate genes and cis-regulatory elements involved in stress adaptation [59, 64]. Pyramiding of multiple QTLs and transgenic traits using marker-assisted breeding techniques can be a viable solution for breeding wheat varieties that can withstand both biotic and abiotic stresses [56, 57]. The knowledge gained about the signaling pathways that operate during stress conditions is critical for the design of new technologies aimed at reducing yield loss in stressful conditions [65, 68]. Foliar applications of growth regulators and hormones or their application to seeds as primers represent a relatively simple and effective method of dealing with stress [66, 67]. Genome editing using CRISPR/Cas technology will play a crucial role in functional gene studies and plant breeding for high yield and stress tolerance in wheat [62, 63].

Table 1: Consequences of Heat stress in Wheat

Trait Category	Specific Consequence
Grain Quality & Yield	Reduced grain weight, smaller size, lower test weight; losses up to 20-30%
Photosynthesis	Inhibition of PSII, chlorophyll loss, and disrupted electron transport
Reproductive Development	Pollen sterility, poor anther dehiscence, and shortened grain-filling
Cell Membrane Integrity	Elevated electrolyte leakage and increased lipid peroxidation
Osmotic Response	Accumulation of ROS and upregulation of Heat Shock Proteins (HSPs)
Water Relations	Reduced root length and decreased leaf relative water content (RWC)

Table 2: Consequences of Drought stress in Wheat

Trait Category	Specific Consequence
Grain Yield & Biomass	Yield reduction up to 50% and decreased above-ground biomass
Root Architecture	Adaptive root elongation; reduced density under prolonged stress
Photosynthesis	Stomatal closure and inhibition of CO_2 assimilation
Osmotic Adjustment	Accumulation of proline, glycine betaine, and soluble sugars
Oxidative Stress	Elevated ROS production and increased malondialdehyde (MDA) levels
Grain Quality	Reduced protein content and altered starch composition

Table 3: Consequences of Salinity stress in Wheat

Trait Category	Specific Consequence
Ion Homeostasis	Excessive Na^+ and Cl^- causing ionic toxicity and nutrient imbalance
Growth & Yield	Stunted growth, reduced tillers, and 20-50% yield losses
Photosynthesis	Reduced chlorophyll content and impaired PSII efficiency
Osmotic Stress	Reduced water potential in soil leading to wilting
Oxidative Damage	Increased lipid peroxidation and induction of antioxidant enzymes
Signaling	Upregulation of SOS pathway and HKT transporters

Table 4: Consequences of Heavy Metal Stress in Wheat

Trait Category	Specific Consequence
Growth Inhibition	Reduced shoot/root length under Cd, Pb, and As exposure
Photosynthesis	Chlorophyll degradation and disruption of the Calvin cycle
Oxidative Stress	Overproduction of ROS and membrane lipid peroxidation
Nutrient Disruption	Competition with essential nutrients (Fe, Zn, Mn) at root sites
Contamination	Accumulation of toxic metals in grain posing food safety risks
Genotoxicity	DNA strand breaks and chromosomal aberrations

Table 5: Conventional Breeding Approaches

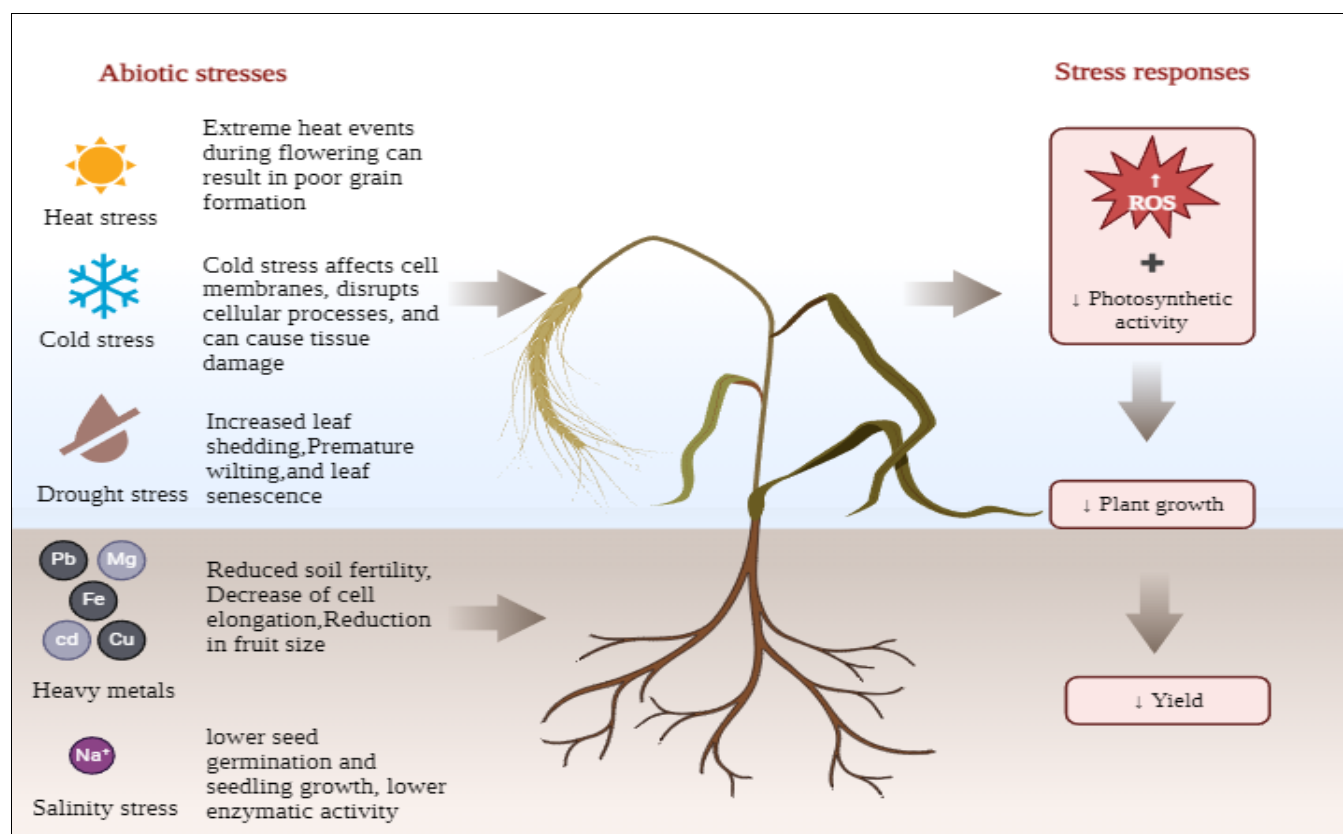
Approach	Description
Phenotypic Selection	Selection based on observable traits (yield, canopy temperature)
Hybridization	Crossing elite cultivars with tolerant landraces
Mutation Breeding	Use of physical or chemical mutagens to generate new alleles
Marker-Assisted Selection	Using molecular markers linked to QTLs to guide selection
DH Technology	Rapid production of homozygous lines via anther culture

Table 6: Molecular Breeding Approaches

Approach	Description
MABC	Tracking introgression of QTLs during backcrossing
GWAS	Mapping diverse panels to identify SNPs linked to traits
Genomic Selection	Predicting breeding values using genome-wide marker data
QTL Mapping	Linkage mapping in bi-parental populations
Transcriptomics	Identifying stress-responsive genes via RNA-seq

Table 7: Biotechnological Breeding Approaches

Approach	Description
CRISPR/Cas9	Targeted editing of susceptibility genes (e.g., knockouts)
Transgenics	Overexpression of stress-responsive genes (DREB, LEA)
RNA Interference	Silencing genes that limit stress tolerance
Speed Breeding	Controlled regimes to complete 4-6 generations per year
Multi-omics	Integration of genomics, proteomics, and metabolomics

**Fig 1:** Various abiotic stress response in wheat

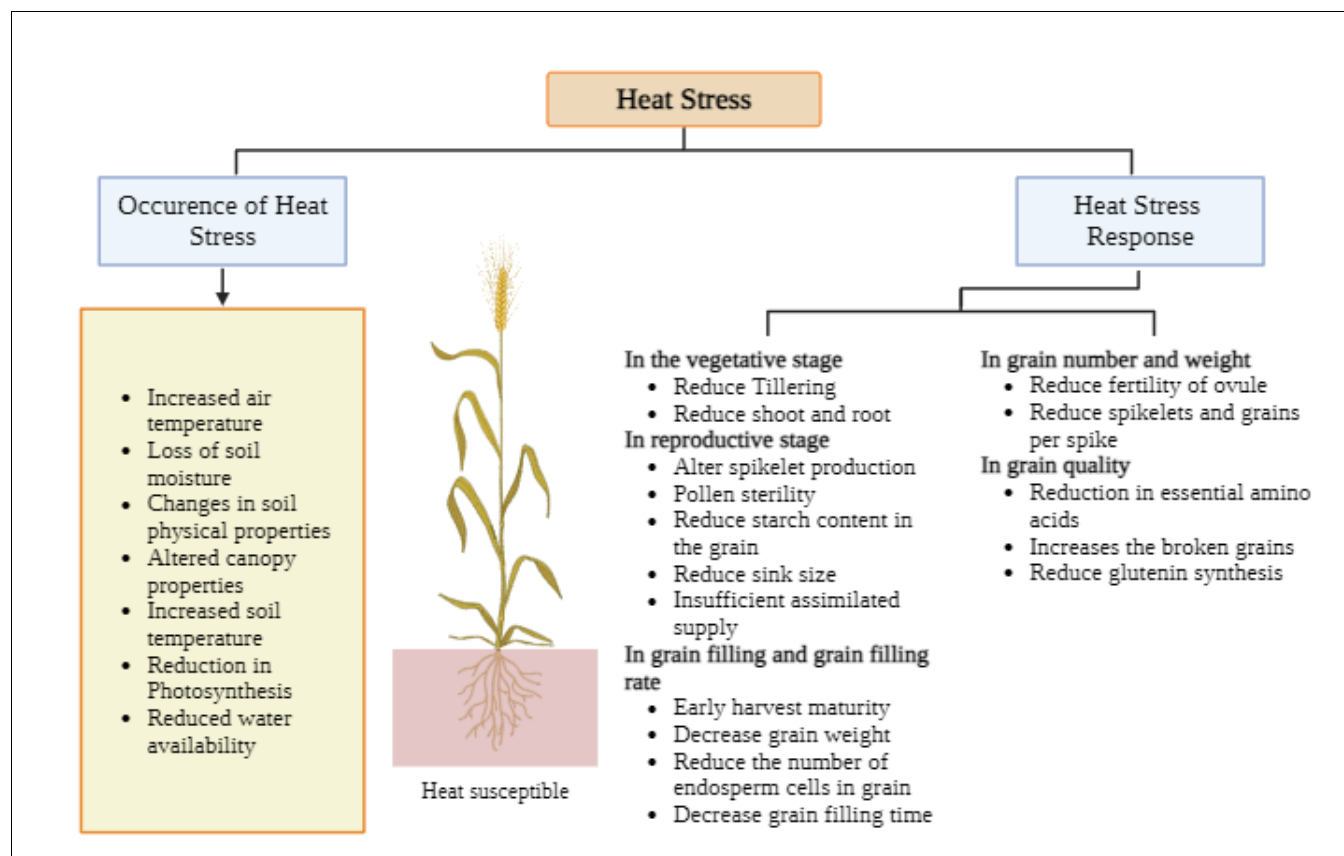


Fig 2: Effect of Heat stress in Wheat

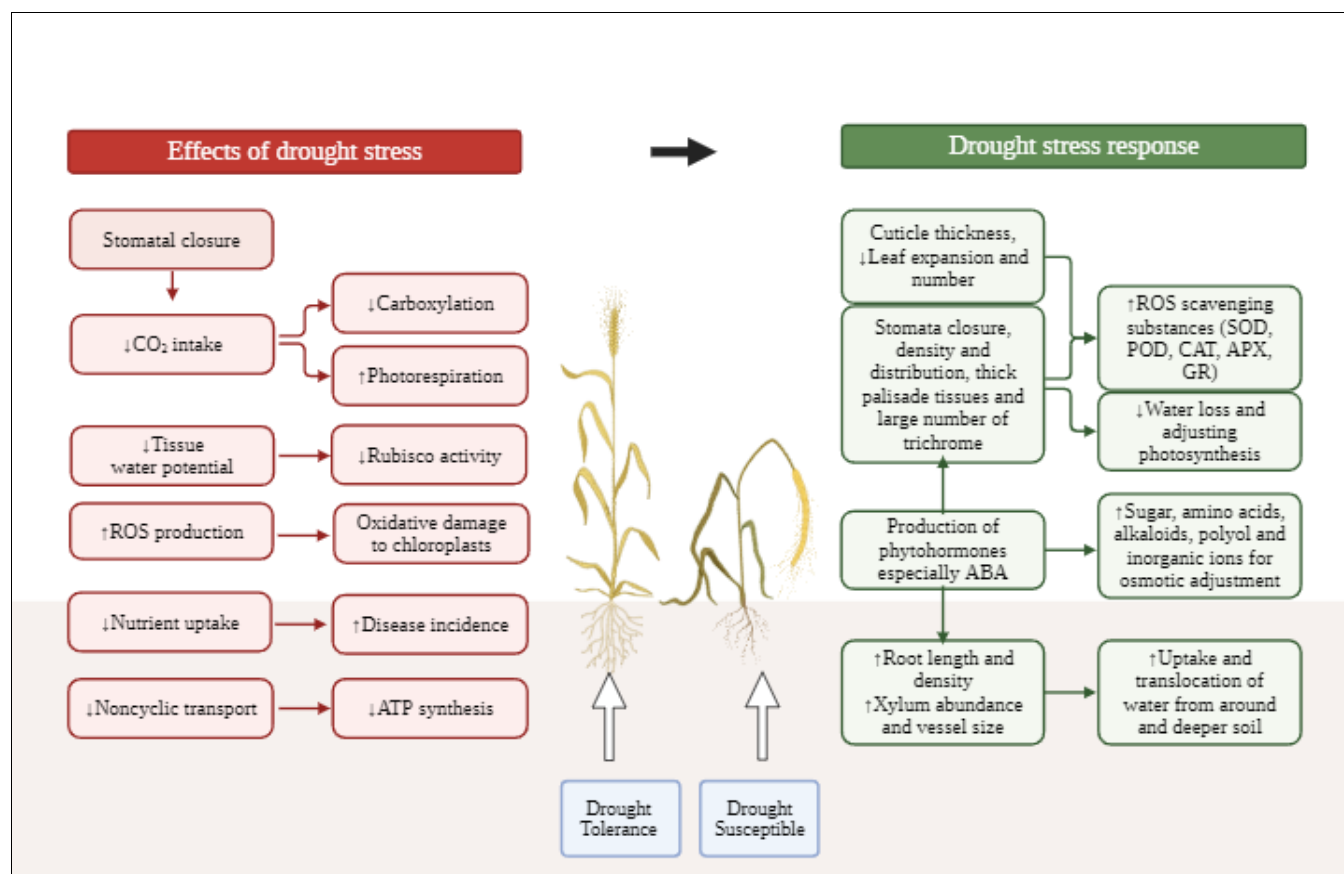


Fig 3: Effect of Drought stress in Wheat

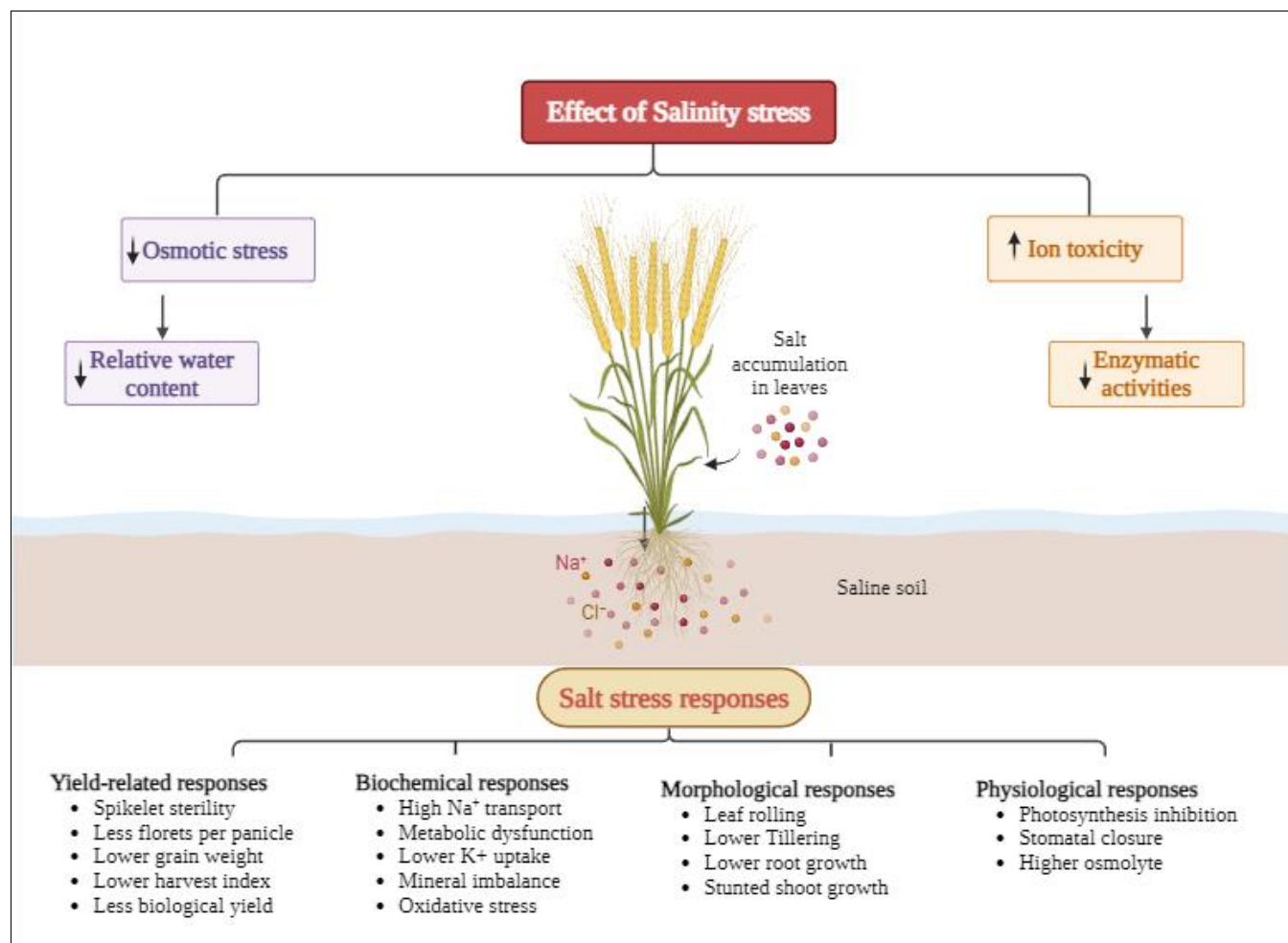


Fig 4: Effect of Salinity stress in Wheat

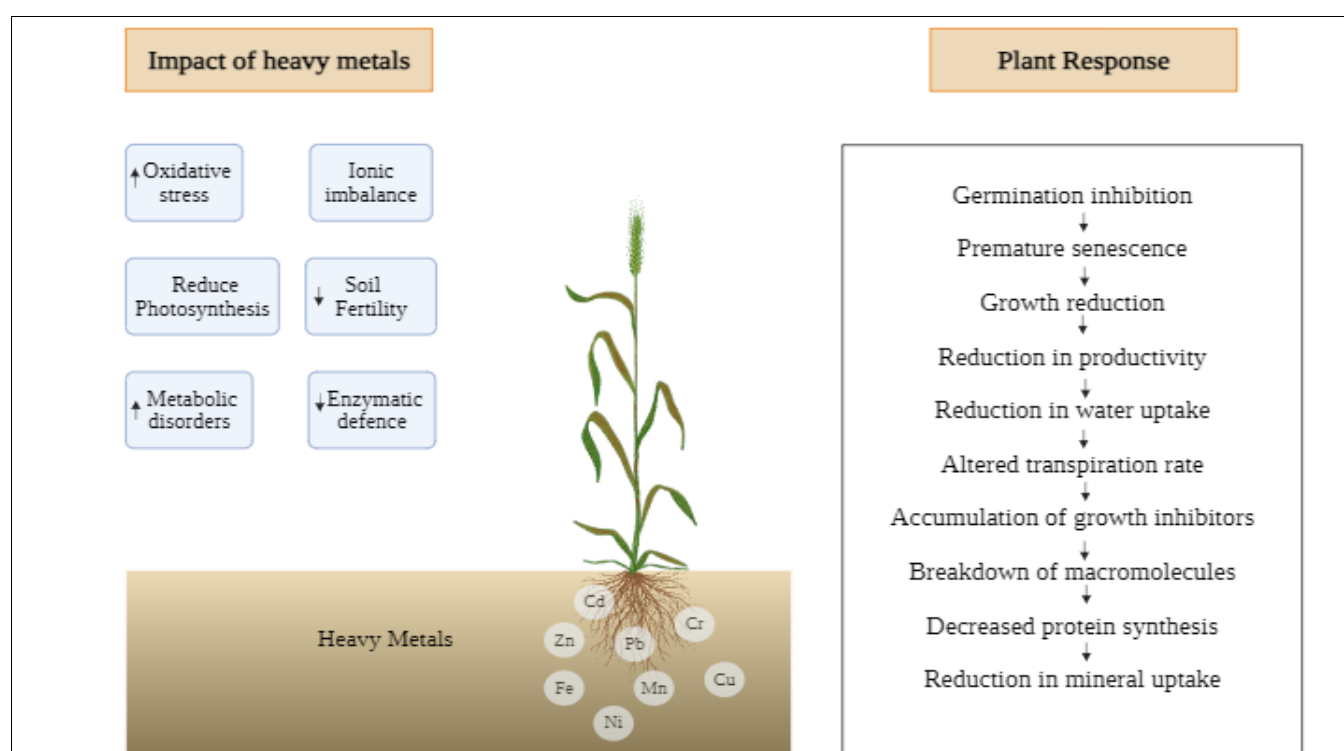


Fig 5: Effect of Heavy metal stress in Wheat

Conclusion

Agricultural productivity is adversely impacted by many biotic factors, but one of the most widespread and costly challenges

faced by the sector today is abiotic stresses. Abiotic stresses pose serious threats to the growth and development of agricultural crops, causing significant reductions in the yield of

crops. Some of the most notable examples of these stresses include drought, soil salinity, temperature extremes, and heavy metal toxicity. Stress injuries can manifest in myriad ways, ranging from minor biochemical alterations to full-blown growth inhibition, dependent on the particular stress factor involved, the severity of the situation, and its persistence. From a mechanistic perspective, abiotic stresses trigger molecular and cellular responses that work against normal plant growth and reproduction. The genetic control of these processes is highly complex, involving elaborate regulatory gene networks, and managing them effectively requires an interdisciplinary approach encompassing genetics, plant physiology, genomics, and biotechnology. Physiologically speaking, stress-injured plants exhibit several typical traits, such as low water content within tissues, increased ROS production, elevated membrane permeability, low chlorophyll content, limited root and shoot extension, and finally, low yields of crops harvested from them. With the development of technologies such as high throughput sequencing, functional genomics, and precise biotechnology, there is an increased capacity to investigate, manipulate, and improve upon these responses to achieve stress-resistant crops appropriate for the challenges posed by climate change.

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