



REVIEW ARTICLE

Morpho-physiological and biochemical adaptation of wheat (*Triticum aestivum* L.) under drought stress: An integrated review

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Abstract

Drought stress is the major factor that causes yield reduction worldwide. Depending on the crop and the intensity of the drought, yield losses of 30–90 % have been reported. Wheat specifically loses 50–60 % of its yield, which may exceed up to 60 % under severe drought. Wheat triggers a wide range of changes under drought stress. Understanding the morphological, physiological and biochemical responses of wheat to drought stress is essential for developing resilient cultivars and improving crop management. This review explores key adaptations that help wheat optimise water uptake and minimise water loss under drought conditions and understanding of how these mechanisms interact as an integrated adaptive network under drought conditions. Morphological changes such as seed germination interference (20–30 %), shoot and root system adjustments have been observed and discussed in detail, followed by physiological responses such as plant-water relation effect of drought on which include reduction in photosynthesis (30–70 %), chlorophyll content (20–40 %) and enhanced osmotic adjustment and hormonal signalling are also investigated. Additionally, biochemical changes such as antioxidant production and Reactive Oxygen Species (ROS) have been explored thoroughly. Collectively, these adaptation responses, constitute a dynamic and extensive network of actions intended for the mitigation of drought-induced damages. By comprehending these mechanisms, we may better understand resilience of wheat and provide the groundwork for creating drought-tolerant cultivars using conventional and novel breeding techniques as well as biotechnological interventions. The aim to underscore the significance of connecting morpho-physiological and biochemical traits to enhance the sustainability of wheat under water-limited environments, highlighting their interconnections relevant for developing resilient cultivars.

Keywords: biochemical mechanisms; climate resilient; drought stress; morphological adaptation; physiological response; wheat

Introduction

Climate change-driven alteration in precipitation patterns and the increasing frequency of drought events pose a significant challenge to global food security, particularly for staple crops such as wheat. Among abiotic stresses, drought is recognised as the most critical factor limiting wheat productivity worldwide, especially in arid and semi-arid regions. Drought, being the most important environmental stress, severely affect plant growth and development, limits plant production and the performance of crop plants alone, than any other environmental factor (1). Therefore, beyond its determinantal effects, drought act as a complex environmental signal that induces a wide array of adaptive response at morphological, physiological and biochemical levels.

Wheat plants are particularly vulnerable to drought during critical growth phases, including germination, seedling development, tillering, stem elongation, anthesis and grain filling. Droughts of varying intensities at different growth stages impact grain yield in distinct ways. During germination, drought stress lowers both the germination rate and percentage, thereby prolonging the process of germination. Higher drought levels

significantly reduce the fresh weight of roots and shoots, while leaf wilting visibly reflects drought's effects on plant foliage. Additionally, plant growth is hindered due to the loss of turgor pressure in cells. Previous studies have highlighted drought's impact on plant density in the early stages, tiller production during tillering and plant height during stem elongation. As drought disrupts cell elongation, wheat growth and height are stunted. Furthermore, drought shortens the stem elongation phase, reducing ear, dry weight and the number of fertile florets at anthesis, ultimately leading to lower grain yields. While drought affects wheat at all growth stages, it is most detrimental during flowering and grain filling, causing significant yield losses. Drought stress also influences grain development, with pre-anthesis drought reducing grain number per unit area and post-anthesis drought affecting grain weight (2). Wheat plant employs diverse morphological-physiological strategies to cope with water deficit conditions, which includes morphological adaptations, such as modification in root system architecture, reduced leaf area and altered plant stature, enhance water acquisition and minimise transpiration losses. Physiologically adaptation includes stomatal regulation, photosynthetic activity and water use-efficiency, enabling plants to maintain cellular homeostasis under limited

water conditions while biochemical regulations comprise accumulation of osmolytes, activation of antioxidant defence system and synthesis of stress-responsive proteins to mitigate oxidative damage and sustaining metabolic processes (3).

Genes such as DREB (Dehydration-Responsive Element Binding), HKT (High-Affinity K Transporters), NHX (Na⁺/H⁺ antiporters) and LEA (late embryogenesis Abundant Proteins), identified as key drought-responsive gene showed differential gene regulation and expression across the genotypes for drought tolerance (4). Regardless to molecular insight, various drought resistant/tolerant wheat varieties have been developed across the countries that showed improved performance under water-deficit conditions like HD 2967 and HI 1544 (5) (India) Seri M82 and Babax (6) (Mexico) Drysdale and RAC 875 (Australia) (7). Recently, a systematic literature search and screening process were also employed through PRISMA (The Preferred Reporting Items for Systematic reviews and Meta-Analysis) guidelines focusing on morpho-physiological and biochemical responses under drought stress, resulting in the enhancement of the reliability, reproducibility and transparency of the selection (8).

Despite the availability of numerous studies and reviews on drought stress in wheat, most existing literature primarily focuses on either physiological responses, morphological traits or biochemical mechanisms in isolation. A comprehensive integration of these responses across different growth stages remains limited. In addition, limited attention has been given to linking these responses with practical breeding implications and trait selection strategies. Thus, the aim of the review is to examine the physiological mechanisms by which different wheat varieties respond to drought stress, highlighting variations in water-use efficiency, biochemical mechanisms and morphological adjustments. By analysing previous research, this review provides comprehensive insights into adaptive strategies of wheat under water-limited conditions and contribute to the development of drought-resistant cultivars.

Genesis of drought

There are multiple factors such as climatic, hydrological, edaphic and anthropogenic conditions (9), which trigger drought conditions. The main causes of drought are as follows:

- **Climatic cause**

Climatic cause such as global warming, low and erratic rainfall, heat waves, La Nina, El Nino, shifting jet streams, makes the weather most unpredictable and extreme. It can make places drier due to intense heat. When land becomes so dry, an impermeable crust forms, so when it does rain, water runs off the surface, resulting in flash floods. These climatic irregularities are particularly critical in major wheat growing semi-arid and Indo-gangetic plains, where terminal heat and moisture stress frequently limit wheat productivity.

- **Deforestation**

It is one of the major anthropogenic activities which cause the drought. Plants and trees capture and release water into the atmosphere, which creates clouds and then rain. So, there is a direct correlation between deforestation and drought, as it indirectly affects wheat-based cropping system by reducing regional rainfall particularly during critical growth stages.

- **Shifting of the climate**

Long-term shift in climate amplifies drought intensity and frequency.

Intense heat increases the evaporation rate, which leads to drying out of the soil and reduces water availability during anthesis and grain filling stages even in moderate rainfall conditions.

- **Agricultural practices**

Reduction in water retention and erosion can happen due to intensive farming with poor soil management. Compact soil is formed due to overgrazing and monoculture, which reduces water infiltration and increases runoff during rain. Over-irrigation and water mismanagement leads to the lowering water table, making water unavailable to the crop in both rainfed and irrigated wheat system.

Adaptive modifications of wheat under water deficit condition

Drought stress induces several complex and coordinated changes at morphological, physiological and biochemical level in plants as adaptive strategies to survive under water-deficient conditions, enabling it to survive and sustain productivity. (Fig. 1). Drought stress is one of the major factors that reduces yield loss in wheat and for decades, plant breeders have been focusing on key changes so that the wheat crop can tackle drought stress without a significant reduction in yield. The extent of these adaptive modifications varies among genotypes and is strongly influenced by the intensity and duration of drought stress as well as developmental stage of the plant. The major changes are as follows:

Adaptive morphological shifts

Plants exhibit a wide range of morphological changes under drought stress as adaptive strategies to reduce water loss and optimise the utilisation of resources. Changes like a reduction in leaf area, increased root growth and stomata closure help the plants to survive under limited water conditions. Drought stress causes notable morphological modifications in wheat, enabling it to adapt and sustain productivity under limited water availability. The primary changes include:

Seed germination interference

Drought stress significantly affects wheat growth by reducing germination rates and seed vigour. Seed germination is a crucial phase in crop establishment and yield formation. A deficiency in soil moisture delays or inhibits seed germination, leading to irregular seedling distribution, poor plant establishment and ultimately lower grain yield in wheat. Research indicates that under drought stress, wheat germination rates decreased by 9.4 %, with a delay of approximately 1.91–2.05 days (10). Reduced water potential is the primary cause of lower germination rates, which also negatively affects seedling vigour in comparison to optimal growth conditions. Drought stress reduces the seedling vigour index by 16.6–21.26 % (10).

Shoot system adjustment

Drought limits leaf expansion due to increased leaf ageing, shading effects resulting from the uneven growth of the plants, thus creating competition for light, ultimately reducing the leaf area index. It also inhibits cell enlargement by reducing their cell volume as a consequence of elastic adjustment in their cell wall, slows growth and increases leaf abscission, further reducing leaf area. Water scarcity leads to decreased nitrogen uptake, triggering nitrogen remobilisation from leaves and stems to seeds, which accelerates early leaf senescence (11).

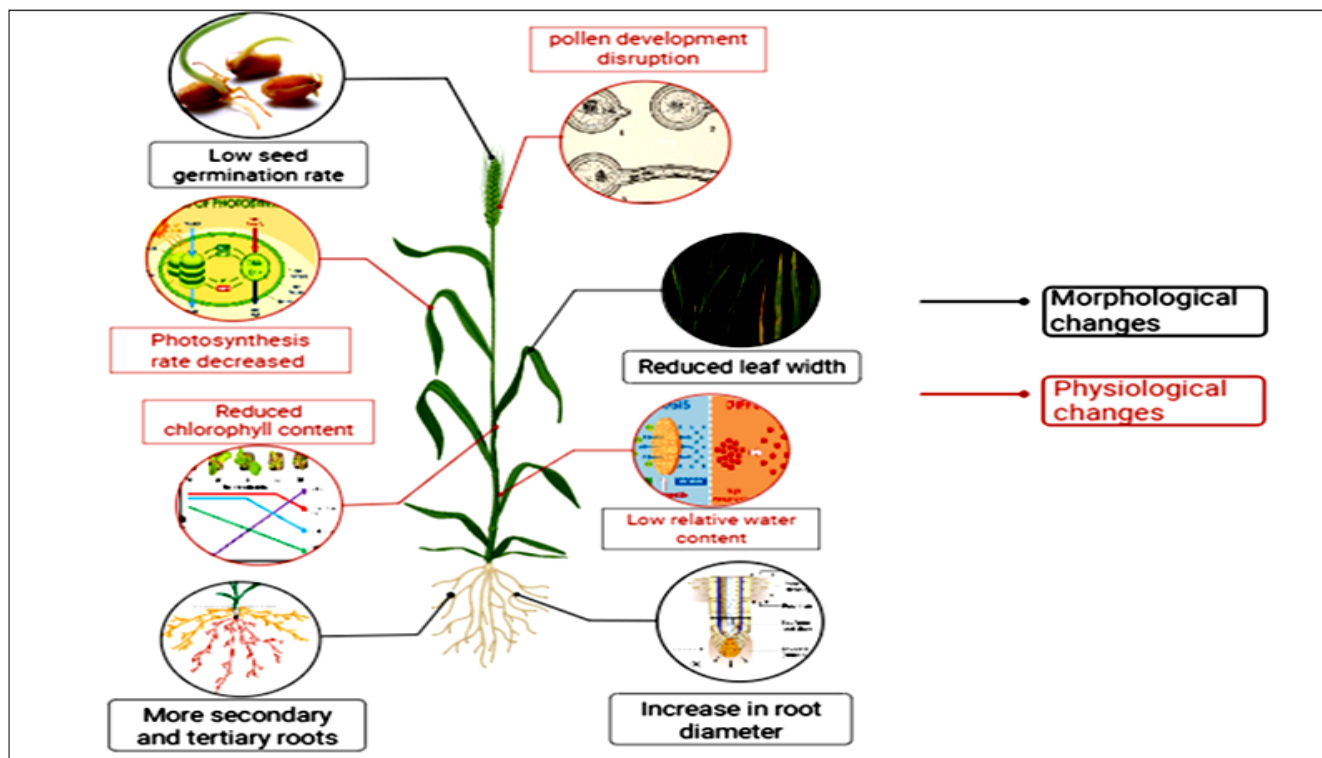


Fig. 1. Morpho-physiological and biochemical modifications in wheat under water stress.

Drought stress also significantly impacts morphological traits, including plant height, tiller production per plant, spike density per square meter, spikelets per spike and spike length (12). Wheat experiences a reduction in plant height under drought conditions. This reduction is largely attributed to protoplasm dehydration, which impairs cell division, expansion and turgidity. Drought conditions also lower spike density per m^2 compared to irrigated environments. Water deficits during the vegetative stage decrease plant water potential, causing tiller mortality and ultimately reducing spike density. The number of spikelets per spike declines by approximately 9.5 % under drought stress due to reduced pollen fertility and an increase in infertile spikelets (13). Drought stress also negatively affects spike length, which is closely linked to reduced plant height. The average grain count per spike drops by 15.32 % due to water deficits that hinder pollen viability and ovule development, ultimately reducing fertilisation success (10). Drought stress also leads to a 10.6 % decrease in thousand-kernel weight compared to irrigated conditions. This decline is attributed to reduced nutrient uptake, impaired photosynthesis, lower carbohydrate translocation and accelerated senescence, all of which contribute to early maturity and a significant drop in kernel weight (13). Additionally, drought conditions have a profound effect on phenological traits, including days to booting, heading and anthesis. Under drought stress, these growth stages occur earlier compared to irrigated conditions. Wheat plants tend to accelerate their life cycle under drought conditions as a survival strategy, leading to an overall reduction in the duration of these key developmental phases.

Root system adjustments

Under drought conditions, root length, diameter, surface area, tissue density, biomass and number of secondary and tertiary root branches are affected (14). Certain parts of the root system can continue to grow and form a relatively well-developed root system under drought conditions, acquiring potential water resources from a deeper soil layer to ensure water supply and improve crop adaptation to drought stress. Even though water-deficit stress

generally affects overall root traits negatively, wheat acquires an ideal root system by maintaining cell elongation in the apical regions under conditions of relatively low water content. The primary root, the first root tissue to emerge from the seed and meet the environment, can sustain growth in comparison shoot growth, resulting in such an ideal root system (15). This adaptive mechanism shown by wheat to fight against drought stress is osmotic adjustment of the root, increased root penetration to the soil, increased root density and increased root-to-shoot ratio (16).

Root growth is favoured over shoot growth when the availability of water is scarce. Osmotic adjustment in the root maintains a level of turgidity up to some level. If there is a reduction in the water potential, the water potential gradient is re-established for water uptake. The formation of secondary and tertiary roots also increases during drought stress to increase surface area for absorbing water. Likewise, there is an increase in root diameter, which helps in maintaining water retention in the vascular bundles of wheat. Also, there is an increase in sclerenchyma cell diameter and a decrease in aerenchyma cell formation during drought stress (17).

Functional dynamics of stress adaptation

Drought stress significantly adjusts the functional dynamics of the plants, affecting water balance, photosynthesis, metabolism and hormone regulation (Fig. 2). These changes help plants survive under water-limited conditions but eventually reduce growth and productivity. However, the extent of this response varies considerably across wheat genotypes, reflecting differential in response in their adaptive response and tolerance mechanisms.

In wheat, physiological changes in traits like cell membrane stability, relative water content, early maturity, decreased leaf area, small plant size, increased dry weight and root-shoot ratio and the whole-plant transpiration rate response to enhanced atmospheric vapour pressure deficit are above-ground physiological traits and vigorous root architecture as primary below-ground physiological traits associated with drought tolerance (11).

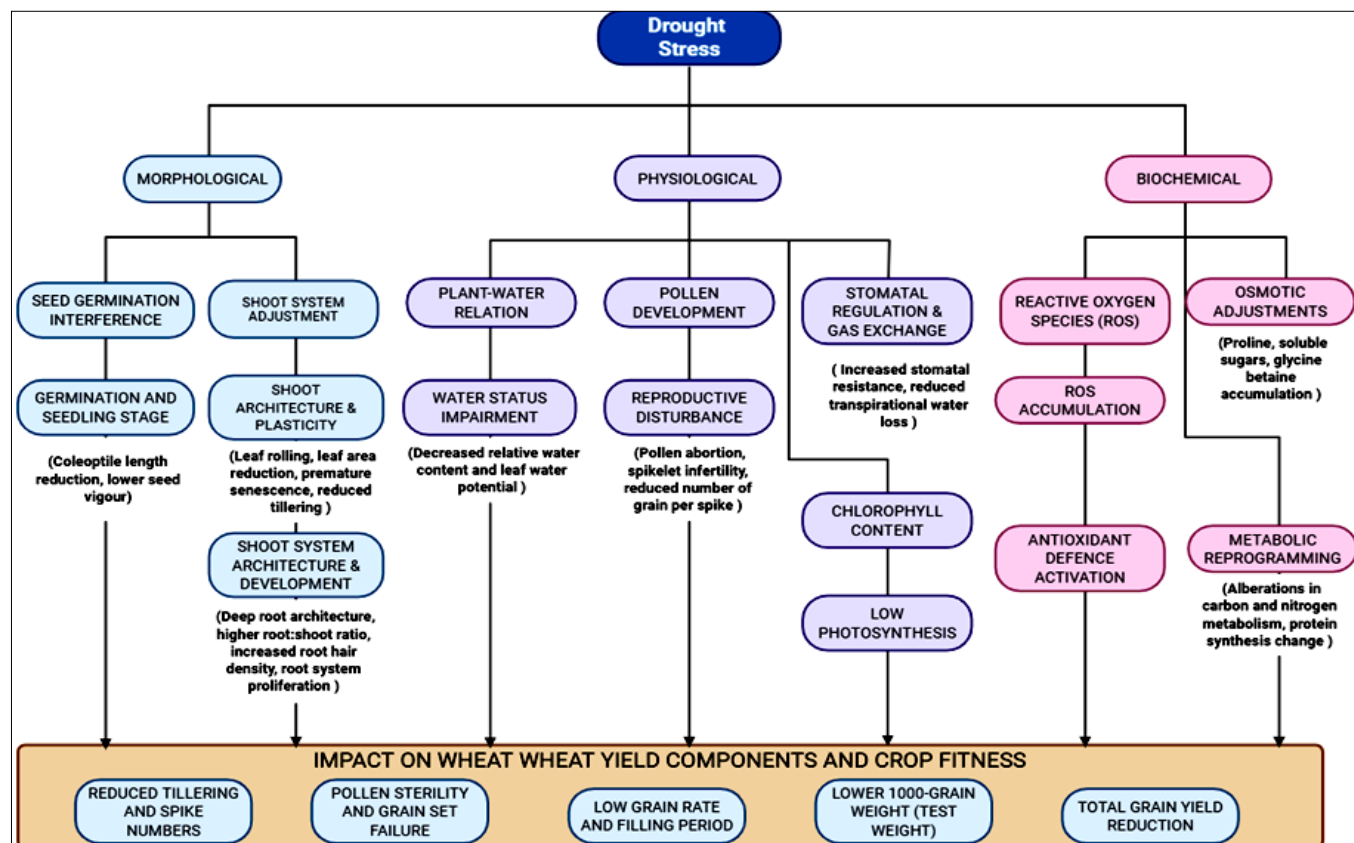


Fig. 2. Drought-driven modulations in wheat growth and metabolism.

Plant-water relations

Relative water content (RWC), leaf water potential, stomatal resistance, rate of transpiration, leaf temperature and canopy temperature are important characteristics that influence plant water relations (1). These factors have been playing an important role in selecting drought-tolerant cultivars in wheat. Studies have shown that a wide variety of plants, including wheat, show a significant decrease in relative water content (RWC) when leaves are exposed to drought (12). The threshold level where yield begins to decline varied largely among genotypes across the environmental conditions, representing inconsistency in defining universal screening criteria. Exposure of plants to drought stress substantially decreased the leaf water potential, relative water content and transpiration rate, with a concomitant increase in leaf temperature (1). Drought-tolerant genotypes maintained high turgor potential and relative water content to signify that limited water had a little effect on their protoplasmic structure, as compared to sensitive genotypes, which indicate a highly positive correlation between RWC and photosynthetic rate (13). However, RWC cannot alone guarantee stability in yield under severe drought, additional physiological traits like root depth and cell osmotic adjustment must also be considered.

The gamete formation stage is particularly sensitive to drought and heat stress. Exposure to these conditions causes meiotic defects due to morphological, structural and metabolic alterations, resulting in premature gametes and reproductive sterility. Drought reduces moisture availability in reproductive structures like the style and stigma, decreasing pollen viability and impairing fertilization. It also lowers plant water uptake, reducing turgor pressure, which in turn inhibits cell extensibility and slows embryo development. Drought prevents proper seed filling, leading to smaller and shriveled seeds with reduced germination potential.

Plants adapt to drought by closing stomata to limit water loss through transpiration.

Chlorophyll content and photosynthesis

Drought stress disrupts photosystem II (which is a multi-subunit protein complex embedded in the thylakoid membrane of plants, algae and cyanobacteria, responsible for splitting water and releasing oxygen during the light-dependent reactions of photosynthesis). By slowing electron transport, increasing non-photochemical activity and ultimately reducing cellular moisture content. It reduces relative water content by an average of 33.25 % (14). The decline in leaf water potential directly affects gas exchange through stomatal conductance and transpiration. Stomatal closure lowers CO₂ availability for photosynthesis, thereby reducing the photosynthetic rate. Drought stress also limits the availability of RuBisCO, also known as Ribulose-1, 5-bisphosphate carboxylase/oxygenase (a crucial enzyme in photosynthesis, responsible for carbon dioxide fixation, converting atmospheric CO₂ into organic carbon) and decreases ATP production (15).

Furthermore, drought damages the photosynthetic system and alters the function of key enzymes such as RuBisCO (which catalyse the initial step of carbon fixation in photosynthesis), which plays a crucial role in the Calvin cycle. This disruption decreases atmospheric carbon fixation and organic matter production, ultimately leading to lower grain yields. In wheat, chlorophyll content peaks at the flowering stage but is significantly reduced by drought, negatively affecting leaf photosynthesis. Under drought stress, chlorophyll levels decline by 13–15 % compared to irrigated conditions due to chlorophyllase activation and enzyme inactivation (16). Additionally, reactive oxygen species (ROS) generated during drought damage chloroplasts, further decreasing chlorophyll content, indicating a fine balance between beneficial and harmful effects (16).

Pollen development

Drought severely affects wheat pollen development, particularly during meiosis and microsporogenesis, leading to pollen sterility, reduced fertilisation and lower grain yield (17). An anther development is very sensitive to drought stress and drought-induced tapetal Dysfunction might be a major cause of pollen sterility. Absciscic Acid (ABA) concentration is increased while Gibberellic Acid (GA) and Indole-3-Acetic Acid (IAA) concentrations are decreased in drought-stressed anthers. Excessive ABA promotes relative oxygen species (ROS) accumulation, which causes oxidative damage to anther tissue. These molecular changes result in tapetal hypertrophy and delay or inhibit its normal programmed cell death (PCD). Lowering ABA and ROS levels by up-regulation of ROS scavenging genes could improve the drought resistance in the reproductive stage and promote seed production in crops (18). Therefore, the extent of reproductive damage varies among genotypes-genotypes due to the complexity of drought response, as some confers partial tolerance through efficient ROS scavenging and hormonal balance.

Water-deficit-mediated metabolic shift

Drought stress induces significant metabolic changes in plants as part of their adaptive response to water scarcity. These changes help maintain cellular homeostasis (the process by which cells maintain a stable internal environment, which is essential for their survival), protect against oxidative stress and regulate metabolic pathways.

To cope with water scarcity, wheat triggers a range of biochemical changes under drought conditions. These changes are crucial for maintaining cellular integrity, energy production and overall plant growth. The changes are as follows:

Reactive oxygen species

The generation of reactive oxygen species (ROS) is one of the earliest biochemical responses of eukaryotic cells to biotic and abiotic stresses (1). Reactive oxygen species (ROS) have many important physiological functions in plant growth. In anthers, the low-level redox status is essential to ensure early differentiation and meiosis in the anther. After meiosis, the ROS concentration is increased in the tapetum, which promotes the initiation of tapetal programmed cell death (PCD) in the late anther development. Therefore, the ROS homeostasis is very important for anther development. Drought stress induces the generation of excessive ROS in anthers, which will cause oxidative stress and be harmful for tapetum development and lead to cell death (18). ROS produced during photosynthesis and respiration cause oxidative damage to proteins, lipids, membranes, chloroplasts, mitochondria and nucleic acids, leading to changes in membrane potential, enzyme deactivation and ultimately programmed cell death. Drought also triggers the production of stress hormones, particularly ABA, which regulates stomatal activity in response to water stress (18). While ABA helps conserve water by closing stomata, it also slows crop growth under drought conditions, presenting both benefits and drawbacks.

Antioxidant production

Antioxidant enzyme activities are known to increase under drought conditions through upregulation and downregulation of antioxidant capacity. In some cases, synthesis of new isoenzymes is induced to overcome the negative impact of progressive water stress (16). These defence mechanisms prevent the destructive effects of toxic

agents by turning off and removing toxicants. Effects of drought stress on antioxidant defence enzymes may vary depending on plant species, developmental stage and stress severity.

Superoxide dismutase is one of the first enzymes in the antioxidant defence system that is responsible for converting superoxide radicals (O_2^-) into hydrogen peroxide (H_2O_2). There are three isoforms of SOD in plants: Cu/Zn SOD (cytoplasm), Mn SOD (mitochondria) and Fe SOD (chloroplasts). Drought stress typically leads to the upregulation of these isoforms in wheat (19). Catalase (CAT) decomposes hydrogen peroxide into water and oxygen, further reducing oxidative stress. Ascorbate Peroxidase (APX) works with ascorbic acid (vitamin C) to convert hydrogen peroxide into water. Glutathione (GSH) and the glutathione reductase system play a key role in reducing oxidative stress by neutralising ROS and protecting cellular components.

Mechanisms of drought tolerance

Wheat plants have developed various adaptive strategies and mechanisms at morphological, physiological and biochemical levels to tolerate drought stress. These mechanisms help in maintaining cellular integrity, water usage optimisation and maintaining productivity under drought conditions.

Morphological Tolerance Mechanisms

These type of adaptations in wheat focuses on changes in structure that enhance water usage, reduce water loss and optimise resource allocation. The key modifications are observed in the root, leaves and overall plant architecture.

- Drought-tolerant cultivars exhibit enhanced root performance. Root system development is crucial for drought tolerance. Increased root length, width and dry weight allow continuous growth and water uptake even though the shoot growth is restricted (20). Overexpression of the TaSNAC8-6A gene can increase the number of lateral roots, enhancing water absorption and drought resistance in wheat (21, 22). TAZFP34, TaRNC1 and TaNAC2-5A are genes that can increase root length and number (23, 24). TaMOR is known for controlling root formation. TaCIPK23 overexpression improved the root system. TaEXO70A3 has been found to regulate root depth, potentially increasing root water acquisition (25, 26).
- Changes in leaves, like a reduction in leaf area and number of leaves, are exhibited to minimize transpiration. Traits such as leaf wax, pubescence and cuticle thickness are increased to reduce water loss through the epidermis (27, 28). Overexpression of the TaSHN1 gene alters cuticle composition, influences cuticle biosynthesis and decreases leaf pore density.
- The entire plant morphology shifts towards smaller stature, early maturity and biomass reduction to conserve water. It also includes shorter plant height, fewer spikes, while tolerant varieties maintain the yield (20, 29).

Physiological tolerance mechanisms

Physiological mechanisms of drought tolerance in wheat involve a complex array of adaptations that enable the plant to survive, grow and reproduce under limited water supply. These mechanisms work at the cellular, tissue and organ levels to mitigate the adverse effects of water scarcity.

- Accumulation of osmolytes like proline, soluble sugar, soluble protein, free amino acids, glycine, betaine and mannitol within their cells can lower the osmotic potential and maintain cell turgor. Proline, for example, aids in the detoxification of reactive oxygen species (ROS), maintains membrane integrity and can store carbon and nitrogen (26).
- Closing their stomata is another response of wheat to water scarcity. This reduces water loss through transpiration and is largely controlled by the hormone ABA. Overexpression of the TaPYL1-1B gene enhances photosynthetic capacity and WUE, contributing to higher drought tolerance and grain yield (30, 31). Additionally, it also impairs photosynthesis due to the reduction of carbon dioxide uptake. Tolerant genotypes maintain higher levels of relative water content in their leaves and show better transpiration efficiency.
- The trait “stay-green” is a key defence mechanism. This trait allows plants to resist early senescence and remain photosynthetically active. It also helps in sustaining carbon assimilation, retaining pollen and ovule viability and ensures a continuous sugar supply for the development of reproductive organs under drought stress (10). The protein HAHB4 delays the plant from entering the senescence phase and allows more time to recover when there is sufficient water.

Biochemical tolerance mechanism

In drought-tolerant wheat, various biochemical mechanisms enable the plant to survive, grow and reproduce under drought conditions. These mechanisms notably reduce the damaging effects caused by water scarcity. The effects, like oxidative stress and cellular function and integrity, are maintained.

- Under drought conditions, proline levels increase and act as an osmo-regulator. It also aids in the detoxification of ROS, maintains membrane integrity and helps in the storage of carbon and nitrogen (32, 33). More soluble sugar accumulation is also

reported in drought-tolerant wheat varieties. They are an important energy molecule that protects the wheat from drought by acting as an osmotic regulator. TaWRKY2 is a gene related to sugar synthesis (34) and overexpression of TabZIP174 leads to higher content of soluble sugar and significantly improves drought tolerance (35).

- Antioxidant enzyme activities are observed in drought-tolerant varieties. They are helpful in detoxifying ROS, which will increase during drought stress and damage cells through peroxidation of membrane lipids (10). The activity of Superoxide Dismutase (SOD) is significantly increased under low availability of water. This enzyme catalyzes the dismutation of superoxide radicals to hydrogen peroxide (36). In varieties like Chakwal-50 and Wafaq-200, the enzyme Catalase (CAT) activity increases under drought stress, reducing hydrogen peroxide to water (36). Other antioxidant enzymes like Peroxidase (POD/POX), Ascorbate Peroxidase (APX) and Glutathione Reductase (GR) also play significant roles in ROS regulation.

Integrated framework of drought tolerance

Wheat plant has developed integrated adaptive systems operating at physiological, morphological and biochemical levels which works in a highly coordinated and interconnected manner under the stress. Morphological traits such as deeper and rigorous root systems enhance the water uptake deeper into the soil, which favours the physiological processes like maintenance of RWC, stomatal (regulations and photosynthetic activity, which further stabilised by biochemical responses like osmotic accumulation and activation of antioxidant defence systems which protect the membrane integrity from oxidative stress. Moreover, hormonal regulation (ABA), act as central signalling link connecting these responses by adjusting the stomatal activity, gene expression and stress-responsive pathways. Thus, ensure that wheat plant maintain cellular homeostasis, optimise water use, sustain vegetative and reproductive growth under water-deficit conditions. A consolidated list of drought resistance or tolerant genes sources are presented in Table 1.

Table 1. List of drought responsive genes from various resources along with their method of incorporation and function.

Gene	Source	Method of incorporation	Functions	Reference
TaSNAC8-6A	<i>Triticum aestivum</i>	Not applicable	Overexpression can increase the number of lateral roots, enhancing the water absorption rate.	(28)
TaNAC69	<i>Triticum aestivum</i>	Not applicable	Better root biomass and promotes root elongation.	(37)
TaMYBsm3	<i>Triticum aestivum</i>	Not applicable	Overexpression leads to better germination rate, higher proline content, lower malondialdehyde (MDA) and less susceptibility to wilting.	(38)
TaWRKY2	<i>Triticum aestivum</i>	Not applicable	Higher survival rate, proline, soluble sugar and chlorophyll.	(39)
HVA1	Barley	Biolistic Bombardment	Improves biomass accumulation, water use efficiency, plant height and grain yield.	(39)
GmDREB1	Soybean	Agrobacterium-mediated transformation	Increase the number of leaves and secondary roots. Higher soluble sugar content.	(40)
DREB1A	<i>Arabidopsis thaliana</i>	Biolistic transformation	Delays wilting under drought conditions, maintains turgor pressure.	(41)
CspA and CspB	<i>Escherichia coli</i>	Agrobacterium-mediated transformation, Biolistic Bombardment	Reduces water loss rate and MDA content. Higher proline and chlorophyll content.	(42)
HaHB4	Sunflower	Gene gun	Delays senescence, improves water use efficiency and enhances yield stability during drought.	(43)
BADH	Mountain Spinach	microprojectile bombardment	Overexpression increases glycine betaine synthesis which maintains osmotic balance.	(44)
MsALR	Alfalfa	Biolistic Bombardment	Better biomass and seed weight.	(45)
AtWRKY30	<i>Arabidopsis thaliana</i>	Agrobacterium-mediated transformation	Better Plants growth, biomass and gas-exchange attributes. Higher RWC, chlorophyll, proline, soluble proteins, soluble sugars content and antioxidant enzymes activities	(46)
AtHDG11	<i>Arabidopsis thaliana</i>	Agrobacterium-mediated transformation	Overexpression leads to lower stomatal density and increased activities of catalase and superoxide dismutase.	(47)

Role of CRISPR-Cas and RNAi technologies

The use of Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR/Cas) alongside RNA interference (RNAi) for creating drought-resistant wheat varieties (Fig. 3) reflects unique, but occasionally intersecting, biotechnological approaches aimed at enhancing plant resilience, especially given the intricate hexaploid wheat genome (42, 48).

I. CRISPR/Cas

A major advancement involves the use of a multiplex sgRNA-CRISPR/Cas9 genome editing system to disrupt genes known to negatively regulate stress responses (48).

Molecular Mechanism

Researchers targeted the TaSal1 gene (3'(2'), 5'-bisphosphate nucleotidase), which is considered a negative regulator of drought tolerance in related species like *Arabidopsis*. The TaSal1 enzyme normally hydrolyses the molecule 3'-phosphoadenosine 5'-phosphate (PAP), a chloroplast stress retrograde signal.

PAP Accumulation: Loss-of-function mutants in TaSal1 lead to the accumulation of PAP, which inhibits 5'- to 3'- exoribonuclease activity and enhances the drought-inducible chloroplast-to-nucleus stress signal. This increased signalling confers drought tolerance and induces stomatal closure.

Multiplex Editing

Due to gene redundancy, the multiplex system was employed to target three conserved sites (exons 4, 5 and 7) across 5 active TaSal1 homeoform genes in the hexaploid wheat cultivar Giza168, successfully generating lines with full 5-gene knock-outs (48).

II. RNA Interference (RNAi)

RNA interference (RNAi) is a method employed to decrease or silence the expression of genes. While RNAi lines (such as D793, T258, E341) were mainly created to lower all gliadin fractions in order to lessen the immunogenicity associated with Celiac Disease (CD), their assessment under drought conditions showed notable molecular reactions connected to tolerance mechanisms (43, 49).

RNAi lines generally showed elevated baseline levels of Glutathione peroxidase (GPX) and Catalase (CAT) expression under normal (non-stressed) conditions in comparison to their wild relatives. Genes associated with osmotic adjustment, such as Pyrroline-5-carboxylate reductase (P5CR, which plays a role in proline synthesis) and Galactinol synthase (GolS1, involved in raffinose production), demonstrated particularly high baseline expression in certain RNAi lines (e.g., T258 and E341). It is suggested that the sustained activation of drought-responsive genes may stem from pleiotropic or off-target effects linked to the gliadin silencing fragment, which could disturb nutrient storage balance and, as a result, initiate compensatory stress signalling pathways even without the presence of water stress (43, 49).

Although CRISPR/Cas and RNA interference (RNAi) technologies provide powerful tools for enhancing drought tolerance in wheat, several limitations constrain their widespread application. The complexity of *Triticum* genome makes precise editing challenging due to the presence of multiple homeologous gene copies, thus required multiplex strategies to achieve complete gene knockouts (50). However, off-target effects in CRISPR/Cas system and gene silencing of non-targeted gene in RNAi may lead to unintended pleiotropic effects, potentially effecting growth and reproduction of the plant. The stability and inconsistent performance of genetically modified lines developed through these technologies across generations and environments also remains a concern, as drought stress rarely occurs in isolation and is frequently combined with other stresses such as heat (51). Furthermore, limited coordinated-yield trials and regulatory restrictions, particularly countries with strict biosafety frameworks, hinder the rapid adaptations of these technologies (52). In contrast, conventional breeding approaches, although time consuming and less precise compare to CRISPR/Cas and RNAi, have proven reliability in improving complex traits like drought tolerance by utilising genetic variation and also ensures the stability. Therefore, while CRISPR/Cas and RNAi offer high precision and faster trait development, their

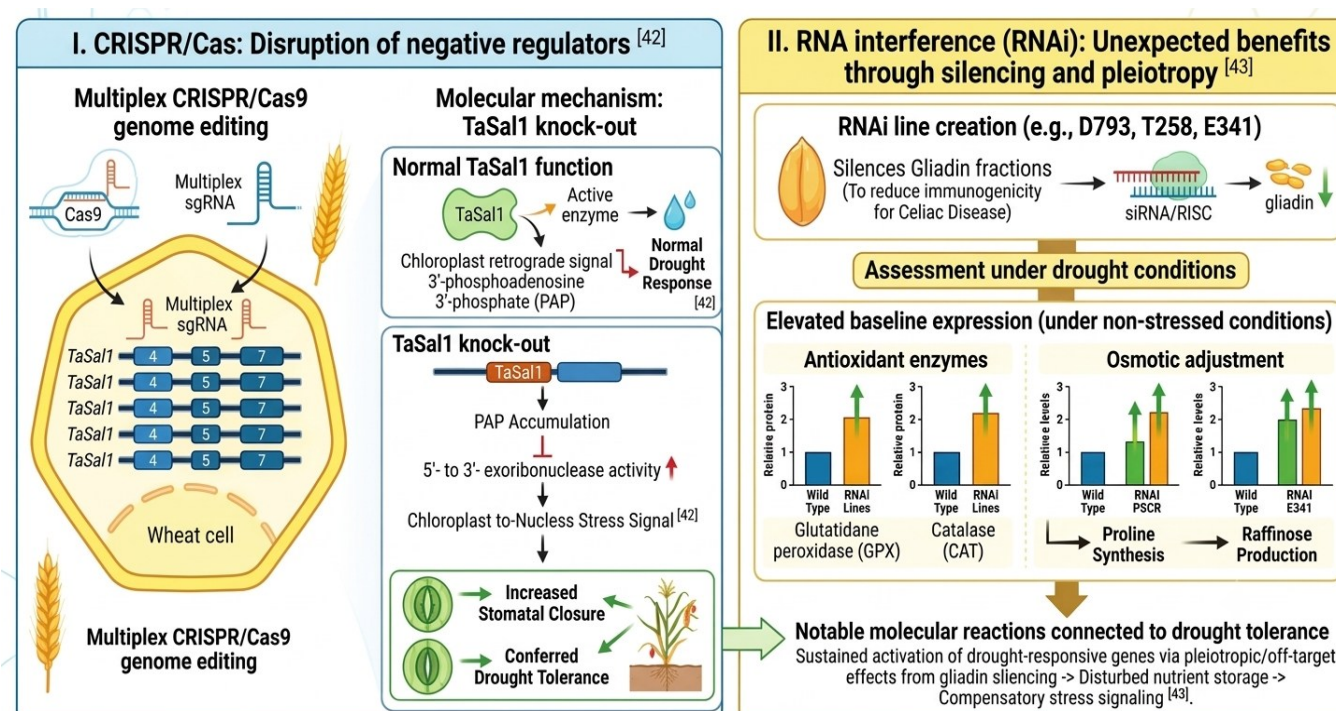


Fig. 3. Role of CRISPR/Cas and RNAi Technologies in developing drought-resistant wheat.

optimal utility lies in integration with conventional breeding methods, such as MAS and genomic selections for sustainable and field relevant improvements in drought tolerance.

Future Prospect

As climate change is becoming more unpredictable, with studies indicating that drought will be more frequent and severe by mid-century, improving drought tolerance in wheat remains crucial for global food security. Future research should prioritise the integration of methods like genomics, proteomics, transcriptomics and metabolomics to study and improve genes responsible for drought tolerance in wheat. Combining AI-driven data analysis with high-throughput phenotyping platforms enhances screening for drought-tolerant genes and helps in identifying ideal cultivars effectively. It is possible to improve the tolerance of wheat to abiotic stresses by the use of novel agronomic techniques like drought priming, also known as transgenerational priming (The phenomenon of "plant memory" occurs when a parent plant experiences drought stress, leading to adaptive modifications in its offspring that enhance their resilience to future drought conditions, even if they do not directly encounter stress in the second or third generations. This process, which is driven by epigenetic factors and biochemical changes, enables plants to predict and more effectively manage upcoming water shortages, resulting in improved drought resistance in crops. However, despite these advancements, several limitations persist. Multi-omics approaches are often constrained by high costs, complex data integration and limited accessibility in developing regions. Likewise, AI-based models required large, high-quality datasets, which are not always available, potentially reducing their predictive accuracy across diverse environments.

Nanotechnology, such as zinc oxide nanoparticles (ZnO-NPs), which act as sustainable nano-fertilisers, has the potential to tackle drought by enhancing antioxidant defenses, photosynthesis and nutrient intake. New drought-resilient pre-breeding materials can be produced by de novo domestication of wild relatives. It can be achieved through combining their inherent drought adaptations with synthetic biology. To reduce yield loss, gene pyramiding could be used to stack multiple drought-tolerant traits and address germination and reproductive vulnerabilities. Collaborative efforts, such as international germplasm banks and open-access databases, help in accelerating progress and guarantee farmers access to drought-tolerant cultivars.

Conclusion

Drought stress remains a critical challenge to wheat (*Triticum aestivum* L.) production, significantly impacting growth, development and yield. This review highlights that wheat employs a wide range of adaptive strategies at the morpho-physiological and biochemical levels to withstand drought conditions. Morphological changes like reduced leaf area, enhanced root growth and delayed senescence optimise water usage and resource allocation. Physiological mechanisms, such as stomatal regulation, osmotic adjustment and maintenance of relative water content, are vital for drought tolerance. Biochemically, the activation of the antioxidant defence system and modulation of reactive oxygen species (ROS) balance help protect cellular integrity under water-deficient conditions. Understanding these complex and interlinked responses is crucial for breeding drought-resilient wheat cultivars. Future research will focus on integrating physiological traits with molecular

tools to further strengthen efforts to develop wheat varieties that can thrive in an increasingly variable climate

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Authors' contributions

HA compiled reviews and wrote first draft of the article. AS identified topic, corrected, curated and added insights to the review and CCP edited, proof read and prepared final draft of article. All authors read and approved the final manuscript.

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References

1. Anjum SA, Xie XY, Wang LC, Saleem MF, Man C, Lei W. Morphological, physiological and biochemical responses of plants to drought stress. *Afr J Agric Res.* 2011;6. <https://doi.org/10.5897/AJAR10.027>
2. Duvnjak J, Lončarić A, Brkljačić L, Šamec D, Šarčević H, Salopek-Sondi B, et al. Morpho-physiological and hormonal response of winter wheat varieties to drought stress at stem elongation and anthesis stages. *Plants.* 2023;12:418. <https://doi.org/10.3390/plants12030418>
3. Sahoo SS, Sahu DP, Behra RK. Drought stress mitigation in wheat seedlings via green synthesized silver nanoparticle priming. *Seeds.* 2025;4(4):1–27. <https://doi.org/10.3390/seeds4040062>
4. Shinta, Bentoy KMY, Fauzia AN, Nampei M, Linh NM, Ueda A. Physiological and transcriptomic insights into mechanisms of salt tolerance in the leaves and roots of the halophyte *Suaeda japonica* Makino under high salinity stress. *J Plant Growth Regul.* 2026;45:321–39. <https://doi.org/10.1007/s00344-025-11864-8>
5. Priyanka, Rana V, Basandrai D, Sood VK, Rana A. Identification of promising and stable genotypes of wheat (*Triticum aestivum* L.) for grain yield under varied climatic conditions of north-western Himalayas using joint regression analysis. *J Cereal Res.* 2024;16(1):44–52. <https://doi.org/10.25174/2582-2675/2024/136259>
6. Pinto RS, Reynolds MP, Mathews KL, McIntyre CL, Olivares-Villegas JJ, Chapman SC. Heat and drought adaptive QTL in a wheat population designed to minimize confounding agronomic effects. *Theor Appl Genet.* 2010;121(6):1001–21. <https://doi.org/10.1007/s00122-010-1351-4>
7. Yadav AK, Carroll AJ, Estavillo GM, Rebetzke GJ, Pogson BJ. Wheat drought tolerance in the field is predicted by amino acid responses to glasshouse-imposed drought. *J Exp Bot.* 2019;70(18):4931–48. <https://doi.org/10.1093/jxb/erz224>
8. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ.* 2021;372:n71. <https://doi.org/10.1136/bmj.n71>
9. Disasa KN, Yan H, Zhang J, Wang G, Zhang C, Zhang D, et al. Comprehensive review of drought characteristics and intensification under climate change: implications for agriculture and water resources. *J Hydrol.* 2026;664:134571. <https://doi.org/10.1016/j.jhydrol.2025.134571>
10. Nyaupane S, Poudel MR, Panthi B, Dhakal A, Paudel H, Bhandari R. Drought stress effect, tolerance and management in wheat: a review.

- Cogent Food Agric. 2024;10. <https://doi.org/10.1080/23311932.2023.2296094>
11. Seleiman MF, Al-Suhaibani N, Ali N, Akmal M, Alotaibi M, Refay Y, et al. Drought stress impacts on plants and different approaches to alleviate its adverse effects. *Plants*. 2021;10:259. <https://doi.org/10.3390/plants10020259>
 12. Tatar O, Brück H, Asch F. Photosynthesis and remobilization of dry matter in wheat as affected by progressive drought stress at stem elongation stage. *J Agron Crop Sci*. 2016;202:292–99. <https://doi.org/10.1111/jac.12160>
 13. Poudel MR, Ghimire S, P MP, Ey, Dhakal KH, Thapa DB, et al. Evaluation of wheat genotypes under irrigated, heat stress and drought conditions. *J Biol Today's World*. 2020;9:1–12. <https://doi.org/10.35248/2322-3308.20.9.212>
 14. Gašparíková O, Mistrík I. Review of Plant Roots: The Hidden Half. *Ann Bot*. 2002;90:775. <https://doi.org/10.1093/aob/mcf252>
 15. Kang J, Peng Y, Xu W. Crop root responses to drought stress: molecular mechanisms, nutrient regulations and interactions with microorganisms in the rhizosphere. *Int J Mol Sci*. 2022;23:9310. <https://doi.org/10.3390/ijms23169310>
 16. Ali M, Fareed A, Jan SU, Gul A, Gul S, Nadeem M, et al. Cellular mechanisms of drought tolerance in wheat. In: *Climate Change and Food Security with Emphasis on Wheat*. 2020. p. 155–67. <https://doi.org/10.1016/B978-0-12-819527-7.00009-1>
 17. Henry A, Cal AJ, Batoto TC, Torres RO, Serraj R. Root attributes affecting water uptake of rice (*Oryza sativa*) under drought. *J Exp Bot*. 2012;63:4751–63. <https://doi.org/10.1093/jxb/ers150>
 18. Ahmad Z, Waraich EA, Akhtar S, Anjum S, Ahmad T, Mahboob W, et al. Physiological responses of wheat to drought stress and its mitigation approaches. *Acta Physiol Plant*. 2018;40:1–13. <https://doi.org/10.1007/s11738-018-2651-6>
 19. Nayyar H, Gupta D. Differential sensitivity of C3 and C4 plants to water deficit stress: association with oxidative stress and antioxidants. *Environ Exp Bot*. 2006;58:106–13. <https://doi.org/10.1016/j.envexpbot.2005.06.021>
 20. Sourour A, Afef O, Mounir R, Younes Mongi B. A review: morphological, physiological, biochemical and molecular plant responses to water deficit stress. <https://doi.org/10.9790/1813-0601010104>
 21. Maghsoudi K, Emam Y, Pessarakli M. Effect of silicon on photosynthetic gas exchange, photosynthetic pigments, cell membrane stability and relative water content of different wheat cultivars under drought stress conditions. *J Plant Nutr*. 2016;39:1001–15. <https://doi.org/10.1080/01904167.2015.1109108>
 22. Mao H, Li S, Wang Z, Cheng X, Li F, Mei F, et al. Regulatory changes in TaSNAC8–6A are associated with drought tolerance in wheat seedlings. *Plant Biotechnol J*. 2020;18:1078–92. <https://doi.org/10.1111/pbi.13277>
 23. Farooq M, Wahid A, Kobayashi N, Fujita D, Basra SMA. Plant drought stress: effects, mechanisms and management. *Agron Sustain Dev*. 2009;29:185–212. <https://doi.org/10.1051/agro:2008021>
 24. Chang H, Chen D, Kam J, Richardson T, Drenth J, Guo X, et al. Abiotic stress upregulated TaZFP34 represses the expression of type-B response regulator and SHY2 genes and enhances root to shoot ratio in wheat. *Plant Sci*. 2016;252:88–102. <https://doi.org/10.1016/j.plantsci.2016.07.011>
 25. Nikolaeva MK, Maevskaya SN, Shugaev AG, Bukhov NG. Effect of drought on chlorophyll content and antioxidant enzyme activities in leaves of three wheat cultivars varying in productivity. *Russ J Plant Physiol*. 2010;57:87–95. <https://doi.org/10.1134/S1021443710010127>
 26. Bhanbhro N, Wang HJ, Yang H, Xu XJ, Jakhar AM, Shalmani A, et al. Revisiting the molecular mechanisms and adaptive strategies associated with drought stress tolerance in common wheat (*Triticum aestivum* L.). *Plant Stress*. 2024;11:100298. <https://doi.org/10.1016/j.stress.2023.100298>
 27. Yu J, Jiang M, Guo C. Crop pollen development under drought: from the phenotype to the mechanism. *Int J Mol Sci*. 2019;20:1550. <https://doi.org/10.3390/ijms20071550>
 28. Nezhadahmadi A, Prodhan ZH, Faruq G. Drought tolerance in wheat. *Sci World J*. 2013;2013:610721. <https://doi.org/10.1155/2013/610721>
 29. Moayed AA, Boyce AN, Barakbah SS. The performance of durum and bread wheat genotypes associated with yield and yield component under different water deficit conditions. *Aust J Crop Sci*. 2010;4(1):70–77.
 30. Zhang Z, Hu M, Xu W, Wang Y, Huang K, Zhang C, et al. Understanding the molecular mechanism of anther development under abiotic stresses. *Plant Mol Biol*. 2021;105:1–10. <https://doi.org/10.1007/s11103-020-01074-z>
 31. Mao H, Jian C, Cheng X, Chen B, Mei F, Li F, et al. The wheat ABA receptor gene TaPYL1–1B contributes to drought tolerance and grain yield by increasing water-use efficiency. *Plant Biotechnol J*. 2022;20:846–61. <https://doi.org/10.1111/pbi.13764>
 32. Saeed-Moucheshi A, Sohrabi F, Fasihfar E, Baniasadi F, Riasat M, Mozafari AA. Superoxide dismutase (SOD) as a selection criterion for triticale grain yield under drought stress: a comprehensive study on genomics and expression profiling, bioinformatics, heritability and phenotypic variability. *BMC Plant Biol*. 2021;21:1–19. <https://doi.org/10.1186/s12870-021-02919-5>
 33. Hashmi QA, Ahmad M, Ahmad E, Tariq M, Rafah A, Awais M. Exploring drought tolerance in wheat: insights from biochemical, morphological and physiological responses. *Asian J Res Crop Sci*. 2023;8:344–60. <https://doi.org/10.9734/ajrcs/2023/v8i4216>
 34. Gao H, Wang Y, Xu P, Zhang Z. Overexpression of a WRKY transcription factor TaWRKY2 enhances drought stress tolerance in transgenic wheat. *Front Plant Sci*. 2018;9:997. <https://doi.org/10.3389/fpls.2018.00997>
 35. Li H, Li L, ShangGuan G, Jia C, Deng S, Noman M, et al. Genome-wide identification and expression analysis of bZIP gene family in *Carthamus tinctorius* L. *Sci Rep*. 2020;10. <https://doi.org/10.1038/s41598-020-72390-z>
 36. Qayyum A, Al Ayoubi S, Sher A, Bibi Y, Ahmad S, Shen Z, et al. Improvement in drought tolerance in bread wheat is related to an improvement in osmolyte production, antioxidant enzyme activities and gaseous exchange. *Saudi J Biol Sci*. 2021;28:5238–49. <https://doi.org/10.1016/j.sjbs.2021.05.040>
 37. Xue GP, Way HM, Richardson T, Drenth J, Joyce PA, McIntyre CL. Overexpression of TaNAC69 leads to enhanced transcript levels of stress up-regulated genes and dehydration tolerance in bread wheat. *Mol Plant*. 2011;4:697–712. <https://doi.org/10.1093/mp/ssr013>
 38. Li Y, Zhang S, Zhang N, Zhang W, Li M, Liu B, et al. MYB-CC transcription factor, TaMYBsm3, cloned from wheat is involved in drought tolerance. *BMC Plant Biol*. 2019;19:1–11. <https://doi.org/10.1186/s12870-019-1751-9>
 39. Sivamani E, Bahieldin A, Wraith JM, Al-Niemi T, Dyer WE, Ho THD, et al. Improved biomass productivity and water use efficiency under water deficit conditions in transgenic wheat constitutively expressing the barley HVA1 gene. *Plant Sci*. 2000;155:1–9. [https://doi.org/10.1016/S0168-9452\(99\)00247-2](https://doi.org/10.1016/S0168-9452(99)00247-2)
 40. Shiqing G, Huijun X, Xianguo C, Ming C, Zhaoshi X, Liancheng L, et al. Improvement of wheat drought and salt tolerance by expression of a stress-inducible transcription factor GmDREB of soybean (*Glycine max*). *Chin Sci Bull*. 2005;50:2714–23. <https://doi.org/10.1007/BF02899641>
 41. Pellegrineschi A, Reynolds M, Pacheco M, Brito RM, Almeraya R, Yamaguchi-Shinozaki K, et al. Stress-induced expression in wheat of the *Arabidopsis thaliana* DREB1A gene delays water stress symptoms under greenhouse conditions. *Genome*. 2004;47:493–500. <https://doi.org/10.1139/g03-140>
 42. Yu TF, Xu ZS, Guo JK, Wang YX, Abernathy B, Fu JD, et al. Improved drought tolerance in wheat plants overexpressing a synthetic bacterial cold shock protein gene ScCspA. *Sci Rep*. 2017;7:1–14. <https://doi.org/10.1038/srep44050>

43. Gupta PK. Drought-tolerant transgenic wheat HB4®: a hope for the future. *Trends Biotechnol.* 2024;42:807–09. <https://doi.org/10.1016/j.tibtech.2023.12.007>
44. Tian F, Wang W, Liang C, Wang X, Wang G, Wang W. Overaccumulation of glycine betaine makes the function of the thylakoid membrane better in wheat under salt stress. *Crop J.* 2017;5:73–82. <https://doi.org/10.1016/j.cj.2016.05.008>
45. Fehér-Juhász E, Majer P, Sass L, Lantos C, Csiszár J, Turóczy Z, et al. Phenotyping shows improved physiological traits and seed yield of transgenic wheat plants expressing the alfalfa aldose reductase under permanent drought stress. *Acta Physiol Plant.* 2014;36:663–73. <https://doi.org/10.1007/S11738-013-1445-0>
46. El-Esawi MA, Al-Ghamdi AA, Ali HM, Ahmad M. Overexpression of AtWRKY30 transcription factor enhances heat and drought stress tolerance in wheat (*Triticum aestivum* L.). *Genes.* 2019;10(2):163. <https://doi.org/10.3390/genes10020163>
47. Li L, Zheng M, Deng G, Liang J, Zhang H, Pan Z, et al. Overexpression of AtHDG11 enhanced drought tolerance in wheat (*Triticum aestivum* L.). *Mol Breed.* 2016;36:1–10. <https://doi.org/10.1007/s11032-016-0447-1>
48. Abdallah NA, Elsharawy H, Abulela HA, Thilmony R, Abdelhadi AA, Elarabi NI. Multiplex CRISPR/Cas9-mediated genome editing to address drought tolerance in wheat. *GM Crops Food.* 2025;16:1–17. <https://doi.org/10.1080/21645698.2022.2120313>
49. Chaouachi L, Guzmán-López MH, Karmous C, Barro F, Marín-Sanz M. Assessing drought stress response in low-gliadin wheat developed via RNAi and CRISPR/Cas. *Plant Stress.* 2025;16:100906. <https://doi.org/10.1016/j.stress.2025.100906>
50. Chen K, Wang Y, Zhang R, Zhang H, Gao C. CRISPR/Cas genome editing and precision plant breeding in agriculture. *Annu Rev Plant Biol.* 2019;70:667–97. <https://doi.org/10.1146/annurev-arplant-050718-100049>
51. Joga RJ, Zotti MJ, Smagghe G, Christiaens O. RNAi efficiency, systemic properties and novel delivery methods of pest insect control: what we know so far. *Front Physiol.* 2016;7:553. <https://doi.org/10.3389/fphys.2016.00553>
52. Lamaoui M, Jemo M, Datla R, Bekkaoui F. Heat and drought stress in crops and approaches for their mitigation. *Front Chem.* 2018;6:26. <https://doi.org/10.3389/fchem.2018.00026>

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