University of Thi-Qar Journal of agricultural research

Thi-Qar Journal of agricultural research

ISSN Onlin:2708 -9347, ISSN Print: 2708 -9339 Volume 15, Issue 1 (2026)

https://iasj.rdd.edu.iq/journals/journal/issue/20226 https://doi.org/10.54174/utjagr.v13ii_138

Morphological Responses of Wheat (Triticum aestivum L.) Cultivars to Water Stress under Field Conditions: A Review Study

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I. Abstract

This review summarizes recent findings regarding the morphological, physiological, and yield responses of wheat (*Triticum aestivum* L.) cultivars to water deficit stress under field conditions. Wheat is one of the world's major cereal crops and provides nearly 35% of global calories and protein; however, its productivity is increasingly threatened by drought and climate change, particularly in arid and semi-arid regions such as Iraq. Water deficit stress causes abscisic acid accumulation, stomatal closure, reactive oxygen species (ROS) production, and reduced photosynthetic activity, ultimately accelerating leaf senescence. Drought conditions also reduce plant height, tiller number, flag leaf area, and total dry matter accumulation due to restricted cell division and elongation. Grain yield is severely affected, especially during flowering and grain-filling stages, where reduced CO_2 availability negatively influences pollination and kernel development. The review highlights the importance of drought adaptation strategies, including drought escape, drought tolerance, and drought avoidance, in wheat breeding programs. Furthermore, field-based evaluation of morphological traits and drought indices such as the Standardized Soil Wetness Index (SSI) and Stress Tolerance Index (STI) is recommended for identifying drought-tolerant wheat cultivars. Long-term yield stability can be improved through efficient irrigation management and the selection of genotypes with high water-use efficiency.

Keywords: Water stress, Triticum aestivum L., Morphological characteristics, Drought tolerance

II. Introduction

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops worldwide and represents a major component of global food security. However, its production is increasingly threatened by climate change, drought, heat stress, and limited water availability, especially in arid and semi-arid regions where crop productivity often remains below the genetic potential of modern cultivars. Pequeno et al. (2021) reported that climate change is expected to negatively affect wheat production, particularly in regions already facing food-security challenges. Similarly, Ahmad et al. (2022) emphasized that water scarcity is one of the major constraints limiting wheat productivity under changing climatic conditions.

Water stress is considered one of the most damaging abiotic factors affecting wheat growth and yield. Its impact depends on the severity of stress, the growth stage at which stress occurs, and the genetic background of the cultivar. Wasaya et al. (2021) found that drought stress reduced important yield-related traits such as grain yield and grain weight in wheat genotypes grown under different water-stress levels. Mahdavi et al. (2022) also showed that drought stress reduced grain yield mainly through reductions in grain number per spike and thousand-grain weight.

Under field conditions, water deficit causes clear changes in wheat morphological and agronomic traits. These include reductions in plant height, tiller number, flag leaf area, spike length, biological yield, biomass accumulation, harvest index, and final grain yield. Farhood et al. (2022), in a study conducted in Iraq, reported that drought stress reduced plant height, flag leaf area, tillers, biological yield, grain yield, and harvest index in wheat cultivars. Makebe et al. (2024) also confirmed that traits such as productive tillers, shoot biomass, root biomass, spike length, thousand-seed weight, and grain yield are strongly associated with drought response in wheat.

The evaluation of wheat genotypes under both drought-stressed and well-watered conditions is essential for identifying cultivars with stable performance. Sewore et al. (2023) evaluated bread wheat genotypes using morpho-physiological traits and found significant genetic variation under drought and non-drought conditions. In another study, Sewore and Abe (2024) reported that yield-related traits such as fertile spikelets, thousand-kernel weight, biomass yield, and harvest index had positive associations with grain yield under drought-stressed and well-watered conditions.

Recent studies also indicate that combining morphological traits with yield components can improve the selection of drought-tolerant wheat genotypes. Shahid et al. (2022) highlighted the importance of agronomic and yield attributes in selecting high-yielding wheat genotypes under water-deficit stress. Mutanda et al. (2024) further showed that agro-morphological traits, yield components, and water-use efficiency are useful indicators for selecting wheat genotypes adapted to drought conditions. Therefore, the present review aims to summarize recent findings on the morphological and productive responses of wheat cultivars to water stress under field conditions, with emphasis on traits that can support the identification of drought-tolerant wheat genotypes in water-scarce environments.

Wheat Plant

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops worldwide and represents a major source of food and economic stability in many arid and semi-arid regions. Its production is strongly influenced by environmental stresses, particularly drought and heat, which reduce crop growth and final productivity. El Gataa et al. (2021) reported that drought and heat stresses affect wheat yield and yield-related traits, especially in dry regions such as West Asia and North Africa. Under water-deficit conditions, wheat cultivars show measurable changes in morphological and agronomic traits, including biomass production, thousand-grain weight, grain number, harvest index, and grain yield. Lateif et al. (2024) showed that drought stress reduced most traits in wheat landraces, including biological yield, thousand-seed weight, and grain yield. Therefore, evaluating morphological traits under drought conditions is important for identifying wheat genotypes capable of maintaining stable productivity in water-limited environments.

Water Stress

Water stress in wheat (*Triticum aestivum* L.) refers to a condition in which insufficient water availability disrupts normal plant-water relations and limits essential growth processes. Drought is considered one of the most damaging abiotic stresses affecting wheat productivity, particularly in arid and semi-arid regions where rainfall is irregular and irrigation water is limited. Wheat is sensitive to water deficit because its growth, tillering capacity, leaf expansion, spike development, and grain filling depend strongly on adequate soil moisture. Under drought conditions, wheat plants commonly show reduced vegetative growth, decreased photosynthetic activity, impaired nutrient assimilation, and lower biomass accumulation, which are ultimately reflected in reduced yield components such as spike number, grain number, and thousand-grain weight (Aslam et al., 2022). The severity of drought damage in wheat depends greatly on the growth stage at which stress occurs. Water deficit during early vegetative growth can reduce seedling establishment, tiller formation, and leaf area development, whereas drought during heading, flowering, and grain-filling stages is usually more destructive because these stages directly determine final grain yield. Stress during reproductive development may reduce pollen viability, spike fertility, assimilate transport, and kernel weight, leading to substantial yield losses. At the cellular level, drought also promotes the overproduction of reactive oxygen species (ROS) in chloroplasts, mitochondria, and peroxisomes. When ROS production exceeds the antioxidant capacity of the plant, oxidative damage occurs through lipid peroxidation, protein degradation, and nucleic acid modification. However, drought-tolerant wheat genotypes are often better able to maintain water status, protect photosynthetic tissues, and activate antioxidant defense systems, allowing them to sustain growth and yield more effectively than drought-sensitive genotypes (Hasanuzzaman et al., 2020).

Effect of Water Stress on Plants and Adaptation Mechanisms

When soil moisture decreases, wheat (*Triticum aestivum* L.) plants first show reductions in cell expansion, leaf growth, and tiller development. These early responses are later reflected in measurable morphological traits such as reduced plant height, smaller flag leaf area, fewer productive tillers, lower biomass accumulation, and shorter spikes. At the physiological level, water deficit stimulates the accumulation of abscisic acid (ABA), which promotes stomatal closure and reduces transpiration. Although this response helps conserve water, prolonged stomatal closure can limit CO_2 uptake and reduce photosynthetic activity, ultimately affecting grain formation and yield. Wheat cultivars differ in their ability to adapt to drought stress through three major strategies: drought escape, drought avoidance, and drought tolerance. Drought escape is commonly associated with early heading and maturity, allowing the plant to complete sensitive reproductive stages before severe water deficit occurs. Drought avoidance involves traits such as deeper root systems, reduced leaf area, leaf rolling, waxy leaves, and better stomatal regulation, which help the plant maintain water status under dry conditions. Drought tolerance, on the other hand, depends on osmotic adjustment through compatible solutes such as proline and soluble sugars, antioxidant defense systems, and cellular protection mechanisms that allow metabolism to continue under low water availability (Jogawat et al., 2021). Although ABA, calcium signaling, reactive oxygen species (ROS), and other phytohormones play important roles in drought response, their practical importance in wheat appears through their effects on field performance. For example, stronger stomatal control, osmotic adjustment, and antioxidant protection can help tolerant wheat genotypes maintain greener leaves, better biomass production, higher spike fertility, and more stable grain yield under drought conditions. Therefore, physiological and biochemical adaptations should not be viewed separately from morphology; rather, they are internal mechanisms that ultimately determine the visible growth performance and yield stability of wheat cultivars under water-stressed environments (Vishwakarma et al., 2017).

Effect of Water Stress on the Morphological Traits of Wheat Plants

Plant Height

Plant height is one of the most visible morphological traits affected by water stress in wheat. Under drought conditions, reduced soil moisture lowers cell turgor pressure, which limits cell division and elongation, particularly in internodal tissues during jointing and stem elongation stages. In addition, reduced photosynthetic activity and nutrient uptake limit the supply of assimilates required for stem growth. Abid et al. (2018) reported that drought imposed during jointing and stem elongation caused marked reductions in plant height because these stages coincide with rapid internode elongation. However, reduced plant height should not always be interpreted as a purely negative response. In many cases, severe height reduction reflects drought injury and is associated with lower above-ground biomass, fewer spikes, and reduced grain yield. Nevertheless, moderately shorter plants may show adaptive advantages under water-limited conditions because they require less water for vegetative growth and may allocate more assimilates toward reproductive structures. Semi-dwarf or naturally shorter wheat genotypes can also have improved lodging resistance and, in some environments, better water-use efficiency. Therefore, plant height can be used as a useful but indirect indicator of drought response, especially when compared across genotypes under both stressed and non-stressed conditions. However, it should not be used alone as a reliable drought-tolerance criterion. Its interpretation should be combined with other field traits such as productive tiller number, flag leaf area, biomass accumulation, harvest index, spike fertility, thousand-grain weight, and final grain yield. In this context, drought-tolerant genotypes are not necessarily the tallest under stress, but those that maintain balanced growth and stable yield performance despite limited water availability.

Number of Tillers

Tiller number is one of the most drought-sensitive morphological traits in wheat because tiller initiation depends strongly on adequate soil moisture, carbohydrate supply, and nutrient uptake during the early vegetative stage. Under water-deficit conditions, reduced photosynthesis, impaired carbohydrate metabolism, and limited root nutrient absorption restrict the development of axillary buds at the basal nodes into productive shoots. As a result, fewer tillers are formed, and a smaller proportion of them survive to produce fertile spikes. Drought occurring during the early vegetative stage is therefore particularly damaging because lost tillers cannot be fully compensated later in the growing season. However, the reduction in tiller number under drought is not uniform among wheat genotypes. Some cultivars show a sharp decline in tillering, while others maintain a higher number of productive tillers under limited water availability. This variation may be related to differences in root development, assimilate partitioning, osmotic adjustment, and the ability to maintain leaf water status during stress. Hussein et al. (2023) reported that water deficit caused a noticeable decrease in tiller number per plant, along with reductions in spike length and grain weight per spike. In comparison, Shahid et al. (2022) showed that more tolerant genotypes, such as Faisalabad-2008, maintained a higher number of tillers under 35% field capacity, which contributed to greater biological and grain yields. These findings indicate that tillering response should be interpreted in relation to genotype performance and stress timing. A high tiller number under drought is valuable only when a large proportion of tillers become productive spikes. Therefore, productive tiller number may be a more reliable selection trait than total tiller number alone. In breeding and field evaluation, genotypes that maintain productive tillers, spike fertility, and grain weight under water stress can be considered better adapted to drought-prone environments.

Flag Leaf Area

The flag leaf is one of the most important morphological and physiological organs in wheat because it is positioned directly below the spike and contributes substantially to grain filling through photosynthesis. Under water-deficit conditions, flag leaf area is commonly reduced as a result of decreased cell division, slower leaf elongation, reduced turgor pressure, and limited assimilate availability. This reduction becomes more severe when drought occurs during the flag leaf expansion stage, because the final leaf area is still being formed and any restriction in cell expansion directly limits the photosynthetic surface available later during grain filling. The timing of water stress is therefore critical. Drought imposed during early leaf development may restrict the formation and expansion of the flag leaf, while drought during heading and grain filling mainly reduces its functional capacity by accelerating senescence, lowering chlorophyll content, and decreasing photosynthetic rate. Ning et al. (2023) reported that severe water deficit can markedly reduce flag leaf area, particularly when stress coincides with leaf expansion. Similarly, Moloi et al. (2024) indicated that reduced water uptake and increased transpiration imbalance limit leaf expansion and reduce photosynthetic performance under drought conditions. The functional consequences of reduced flag leaf area are directly reflected in yield formation. Since the flag leaf supplies a large proportion of assimilates to the developing grains, any decrease in its area, greenness, or photosynthetic activity may reduce grain number per spike, thousand-grain weight, and final grain yield. Therefore, maintaining flag leaf area and delaying flag leaf senescence under drought conditions can be considered important indicators of drought adaptation in wheat cultivars.

Plant Dry Weight

Total dry weight is an integrated morphological indicator that reflects the overall growth performance of wheat under water stress. It combines the effects of several drought-induced reductions, including shorter stems, fewer tillers, smaller leaves, reduced flag leaf area, and lower root and shoot growth. Under prolonged water deficit, limited soil moisture reduces cell expansion, photosynthetic activity, nutrient uptake, and assimilate production, leading to a clear decline in dry matter accumulation in both vegetative and reproductive organs. The reduction in total dry weight is particularly important because biomass production is closely related to yield formation. Lower shoot biomass usually means reduced photosynthetic surface area and fewer assimilates available for spike development and grain filling. Sattar et al. (2019) reported that wheat plants grown under 35–40% field capacity showed considerable reductions in shoot dry weight, indicating that severe drought strongly limits biomass accumulation. In addition, water stress may reduce stem thickness and alter plant architecture, producing weaker stems with lower capacity to support spike development and grain load. However, dry weight reduction should be interpreted together with yield-related traits. Some drought-tolerant genotypes may not maintain the highest total biomass, but they may show better biomass partitioning toward grains, resulting in a higher harvest index under stress. Therefore, total dry weight is a useful indicator of drought impact, but its value becomes more meaningful when assessed alongside productive tillers, spike traits, harvest index, thousand-grain weight, and final grain yield.

Yield Components

Yield is the final outcome where the morphological and physiological costs of drought converge. Under water-deficit conditions, stomatal closure reduces intercellular CO_2 concentration, limits photosynthetic activity, and decreases assimilate availability for spike development and grain filling. Drought can also disturb pollen development, anther dehiscence, fertilization, and floret fertility, leading to fewer grains per spike. In wheat, grain yield is mainly determined by three major components: spikes per unit area, grains per spike, and thousand-grain weight. However, these components differ in their sensitivity to drought depending on the timing and severity of stress. Among these components, spikes per unit area is mainly affected when drought occurs during tillering and early stem elongation, because water deficit reduces tiller initiation and tiller survival. This component may be relatively stable if the crop has already established enough productive tillers before stress occurs. Grains per spike is often one of the most drought-sensitive components because it is strongly affected by stress during booting, heading, and anthesis, when spike fertility, pollen viability, and fertilization are being determined. Therefore, drought at reproductive stages commonly causes sharp reductions in grain number. Thousand-grain weight, on the other hand, is most sensitive during grain filling, when water stress shortens the filling period and reduces assimilate translocation from the flag leaf and stem reserves to the developing grains. Itam et al. (2020) reported that drought during tillering reduces spike-bearing shoots, drought during booting and anthesis lowers grains per spike, and drought during grain filling decreases thousand-grain weight. This indicates that each yield component has a specific stress-sensitive window. In general, grains per spike and thousand-grain weight tend to be more directly and rapidly affected by reproductive and terminal drought, whereas spikes per unit area may be more stable if early vegetative growth is not severely stressed. However, the relative stability of each component varies among genotypes and environments. Because of these differences, final grain yield alone may not fully explain drought adaptation. A genotype may maintain yield under stress through different strategies, such as preserving productive tillers, maintaining spike fertility, or sustaining grain filling. Therefore, breeding programs increasingly rely on both yield components and stress tolerance indices to identify genotypes that perform consistently under well-watered and water-limited conditions. Sharma et al. (2022) emphasized that genotype-by-environment interactions are important in drought response, making stress tolerance indices useful tools for selecting stable wheat lines across contrasting moisture environments.

Response of Wheat Cultivars to Water Stress

Wheat cultivars differ widely in their response to water shortage, and that variation is rooted in genotype-driven differences in morphology, phenology and physiology. For breeders working in arid and semi-arid regions, identifying genotypes that combine acceptable yield potential with stable performance under drought has become a top priority, particularly as climate projections point toward more frequent and severe water deficits (Ahmed et al., 2023).

Field-based criteria for variety evaluation

When evaluating wheat cultivars under field conditions, breeders commonly rely on morphological and yield-related traits that reflect the integrated response of the crop to drought stress. These traits include plant height, number of productive tillers, flag leaf area, spike length, spikelets per spike, grains per spike, thousand-grain weight, biological yield, harvest index, and grain yield per unit area. Among these traits, grain yield remains the final and most important selection criterion; however, it is highly influenced by environmental variation and does not clearly explain the mechanism of drought adaptation by itself. Therefore, breeders usually interpret grain yield together with its major components, particularly productive tiller number, grains per spike, and thousand-grain weight. Under drought conditions, some traits are more practically useful than others. Productive tiller number is important because it determines the number of spike-bearing shoots, especially when drought occurs during vegetative growth. Grains per spike is highly sensitive to water stress during booting, heading, and anthesis, making it a useful indicator of reproductive-stage drought damage. Thousand-grain weight is particularly important under terminal drought because it reflects the ability of the cultivar to maintain grain filling when water availability becomes limited. In addition, flag leaf area and delayed leaf senescence are useful field indicators because they are closely related to photosynthetic capacity and assimilate supply during grain filling. Although modern tools such as hyperspectral reflectance, canopy temperature indices, chlorophyll measurements, and stress tolerance indices can improve selection accuracy, they may require specialized equipment and technical expertise. In contrast, traits such as productive tillers, spike traits, thousand-grain weight, biological yield, harvest index, and grain yield are widely used in practical field screening because they are easier to measure and directly related to yield performance. Darwish et al. (2023) emphasized the importance of field-based morphological and yield descriptors because they capture genotype–environment interactions more realistically than controlled conditions. Similarly, Jahan et al. (2025) suggested that combining traditional traits with modern indices can improve the identification of wheat genotypes with stable performance under contrasting water regimes. Therefore, the most useful traits under drought are not simply the largest number of measured traits, but those that combine practical measurability with strong association to yield stability. In this context, productive tiller number, grains per spike, thousand-grain weight, harvest index, and grain yield are among the most important practical criteria for selecting drought-tolerant wheat cultivars under field conditions.

Differences between drought-tolerant and drought-sensitive cultivars

Drought-tolerant wheat varieties often share several adaptive attributes that help them maintain growth and yield under limited water availability. These include deeper and more extensive root systems, narrower or rolled leaves, better stomatal regulation, relatively early flowering or maturity, and the ability to maintain higher relative water content under stress. Early flowering and maturity may help some genotypes escape terminal drought by completing reproductive development before severe water deficit occurs, while deeper roots and reduced leaf area contribute to drought avoidance by improving water uptake and reducing water loss (Mutanda et al., 2024). However, these traits are not always sufficient to clearly separate drought-tolerant from drought-sensitive genotypes. Considerable overlap may occur between tolerant and sensitive lines because some sensitive genotypes may express one adaptive trait, such as early maturity or leaf rolling, without maintaining grain yield under stress. Similarly, some tolerant genotypes may not show the deepest roots or the earliest maturity but may perform better because they combine several moderate advantages, such as stable tillering, higher spike fertility, better grain filling, and efficient biomass partitioning. Biochemical and physiological traits can also help explain differences in drought response. Tolerant wheat genotypes often maintain higher relative water content, accumulate compatible osmolytes such as proline and soluble sugars, activate stronger antioxidant enzymes such as SOD, CAT, and APX, and suffer less membrane lipid peroxidation than sensitive genotypes under the same stress conditions (Vukovic et al., 2022). Nevertheless, these internal responses should be interpreted together with field performance, because biochemical tolerance does not always translate directly into higher yield. Therefore, no single trait can be considered completely decisive for distinguishing drought-tolerant from drought-sensitive wheat cultivars. Among field traits, grain yield under stress, harvest index, productive tiller number, grains per spike, and thousand-grain weight are usually more practical and decisive because they reflect the final outcome of drought adaptation. Root depth, leaf rolling, osmotic adjustment, and antioxidant activity are useful supporting traits, but the strongest classification comes from genotypes that maintain stable yield and yield components under water-deficit conditions.

Effect of water stress on wheat cultivars under field conditions

Field research has shown that wheat genotypes do not respond to water deficit in the same way. In multi-cultivar screening trials, drought-tolerant lines usually show lower yield losses and more stable performance across seasons compared with drought-sensitive lines. This stability is often associated with their ability to maintain a higher number of productive tillers, more spikelets per spike, better grain filling, and higher harvest index under stress conditions. Similar genotype-dependent responses to water regime have been reported in field trials conducted in different environments, including Egypt, Bangladesh, and South Africa (Alsamadany et al., 2023). Phenology is another important factor explaining variation among wheat genotypes under drought. Early-maturing genotypes may perform better under terminal drought because they complete flowering and grain filling before soil moisture becomes severely limited. In contrast, late-maturing genotypes may have higher yield potential under favorable conditions, but they are often more exposed to water stress during reproductive and grain-filling stages. Therefore, the advantage of early maturity depends on the type and timing of drought rather than being universally beneficial. Because drought response is strongly influenced by genotype, environment, and their interaction, selection should not depend on a single location or one growing season. Multi-environment trials are necessary to identify genotypes that maintain stable yield and favorable morphological traits under contrasting water regimes. In addition, genetic approaches such as QTL and meta-QTL analyses can support field selection by identifying genomic regions associated with drought adaptation.

However, these molecular tools should complement, not replace, field-based evaluation of morphological and yield-related traits (Saini et al., 2021).

Harvest index of cultivars under water stress

Harvest index (HI) represents the ratio of grain yield to total above-ground biomass and reflects the ability of wheat cultivars to partition assimilates toward the harvested grain. This trait is strongly connected with the morphological traits discussed earlier, because reductions in plant height, tiller number, flag leaf area, biomass accumulation, and spike fertility all influence the balance between vegetative growth and grain production. Under drought conditions, total biomass often declines, but drought-tolerant cultivars are usually those that can maintain a relatively higher proportion of assimilates directed to grain filling. In this context, HI is not simply a yield-related measurement but an important indicator of drought adaptation. A cultivar may produce moderate biomass under stress, yet still perform well if it efficiently transfers stored stem reserves and current photosynthates from the flag leaf to the developing grains. Jatoi (2024) reported that drought-tolerant wheat cultivars generally maintain higher HI under water stress because they continue allocating assimilates to grain formation despite reductions in vegetative growth. In contrast, sensitive genotypes may show large biomass losses accompanied by poor grain filling, resulting in a sharp decline in HI. Modern improved wheat cultivars commonly show HI values around 0.40–0.55 under favorable conditions, whereas severe drought can reduce HI substantially, especially in sensitive lines. However, HI should not be interpreted alone; it becomes more meaningful when evaluated together with grain yield, biological yield, productive tillers, grains per spike, and thousand-grain weight. Molecular and proteomic studies may help explain the internal mechanisms behind assimilate partitioning under drought, but for field-based selection, HI remains most useful as a practical indicator of how efficiently a genotype converts limited biomass into grain yield (Michaletti et al., 2018). Therefore, HI provides a strong link between the earlier morphological responses and final yield performance. Genotypes that maintain a stable HI under drought are often better adapted because they combine acceptable biomass production with efficient assimilate partitioning toward the grain.

Importance of Field Evaluation for Wheat Water Stress Tolerance

Field evaluation is essential in studies of wheat drought resistance because drought response under natural conditions is influenced by several interacting environmental factors. Soil heterogeneity, wind, vapor pressure deficit, temperature fluctuations, irrigation pattern, and root development in real soil all affect wheat growth and yield. These factors cannot be fully reproduced in growth chambers or controlled pot experiments. Therefore, field trials provide a more realistic assessment of morphological traits such as plant height, productive tillers, flag leaf area, biomass accumulation, harvest index, and grain yield under water-limited conditions. Controlled experiments, however, remain useful because they help explain the physiological mechanisms behind field responses. Laboratory and growth-chamber studies have shown that ABA, ROS, and Ca^{2+} signaling play important roles in regulating stomatal closure and water balance in drought-stressed wheat plants. Such information is valuable, but it should be linked to field performance rather than treated separately. For example, stronger stomatal regulation may help reduce water loss, but its practical value depends on whether the genotype can also maintain biomass production, spike fertility, and grain filling under field drought conditions (Liu et al., 2022). Another important advantage of field trials is their ability to reveal genotype × environment (G × E) interactions. A genotype that performs well in one location or season may not show the same performance elsewhere because drought timing, soil type, temperature, and rainfall pattern can differ widely. For this reason, multi-environment field trials are needed before recommending drought-tolerant cultivars. In a multi-environment study, Zhang et al. (2018) investigated G × E interactions and identified QTLs associated with

ISSN Onlin:2708 -9347, ISSN Print: 2708 -9339 Volume 15, Issue 1 (2026)

https://iasj.rdd.edu.iq/journals/journal/issue/20226 *https://doi.org/10.54174/utjagr.v13ii 138*

grain yield and plant water-related traits in spring wheat across 11 sites under contrasting drought-stress levels. Their findings showed that one QTL contributed significantly to grain-yield variation across several environments, with a stronger effect under more severe drought conditions. Thus, molecular tools such as QTL analysis should be considered complementary to, not a replacement for, field-based evaluation of morphological and yield traits.

Conclusion

Water deficit stress remains one of the most damaging abiotic constraints on wheat (*Triticum aestivum* L.) productivity, reducing plant height, tiller number, flag leaf area, dry matter accumulation, and all three major yield components. Drought during flowering and grain filling causes the deepest losses. Cultivar responses vary considerably depending on the genetic capacity for drought escape, avoidance, and tolerance, as well as the efficiency of osmotic adjustment and assimilate partitioning toward the grain. Field-based evaluation across multiple environments, using stress tolerance indices such as STI and SSI alongside key morphological and yield traits, remains the most reliable approach for identifying wheat genotypes capable of sustaining acceptable productivity under water-limited conditions.

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