AGRICULTURAL SCIENCE AND TECHNOLOGY, VOL. 14, No 1, pp 3-14, 2022
Published by Faculty of Agriculture, Trakia University, Bulgaria
ISSN 1313-8820 (print)
ISSN 1314-412X (online)
http://www.agriscitech.eu
DOI: 10.15547/ast.2022.01.001

Review

Drought stress and its management in wheat (*Triticum aestivum* L.): a review

B. Sharma[1*], L. Yadav[2], A. Shrestha[3], S. Shrestha[3], M. Subedi[4], S. Subedi[4], J. Shrestha[4]

[1]Institute of Agriculture and Animal Science, Tribhuvan University, Kritipur, Kathmandu, Nepal
[2]Paklihawa Campus, Institute of Agriculture and Animal Science, Tribhuvan University, Bhairahawa, Rupandehi, Nepal
[3]Himalayan College of Agricultural Science and Technology, Purbanchal University, Kathmandu, Nepal
[4]Nepal Agricultural Research Council, National Plant Breeding and Genetics Research Centre, Khumaltar, Lalitpur, Nepal

(Manuscript received 2 December 2021; accepted for publication 7 February 2022)

Abstract. *Drought is one of the major constraints to wheat production, and it is becoming a more serious problem in many wheat-growing regions of the world. It causes a severe reduction in wheat crop growth and productivity. Water stress at critical growth stages namely tillering, grain filling and flowering stages causes serious yield loss. Morphological, physiological, biochemical, and molecular changes are seen as a result of drought stress in wheat. When plants are exposed to drought stress, they use three basic survival strategies, stress avoidance, escape, and tolerance. Growing drought tolerant varieties and applying agronomic management to create innovative water-use approaches is important for drought management. This review summarizes the effects of drought stress on wheat growth and productivity. This review could be useful for wheat researchers and growers for making the right decision on drought management in wheat.*

Keywords: wheat, water stress, crop growth, yield, yield component

Introduction

Wheat (*Triticum aestivum* L.) is the world's most widely grown cereal crop (Akbar et al., 2001). Common wheat is the staple grain in forty-three countries. Due to the effects of climate change, the extreme adverse natural events are increasing, and environmental stress is one of the major causes of crop loss around the world, with annual yield losses of more than 50% for major crops (Chaves and Oliveira, 2004). The monsoon has become more irregular, contributing to the upscaling of droughts. After diseases, drought stress is the second most important constraint to crop productivity (Singh and Bhalla, 1994). A study for characterizing the agricultural drought prone areas on a global scale reported eastern and southern Africa, the Mediterranean region, the western United States, South American countries, India, China, Sri Lanka among the major drought hotspots (Cumani and Rojas, 2016). Droughts are becoming more common in South and Southeast Asia. Countries such as Bangladesh, Nepal, Bhutan, Cambodia, and Philippines all fall in the monsoon climatic zone (Miyan, 2015). The ill-effect of drought is direr on the agricultural sector and overall livelihood of developing nations (Cumani and Rojas, 2016).

Drought stress can be defined as a shortage of water that results in substantial morphological, biochemical, physiological, and molecular changes (Sallam et al., 2019). Reduced leaf water potential and turgor pressure, stomatal closure, and decreased cell growth and enlargement are all symptoms of drought stress in plants (Farooq et al., 2009). The crop's performance is determined by the availability of water during different critical stages (Ashraf et al., 1994; Jamal et al., 1996). When moisture stress occurs, it is known to lower biomass, tillering ability, grains per spike, and grain size. As a result, the overall effect of moisture stress is determined by the degree and duration of the stress (Bukhat, 2005). Water stress at later stages may also result in a decrease in the number of kernels per ear

*e-mail: agribarsha77@gmail.com

and the weight of the kernels (Gupta et al*.,* 2001; Denčić et al*.,* 2000). Drought stress can cause loses at any time during the crops growing season (Blum, 2005), although its impact on yield reduction is the greatest during anthesis. Water stress during anthesis lowers pollination, resulting in fewer grains being generated per spike, lowering grain production. Adequate water during or after anthesis permits the plant to enhance photosynthetic rate while also giving it more time to translocate carbohydrates to grains (Zhang and Oweis, 1998), resulting in larger grains and higher grain production. Drought during critical growth phases, such as tillering, booting, earing, anthesis, and grain development stages, causes the loss in radiation usage efficiency resulting in decreased growth rate. The availability of water during these critical stages determines the crop's performance (Ashraf et al., 1994; Sarwar, 1994; Jamal et al., 1996).

Plant responses to drought are influenced by a variety of parameters including growth rate, severity, genotype, duration of stress, photosynthetic machinery activity, respiration, and transpiration, as well as environmental conditions. Several genes in wheat are involved in drought stress tolerance and produce several enzymes and proteins, such as late embryogenesis abundant (LEA), responsive to abscisic acid (Rab), rubisco, helicase, proline, glutathione-S-transferase (GST), and carbohydrates (Nezhadahmadi et al., 2013). There are three known strategies for dealing with drought stress: tolerance, escape and avoidance. Avoidance or tolerance can reduce detrimental effect of drought in plants. Avoiding drought is the ability of plants to provide a high-water potential with reduced water availability in the soil and in fact avoid dehydration. Tolerance to dehydration is the ability of plants to withstand minimum water injury and internal water deficits. Another way to face the drought is to escape. This is where the plant completes its life cycle long before the onset of drought.

To combat drought, an interdisciplinary approach involving agronomy, plant breeding, plant physiology, plant biotechnology, water engineering, and other disciplines is required to create innovative water-use approaches. Mulching, conservation tillage, intercropping, early sowing, crop selection and variety selection, and micro-irrigation are all agronomic practices that can help crops cope with drought. Drought-tolerant wheat cultivars are being developed using modern approaches such as physiological trait-based breeding, molecular breeding, marker-assisted backcrossing, aerial phenotyping, water budgeting, and resource allocation (Ahmad et al., 2018). The objective of this review is to gather information on drought stress's effects on wheat growth and productivity.

Effect of drought stress on morphological changes

The most prevalent symptoms of water stress are poor germination and crop establishment (Harris et al., 2002). Cell development is an important drought-sensitive physiological function due to a decrease in turgor pressure. Water stress induces a drop in leaf area index that is equal to or larger than that induced by reproductive growth. According to Cui et al. (2015), moderate or severe water deficit during tillering had no effect on flag leaf area but reduced it significantly when it occurred during jointing stage in wheat. When there is a dearth of water, many metabolic processes including the rate of photosynthesis in plants slows down (Wang et al., 2018). Lack of water causes discoloration, as well as an increase in leaf trichomes and stomata on the leaf surface. Proline buildup and abscisic acid stress rise when CO_2 flow and leaf transpiration decrease (Heidaiy and Moaveni, 2009). Chlorosis, which causes a decline in photosynthesis, is one of the most evident indicators of leaf senescence. Senescence usually begins in older leaves and extends to younger ones. Drought stress reduces plant height, dry weight, and root canopy ratio while increasing leaf rolling and drying scores (Samyuni and Purwanto dan, 2015). Plant roots obtain nutrients and water from the ground, and they play a crucial role in drought conditions as well. When water sources are few, plant roots descend deep into the earth to absorb water from the soil.

Effect of drought stress on physiological changes

In current and future climate change scenarios, drought stress (water shortage) is the principal abiotic stress that substantially lowers yield and productivity. According to the IPCC (2014) study, the reduction in yield, productivity, and quality is mostly due to a severe water shortage and poses a serious threat to agriculture. Drought has a complex effect on grain output, involving processes such as nutrient assimilation and mobilization to multiple reproductive organs, stem reserve accumulation, gametogenesis, fertilization, embryogenesis, endosperm and seed growth. Because these pressures can affect crop output at any stage of development, the seed filling stage is critical for calculating average seed weight and seed composition, and thus the final quantitative and qualitative yield is reduced (Cakir, 2004). In higher plants, drought stress causes mycological changes such as turgor loss, osmotic adjustment, and a decrease in leaf water capacity. Turgor potential is the physical force required to cause cell expansion, which is largely influenced by the extensibility of the cell walls. A low turgor pressure caused by water stress induces a reduction or stoppage of growth by limiting cell extensibility. During a water scarcity, plants' water balance is disrupted, resulting in a drop in relative water content (RWC) and water capacity of the leaves (Siddique et al., 2000; Gupta et al., 2001). Changes in the relative water content of leaves are supposed to indicate drought stress. Various forces work on the soil-plant-atmosphere continuum, allowing water to be taken in and lost, thus forming the water interactions. Relative water contents, water potential, osmotic potential, and turgor potential are the plant components. Water relations are vital for a variety of reasons. To begin with, changes in water-related characteristics represent variances between species and cultivars and are used as a measure of drought tolerance or adaptability (Ashraf et al., 1994). The drop in RWC has been shown to alter plant growth and yield (El Hafid et al., 1998; Pereira-Netto et al., 1999; Molnár, 2002). The excised leaf water retention capacity of wheat cultivars was investigated by Ashraf and Khan (1993) and Ashraf et al. (1994), who discovered that genotypes with higher RWC were more tolerant to drought. Leaf survival required for absorption is determined by RWC rather than leaf water potential, according to Ashraf et al. (1994), Pereira-Netto et al. (1999), Molnár (2002), and Siddique et al. (2000). Water stress reduces plant leaf water potential, which is a reliable metric for assessing plant water stress response and screening drought-tolerant genotypes (Ashraf et al., 1994). According to Sairam et al. (1990), a decrease in leaf water potential exacerbated drought stress. Similar findings were reported by Ashraf et al. (1994). According to Ashraf et al. (1994), osmotic adjustment is caused by the buildup of solutes, which reduces the osmotic potential and aids in the maintenance of turgor in plants under water stress. Plants lose their turgor when exposed to water stress, limiting cell proliferation and growth (Siddique et al., 2000). As a result, the plants' turgor must be adjusted for cell expansion and growth to resume. The major mechanism of major maintenance, according to Munns (1979), is osmoregulatory. Solutes accumulate during osmoregulation. Ashraf et al. (1994) discovered that genotypes with increased turgor were drought tolerant. Growth analysis is the foundation for determining a plant's response to environmental challenges. The key physiological determinant of crop productivity is the leaf area index (LAI). Lower cell enlargement (McCree and Davis, 1974), stunted growth (Jones et al., 1980) are all possible causes of reduced leaf area index (Oppenheimer, 1960). Another reason for the reduction in LAI could be an increased abscission rate caused by a decrease in the water status of the plant under stress. Water stress during vegetative growth induced a drop in wheat LAI, according to Qadir et al. (1999).

Many essential physiological and morphological processes, such as leaf expansion, stomatal conductance, and photosynthetic activity, are directly controlled by leaf turgor potential (Ashraf et al., 1994). Drought stress causes the stomata to close, reducing the amount of CO_2 available for photosynthesis and hence slowing photosynthesis. Reduced photosynthetic rates can result in the lower starch buildup and invertase activity, which can lead to pollen sterility and ovary abortion (Farooq et al., 2014). As a result, the yield is reduced. Chlorophyll is a good measure of a plant's photosynthetic capacity, which both directly and indirectly reflects the plant's health and responsiveness to water stress. It is a good indicator of a plant's photosynthesis capability, which directly reflects the plant's health and indirectly reflects its response to water stress (Guo et al., 2003).

Effect of drought stress on biochemical changes

Drought stress causes an imbalance between electron excitation and photosynthetic consumption, leading to the formation of reactive oxygen species (ROS), primarily superoxide and hydrogen peroxide (H_2O_2) (Reddy, 2004). By damaging cell membrane proteins and nucleic acid, these ROS cause oxidative stress (Liu et al., 2015). The absence of oxidative stress is shown by the presence of malondialdehyde (MDA) in the intracellular environment (Sabra, 2012). The plant has both enzymatic and non-enzymatic activity to detoxify ROS (Abid et al., 2016). The enzyme superoxide dismutase (SOD) catalyzes the transformation of O_2- into the less reactive H_2O_2 (Helena and Carvalho, 2008). This H_2O_2 is further detoxified to O_2 and H_2O by the enzymes catalase (CAT) and ascorbate peroxidase (APX). When the enzymes listed above are coupled, they assure a low level of O_2- and H_2O_2 in the intercellular space. Antioxidants that are not enzymes, such as glutathione (GSH) and carotenoids, have a function in cellular defense. GSH protects the chloroplast from ROS damage by raising the ratio of reduced to oxidized glutathione, whereas carotenoid protects the photosynthetic system by turning excess excitation energy into heat. Drought stress adaptation relies heavily on proline aggregation and catabolism. Proline can be degraded by plants using an oxidation process. Proline aids in adjustment, ROS detoxification, and membrane integrity protection. Proline accumulation has been proposed as a suitable osmolyte and a mechanism to store carbon and nitrogen, as well as a role in plant stress tolerance adaption. It functions as an osmoregulator. Proline increases in response to water stress and dissipates quickly after the stress is alleviated due to differences in cytosolic synthesis and mitochondrial breakdown rates (Kiyosue et al., 1996). Drought causes morphological, physiological and biochemical changes in wheat (Table 1).

Table 1. Morphological, physiological and biochemical changes caused by drought stress in wheat

Parameters	Changes
Morphology	Plants of a small size, maturity at an early age, reduced leaf surface area limited leaf extension, decreased leaf size, decreased number of leaves, reduced yield and yield attributing traits (plant height, grains per spike, spikes per plant and 1000-grain weight).
Physiology	Closure of stomata, photosynthesis declines, rise in oxidative stress, changes in cell wall integrity, reduced leaf water potential, reduced stomatal conductance, reduced internal CO_2 concentrations, decreased growth rates, water use efficiency has improved, decrease in transpiration, improvements to the AOX pathway, decreased relative water content
Biochemistry	Rubisco efficiency decreases, photochemical efficiency deteriorates, reactive oxygen species (ROS) were produced, damage from oxidation, antioxidant defense, ABA production, chlorophyll content has decreased, production of proline, the production of polyamines, an increase in antioxidative enzymes is seen, carbohydrates are made, reduction in cytokinin contents, accumulation of ABA.

[Source: Fischer et al. (1980), Powel et al. (1996), and Russell et al. (1997) Lawlor and Cornic (2002), Karthikeyan et al. (2007), Ji et al. (2010), Kilic and Yağbasanlar (2010), Nezhadahmadi et al. (2013)]

Effect of drought stress on yield and yield components

It is true that even in resistant genotypes, grain yield and yield components are reduced in drying soil. The number of tillers that survive to maturity, spike length, viable spikelets, seed per spike, and grain size all influence grain yield (1000-grain weight). Both Sharif (1999) and Musaddique et al. (2000) found that wheat yielded the maximum of tillers (more than 400 tillers/m^2) when the maximum number of irrigations was administered. McDonald et al. (1984) discovered that having the most tillers was associated with having the most irrigations. The significance of fertile tillers can be seen in the fact that they have a direct impact on the eventual grain production. The number of spikes/m^2 increased as irrigation increased, according to Matsunaka et al. (1992) and Ghazal et al. (1998). Many studies have found that irrigation has a comparable effect on wheat spike length (Swati et al., 1985; Ahmad, 1994). In diverse wheat cultivars, Denčić et al. (2000) and Shehzadi (1999) found that spikelets/spike are more vulnerable to drought stress. Water stress has been shown to have similar effects on 1000-grain weight (Qadir et al., 1999; Shehzadi, 1999; Denčić et al., 2000). The productive spikes per plant help to increase yield when there is a water shortage. The water stress administered at different phases affects the number of viable spikelets per ear and the 1000-grain weight in this study.

According to Akram (2011), grain yield sensitivity to drought was shown to be dependent on the severity of stress and the stage at which it was applied. He also found that combined stress at the tillering and anthesis stages resulted in a greater drop in grain production than either stage alone. It is plausible to deduce that if irrigation is not applied throughout the tillering and anthesis stages, grain production is drastically diminished (Pannu et al., 1996). When comparing water stress at the vegetative stage (tillering stage) to water stress at the blooming, grain filling stage, Sokoto and Singh (2013) found that water stress during the vegetative stage (tillering stage) resulted in shorter spike length. Water stress administered at that stage may have resulted in shorter plants, as seen by the shorter spikes detected during stress at tillering. There is a link between incoming radiation and the number of photosynthates available for spike growth in wheat (Acevedo et al., 2009). Photosynthesis and photosynthate transfer to spike growth are slowed by water stress. Under water stress, Mirbahar et al. (2009) reported a drop in spike length. Water stress causes a decrease in the number of spikelets per spike at tillering and blooming. Water stress-induced at tillering and flowering could result in fewer spikelets primordial being generated during tillering, or floret death at the terminal and basal end of the spike during stem extension could explain the reduced number of spikelets per spike observed. Water stress has a considerable inhibitory influence on the number of grains per spike, according to Tompkins et al. (1991). When there is less water stress during blooming, the quantity of grains per spike is smaller than when there is less water stress during tillering and grain filling. Because photosynthesis and translocation decrease with water stress, the number of blooms and grains decreases. Pollen generation and fertilization can be severely hampered by water stress. Water stress during vegetative and reproductive development caused a considerable reduction in the number of grains per spike in wheat, according to Khanzada et al. (2001) and

Qadir et al. (1999). Water stress at flowering and grain filling affected grain production more than water stress at tillering did. Water stress may reduce yield by reducing photosynthesis and translocation, leading to a drop in spikelets per spike, grain per spike, and 1000-grain weight. Water stress resulted in yield reductions of 16.50%, 34% and 25% in the combined study as a result of tillering, blooming, and grain filling, respectively. Drought stress occurred at different stages causing yield loss (Table 2).

According to various researchers, there was a linear link between available water and yield, where a reduction in available water inhibits evapotranspiration and, as a result, reduces production (Shani and Dudley, 2001). The number of tillers and spikes per m2, the number of grains per spike, and the thousand kernel weights all increased significantly as a result of irrigation. Similar finding was reported by Wajid (2004) in Pakistan, who discovered that irrigation is a production component that has a considerable impact on wheat yield. The flowering season is said to be the most vulnerable to water deficits, because pollen generation and fertilization can be severely hampered by drought, resulting in a decrease in yield due to a fall in fertile spikelet number and filled grain percentage. The 1000-grain weight of wheat was also lowered due to water stress, according to Khan et al. (2005) and Qadir et al. (1999). Plants have been discovered to have the potential to adapt to changing environmental conditions, which are often unstable due to a variety of variables. Water stress has a significant impact on the plant height of wheat, which has been employed in numerous studies. Plant height, spike length, number of grains per spike, and 1000 grain weight of wheat exhibited significant variations as water stress increased.

Cui et al. (2015) conducted a pot experiment using winter wheat cultivar (Yangmai16) to investigate the effects of different water deficit levels during vegetative periods on post-anthesis photosynthetic capacity and the relationship with grain yield. Cui et al. (2015) showed that water deficit during tillering significantly increased grain yield through an enhanced yield capacity per stem and moderate water deficit during jointing resulted in similar grain yields as compared to control, while severe water deficit during both periods significantly reduced grain yield due to strong reduction in a number of spikes as compared to control. They concluded that improved photosynthetic capacity by moderate water deficit during vegetative growth period highly contributed to grain yield, especially during the tillering period, while grain yield decreased by the limitation of leaf area and spikes under severe water deficit.

Table 2. Yield loss in wheat caused by drought stress in different growth stages

Stages	Yield loss (%)	References
Tillering stage	46.85	Schneekloth et al. (2009)
Booting stage	20.74	Schneekloth et al.(2009)
Booting to maturity	27	Shamsi and Kobraee (2011)
Heading	57	Balla et al (2011)
Heading to maturity	44	Prasad et al. (2011)
Pre-anthesis	18-53	Majid et al. (2007)
Anthesis	11-39	Jatoi et al. (2011)
Post- anthesis	13-38	Majid et al. (2007),
Grain formation stage	65.5	Tuberosa and Salvi (2006), Sivamani et al. (2000).
Grain filling to maturity	35	Shamsi and Kobraee (2011)

(Source: Nezhadahmadi et al., 2013)

Agronomic management of drought stress

Drought management measures are designed to protect water sources such as rain, irrigation water, and snow. Drought stress in wheat can be mitigated by using the drought tolerant wheat genotypes and adjusting agronomic methods (plant density, sowing time, and management of soil). These strategies must ensure that the crop-sensitive stages of wheat development occur when the risk of drought is at its lowest. Agronomic methods like efficient irrigation water use, shifting sowing schedules, and seed priming can all help to mitigate the effects of drought (Hussain et al., 2019). Seed priming aids in seedling vigor, germination, and emergence. Mulches inhibit weed growth by limiting light penetration into the soil, hence improving water availability to crop plants in drought conditions (Rakshit et al., 2020). During the growth season, surface residue helps to prevent evaporation.

Drought management techniques must concentrate on efficient soil moisture extraction, crop establishment, biomass, growth, and grain yield. Under water shortage conditions, the key priority should be to preserve yield stability. Crop rotation and diversification also aids in water conservation. Crop rotation is thought to assist enhance the water relationship in soils, as well as the yield and biomass of the crop (Pierce and Rice, 1988). Similarly, applying macro and micronutrients externally to wheat improves drought resistance. Exogenous silicon (Si) has been used to reduce the effects of drought on wheat and rice (Gong et al., 2005; Gautam et al., 2016). Plants treated with Si had higher antioxidant activity (Gong et al., 2005; Ma et al., 2016), more photosynthetic pigments (Gong et al., 2005), and changes in the expression of genes involved in the ascorbate-reduced glutathione cycle, flavonoid biosynthesis, and antioxidant response (Ma et al., 2016). Under drought stress circumstances, applying an adequate amount of nitrogen fertilizer helps to enhance re-mobilization and grain filling, which helps to compensate for the loss caused by lower photosynthesis and reduced grain filling (Yang and Zhang, 2006). The use of organic manure has also been shown to improve the soil's water retention capacity (Carter, 2002). As a result, applying organic manure to the wheat field improves the potential impact of drought to the crops production.

Drought tolerance in wheat

In a water-scarce environment, drought avoidance is a critical adaptation for survival. The ability of a plant to live in a dry environment is referred to as drought tolerance (Ashley, 1993). Drought tolerance is a complicated polygenic characteristic, which means that several factors influence a plant's ability to withstand drought. Drought has an impact on the cellular, tissue, and organ levels of plants (Beck et al., 2007). Drought-tolerant plants respond to drought by activating a range of defense mechanisms, all of which must be understood to create drought-tolerant cultivars (Chaves and Oliveira, 2004). The mechanisms of drought resistance can be morphological, physiological, or molecular (Farooq et al., 2009). One of the morphological processes is drought escape, which is the ability of plants to complete their life cycle before the onset of the drought season (Mitra, 2001). Drought avoidance refers to a plant's ability to retain water by boosting intake and decreasing loss through reduced transpiration, which is aided by the plant's long and dense root network, as well as leaf and stomatal features. Osmotic adjustment (OA) is one of the most critical elements that permits a cell's osmotic potential to be reduced while maintaining turgor, allowing the plant to live in a low-water environment (Blum, 2005; Farooq et al*.,* 2009). Wheat plants' glaucousness (a waxy layer over the cuticle) is also regarded to be a valid measure for boosting water usage efficiency and offering drought tolerance mechanisms (Richards et al., 1986).

Drought tolerance indices provide us a better chance to select genotypes that perform well in both normal and stress conditions. As a selection criterion, scientists have developed several different drought tolerance indexing methods. Some drought tolerance indices used in wheat are given in Table 3.

Table 3. List of the drought tolerance indices and formulae

Index	Symbol	Formula	References
Mean productivity	MP	(Yp+Ys)/2	Rosielle and Hamblin (1981)
Geometric Mean Productivity	GMP	$\sqrt{(Yp \times Ys)}$	Fernandez (1992)
Stress susceptibility index	SSI	(1-(Ys/Yp))/SI, Where SI = 1-($\overline{Y}s/\overline{Y}p$)	Fischer and Maurer (1978)
Stress Tolerance	ST	Yp-Ys	Rosielle and Hamblin (1981).
Stress Tolerance Index	STI	(Ys ×Yp)/($\overline{Y}p^2$)	Fernandez (1992)
Drought Resistance Index	DRI	Ys ×(Ys/Yp)/$\overline{Y}s$	Lan (1998)
Yield Index	YI	Ys/$\overline{Y}s$	Gavuzzi et al. (1997)
Yield stability index	YSI	Ys/ Yp	Bouslama and Schapaugh (1984)
Drought Index	DI	Regression method	McDonald and O'Leary (2016)

Note: Yp is the yield under non-stress; Ys the yield under stress condition; □p is the mean yield of all genotypes; □s is the mean yield of all genotypes; SI is susceptibility index.

Molecular breeding for drought tolerance in wheat

Drought tolerance is a common quantitative trait in plants (Zhu, 2002). Researchers perform QTL mapping to explore drought-resistance genes in wheat (Luo et al., 2021). Identifying drought-resistance QTLs is vital for crop breeding because it gives valuable targets. Quantitative trait loci (QTL) analysis is a successful approach for dissecting QTL and has been used in crop gene mining (Liu et al., 2019). In wheat, efforts have been made to find QTLs for drought tolerance, particularly for physiological traits such as net photosynthesis, relative water content, cell membrane stability, and so on (Gupta et al., 2017). Several drought tolerance traits have already been found linked to a large number of QTLs. Some QTLs are reported to contribute up to 20% of phenotypic variation for each of these individual traits (Luo et al., 2021). Quarrie et al. (1994) discovered that the 5A chromosome transports gene(s) for ABA concentration under drought stress. Various drought tolerance related QTLs were mapped on chromosomes 1A, 1B, 2A, 2B, 2D, 3D, 5A, 5B, 7A, and 7B by Quarrie et al. (2005). QTL mappings in double haploid populations and recombinant inbred lines (RILs), advanced backcross populations, are reported by many researchers for studying yield and associated linked traits under drought (Tuberosa et al., 2002; Mwadzingeni et al., 2016). Two QTL linked to coleoptile length (CL) in durum wheat under osmotic stress, situated on chromosomes 3B and 6A, respectively, explained 8.9% and 12.1% of the phenotypic variances (Nagel et al., 2014). Under drought, two loci Qgrd2C and Qgpd2C on wheat chromosome 5B influenced germination rate (GR) and germination percentage, accounting for 6–10% of the phenotypic variances (Ashraf et al., 2015). In a F8,9 recombinant inbred line (RIL) population, QTL for wheat drought tolerance coefficient (DTC) were discovered at seedling stage, and three QTL, QRLR-WL-1D, QCLR-WL-3D, and QPHR-WL-7A, were identified on chromosomes 1D, 3D, and 7A, for the longest root length (RL), a ratio of CL, and seedling height, respectively, explaining 10.2–13.1% phenotypic variance (Liu et al., 2017). The traits associated with QTLs for drought tolerance are given in Table 4.

Table 4. Quantitative trait loci (QTL) regions identified for drought tolerance related traits in wheat

Chromosomal location of QTL	Traits linked with the QTL for drought tolerance	Mapping populations	References
6A	Coleoptiles, seedling vigour and plant height	RILs produced by crossing a Chinese semi-dwarf wheat, Chuanmai 18, with a tall breeding line, Vigour 18.	Spielmeyer et al. (2007)
2A	Coleoptile’s length, shoot length, and extrusion length, awn length, grain weight, relative water content,	Core collection	Ahmad et al. (2014)
1D, 2A, 2B, 2D, 3A, 4A, 4B, 5B, 5D, 6D, 7A, 7D	Root diameter, volume, surface area, crossings, forks, and tips	Devon, a spring wheat cultivar, and Syn084, a synthetic hexaploid accession, were used to develop an advanced backcross population.	Ibrahim et al. (2012)
1B, 2B, 3B, 5B, 7B, 7A	Grain weight, grain weight per spike, grain number per spike, spikes per m^2, spike weight, spike harvest index, and harvest index	RILs resulting from a cross of geno-types	Golabadi et al. (2011)
3BL	Grain yield	From a cross between line RAC875 and variety Kukri, a doubled haploid (DH) population was developed.	Bennett et al. (2012)
3B, 6A	Coleoptile length	RILs developed from the cross of durum wheat cultivars Omrabi5 and Belikh2	Nagel et al. (2014)

(Source, Modified from Mwadzingeni et al., 2016)

Drought-tolerant wheat genotypes can be developed through genetic engineering. There are two strategies to improve water use efficiency via genetic engineering. One method is to insert genes for suitable osmolytes such as, amino acids and sugar, while another method is to over-express late embryogenic proteins that give dehydration tolerance (Abebe et al., 2003). In wheat, Dehydration-responsive Element Binding (DREB) and Heat Shock Factors (HSFs) are key regulators of heat-drought stress genetic networks. Drought tolerance in wheat was improved by stress-induced expression of Arabidopsis DREB1A, showing that DREBs may play a role in increasing wheat response to drought stress (Pellegrineschi et al., 2004). Under drought stress, zinc finger proteins (ZFPs) with a QALGGH conserved domain have been linked to gene expression modulation (Cheuk and Houde, 2016). The role of ZFPs in wheat drought tolerance has been well established (Cheuk and Houde, 2016). In wheat, TaZFP22, TaZFP34, and TaZFP46 are Q-type C2H2 zinc finger transcriptional repressors which are expressed in the roots under drought (Chang et al., 2016).

Conclusion

Drought stress causes a severe reduction in wheat crop growth and productivity. Wheat suffers from various morphological, physiological, and biochemical changes as a result of drought stress. The knowledge of these changes in wheat will help researchers to identify drought tolerance pathways and develop drought-tolerant wheat cultivars. Markers associated with QTLs can be used for marker-assisted selection in order to develop drought-resistant wheat cultivars. Increased moisture availability to crops through various agronomic practices, crop diversification, varietal development, water conservation and harvesting, and watershed development is an important component of drought management. A multidisciplinary approach involving all components should be integrated to create innovative water-use approach and foster climate resilient agriculture to mitigate the impacts of drought stress. While, drought forecasting and timely dissemination of relevant advice to farmers is also an important drought mitigation strategy that can help reduce the potential economic loss from drought.

Conflict of interest

The authors have no conflict of interest.

References

Abebe T, Guenzi AC, Martin B and Cushman JC, 2003. Tolerance of mannitol-accumulating transgenic wheat to water stress and salinity. Plant physiology, 131, 1748-1755. doi: 10.1104/pp.102.003616

Abid M, Tian Z, Ata-Ul-Karim ST, Liu Y, Cui Y, Zahoor R, Jiang D and Dai T, 2016. Improved tolerance to post-anthesis drought stress by pre-drought priming at vegetative stages in drought-tolerant and-sensitive wheat cultivars. Plant Physiology and Biochemistry, 106, 218-227. doi: 10.1016/j.plaphy.2016.05.003

Acevedo E, Silva P and Silva H, 2009. Wheat Growth and Physiology. FAO Corporate Repository, pp. 1-24.

Ahmad J, 1994. Effect of varying irrigation frequencies on phenology, growth and yield of three wheat varieties. Thesis for MSc, University of Agriculture, Faisalabad.

Ahmad MQ, Khan SH, Khan AS, Kazi AM and Basra S, 2014. Identification of QTLs for drought tolerance traits on wheat chromosome 2A using association mapping. International Journal of Agriculture and Biology, 16, 862-870.

Ahmad Z, Waraich EA, Akhtar S, Anjum S, Ahmad T, Mahboob W, Hafeez OB, Tapera T, Labuschagne M and Rizwan M, 2018. Physiological responses of wheat to drought stress and its mitigation approaches. Acta Physiologiae Plantarum, 40, 4. doi: 10.1007/s11738-018-2651-6

Akbar M, Tariq M, Jamil T and Arshad M, 2001. Evaluation of exotic wheat germplasm for seed yield and its components under rainfed conditions. Sarhad Journal of Agriculture, 17, 511-513.

Akram M, 2011. Growth and yield components of wheat under water stress of different growth stages. Bangladesh Journal of Agricultural Research, 36, 455-468.

Ashley J, 1993. Drought and crop adaptation (ed). by J.R.J. Rowland, Dryland In farming in Africa 1993. Macmillan press Ltd, London, p. 46-67.

Ashraf MY and Khan AH, 1993. Effect of drought stress on wheat plant in early stage. Pakistan Journal of Agricultural Research, 14, 261-269.

Ashraf MY, Azmi AR, Khan AH and Naqvi SSM, 1994. Water relation in different wheat (*Triticum aestivum* L.) genotypes under water deficit. Acta Physiologiae Plantarum, 3, 231-240.

Ashraf S, Shahzad A, Karamat F, Iqbal M and Ali GM, 2015. Quantitative trait loci (QTLs) analysis of drought tolerance at germination stage in a wheat population derived from synthetic hexaploid and Opata. The Journal of Animal and Plant Sciences, 25, 539-545.

Balla K, Rakszegi M, Li Z, Bekes F, Bencze S and Veisz O, 2011. Quality of winter wheat in relation to heat and drought shock after anthesis. Czech Journal of Food Sciences, 29, 117-128.

Beck EH, Fettig S, Knake C, Hartig K and Bhattarai T, 2007. Specific and unspecific responses of plants to cold and drought stress. Journal of biosciences, 32, 501-510.

Bennett D, Reynolds M, Mullan D, Izanloo A, Kuchel H, Langridge P and Schnurbusch T, 2012. Detection of two major grain yield QTLs in bread wheat (*Triticum aestivum* L.) under heat, drought and high yield potential environments. Theoretical and Applied Genetics, 125, 1473-1485.

Blum A, 2005. Drought: Drought stress and its impact. https://plantstress.com/drought/

Bouslama M and Schapaugh W, 1984. Stress tolerance in soybean. Part 1, Evaluation of three screening techniques for heat and drought tolerance. Crop Science, 24, 933-937.

Bukhat NM, 2005. Studies in yield and yield associated traits of wheat (*Triticum aestivum* L.) genotypes under stress conditions. Thesis for MSc, Department of Agronomy, Sindh Agriculture University Tandojam and Pakistan.

Cakir R, 2004. Effect of water stress at different developmental stages on vegetative and reproductive growth of corn. Field Crops Research, 89, 1-16.

Carter MR, 2002. Soil quality for sustainable land management, organic matter and aggregation interactions that maintain soil functions. Agronomy Journal, 94, 38-47. doi: 10.2134/agronj2002.3800

Chang H, Chen D, Kam J, Richardson T, Drenth J, Guo X, McIntyre CL, Chai S, Rae AL and Xue GP, 2016. Abiotic stress upregulated TaZFP34 represses the expression of type-B response regulator and SHY2 genes and enhances root to shoot ratio in wheat. Plant Science, 252, 88-102. doi: 10.1016/j.plantsci.2016.07.011

Chaves MM and Oliveira MM, 2004. Mechanisms underlying plant resilience to water deficits, prospects for water-saving agriculture. Journal of Experimental Botany, 55, 2365-2384.

Cheuk A and Houde M, 2016. Genome wide identification of C1-2i zinc finger proteins and their response to abiotic stress in hexaploid wheat. Molecular Genetics and Genomics, 291, 873-90.

Cui Y, Tian Z, Zhang X, Muhammad A, Han H, Jiang D, Cao W and Dai T, 2015. Effect of water deficit during vegetative growth periods on post-anthesis photosynthetic capacity and grain yield in winter wheat (*Triticum aestivum* L.). Acta Physiologiae Plantarum, 37, 1-10. doi: 10.1007/s11738-015-1944-2

Cumani M and Rojas O, 2016. Characterization of the agricultural drought prone areas on a global scale. Food and Agriculture Organization for the United States, Rome, 30p. ISBN 978-92-5-109286-6

Denčić S, Kastori R, Kobiljski B and Duggan B, 2000. Evaluation of grain yield and its components in wheat cultivars and landraces under near optimal and drought conditions. Euphytica, 113,43-52.

El Hafid R, Smith DH, Karrou M and Samir K, 1998. Physiological responses of spring durum wheat cultivars to early-season drought in a Mediterranean environment. Annals of Botany, 8, 363-370.

Farooq M, Hussain M and Siddique KH, 2014. Drought stress in wheat during flowering and grain-filling periods. Critical reviews in plant sciences, 33, 331-349.

Farooq M, Wahid A, Kobayashi N, Fujita D and Basra SMA, 2009. Plant drought stress: Effects, mechanisms and management. Agronomy for sustainable development, 29, 185-212.

Fernandez GCJ, 1992. Effective selection criteria for assessing plant stress tolerance. In, Kuo CG (eds). Adaptation of Food Crops to Temperature and Water Stress. International symposium, Taiwan, 13-18 August 1992.

Fischer R, Turner N and Kramer P, 1980. Influence of water stress on crop yield in semiarid regions. In: Turner NC & Kramer PJ (eds) Adaptation of plants to water and high temperature stress. Wiley, New York, pp. 323-339.

Fischer RA and Maurer R, 1978. Drought resistance in spring wheat cultivars. Australian Journal of Agricultural Research, 29, 897-912.

Gautam P, Lal B, Tripathi R, Shahid M, Baig MJ, Raja R, Maharana S and Nayak AK, 2016. Role of silica and nitrogen interaction in submergence tolerance of rice. Environmental and Experimental Botany, 125, 98-109.

Gavuzzi P, Rizza F, Palumbo M, Campaline RG, Ricciardi GL and Borghi B, 1997. Evaluation of field and laboratory predictors of drought and heat tolerance in winter cereals. Canadian Journal of Plant Science, 77, 523-531.

Ghazal HM, Wassouf MZ, Nachit MM and Jaradat AA, 1998. Yield and yield components of durum wheat as influenced by irrigation and nitrogen fertilization. In Proc. 3rd Int. Triticeae Symp, Aleppo, Syria. pp. 4-8.

Golabadi M, Arzani A, Maibody SM, Tabatabaei BS and Mohammadi S, 2011. Identification of microsatellite markers linked with yield components under drought stress at terminal growth stages in durum wheat. Euphytica, 177, 207-221.

Gong H, Zhu X, Chen K, Wang S and Zhang C, 2005. Silicon alleviates oxidative damage of wheat plants in pots under drought. Plant Science, 169, 313-321. doi: 10.1016/j.plantsci.2005.02.023

Guo FQ, Young J and Crawford NM, 2003. The nitrate transporter AtNRT1.1 (CHL1) functions in stomatal opening and contributes to drought susceptibility in Arabidopsis. The Plant Cell, 15, 107-117.

Gupta NK, Gupta S and Kumar A, 2001. Effect of water stress on physiological attributes and their relationship with growth and yield of wheat cultivars at different stages. Journal of Agronomy and Crop Science, 186, 55-62.

Gupta PK, Balyan HS and Gahlaut V, 2017. QTL analysis for drought tolerance in wheat, present status and future possibilities. Agronomy, 1, 5. doi: 10.3390/agronomy7010005

Harris D, Tripathi RS and Joshi A, 2002. On-farm seed priming to improve crop establishment and yield in dry direct-seeded rice. Direct seeding, Research Strategies and Opportunities, International Research Institute, Manila, Philippines. P. 231-240.

Heidaiy Y and Moaveni P, 2009. Study of drought stress on accumulation and proline among aba in different genotypes forage corn. Research Journal of Biological Sciences, 4, 1121-1124.

Helena M and Carvalho CD, 2008. Drought stress and reactive oxygen species. Plant Signaling & Behavior, 3, 156-165.

Hussain S, Hussain S, Qadir T, Khaliq A, Ashraf U, Parveen A, Saqib M and Rafiq M, 2019. Drought stress in plants. An overview on implications, tolerance mechanisms and agronomic mitigation strategies. Plant Science Today, 6, 389-402.

Ibrahim S, Schubert A, Pillen K and Léon J, 2012. QTL analysis of drought tolerance for seedling root morphological traits in an advanced backcross population of spring wheat. International Journal of Agricultural Sciences, 2, 619-629.

IPCC, 2014. Climate Change 2014, Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Jamal M, Nazir MS, Shah SH and Ahmed N, 1996. Varietal's response of wheat to water stress at different growth stages III. Effect on grain yield, straw yield, harvest index and protein content in grains. Rachis, 2, 38-45.

Jatoi WA, Baloch MJ, Kumbhar MB, Khan NU and Kerio MI, 2011. Effect of water stress on physiological and yield parameters at anthesis stage in elite spring wheat cultivars. Sarhad Journal of Agriculture, 27, 59-65.

Ji X, Shiran B, Wan J, Lewis DC, Jenkins CL, Condon AG, Richards RA and Dolferus R, 2010. Importance of pre-anthesis anther sink strength for maintenance of grain number during reproductive stage water stress in wheat. Plant, Cell and Environment, 33, 926-942.

Jones MB, Leafe EL and Stiles W, 1980. Water stress in field-grown perennial ryegrass. I. Its effect on growth, canopy photosynthesis and transpiration. Annals of Applied Biology, 96, 87-101.

Karthikeyan B, Jaleel CA, Gopi R and Deiveekasundaram M, 2007. Alterations in seedling vigour and antioxidant enzyme activities in *Catharanthus roseus* under seed priming with native diazotrophs. Journal of Zhejiang University Science B, 8, 453-457.

Khan AJ, Azam F, Ali A, Tariq M and Amin M, 2005. Inter-relationship and path coefficient analysis for biometric traits in drought tolerant wheat (*Triticum aestivum* L.). Asian Journal of Plant Sciences, 4, 540-543.

Khanzada BA, Ashraf MY, Ala SA, Alam SM, Shirazi MU and Ansari, 2001. Water relations in different guar (*Cyamopsis tetragonoloba* (L.) Taub) genotypes under water stress. Pakistan Journal of Botany, 33, 279-287.

Kilic H and Yağbasanlar T, 2010. The effect of drought stress on grain yield, yield components and some quality traits of durum wheat (*Triticum turgidum*) cultivars. Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 38, 164-170.

Kiyosue T, Yoshiba Y, YamaguchiShinozaki K and Shinozaki K, 1996. A nuclear gene encoding mitochondrial proline dehydrogenase, an enzyme involved in proline metabolism, is upregulated by proline but downregulated by dehydration in Arabidopsis. Plant Cell, 8, 1323-1335.

Lan J, 1998. Comparison of evaluating methods for agronomic drought resistance in crops. Acta Agriculturae Boreali Sinica, 7, 85-87.

Lawlor DW and Cornic G, 2002. Photosynthetic carbon assimilation and associated metabolism in relation to water deficits in higher plants. Plant, Cell and Environment, 25, 275-294.

Liu C, Sukumaran S, Claverie E, Sansaloni C, Dreisigacker S and Reynolds M, 2019. Genetic dissection of heat and drought stress QTLs in phenology-controlled synthetic-derived recombinant inbred lines in spring wheat. Molecular Breeding, 39,1-8.

Liu H, Sultan MA, Liu XL, Zhang J, Yu F and Zhao HX, 2015. Physiological and comparative proteomic analysis reveals different drought responses in roots and leaves of drought-tolerant wild wheat (*Triticum boeoticum*). PLoS One, 10, e0121852.

Liu X-Y, Zhang H, Hu X-W, Wang H-G, Gao J-R, Liang S-X and Feng J-Y, 2017. QTL Mapping for drought-tolerance coefficient of seedling related traits during wheat germination. Journal of Nuclear Agricultural Sciences, 31, 209-217.

Luo L, Xia H and Lu BR, 2021. Crop breeding for drought resistance. Frontiers in Plant Science, 10, 314.

Ma D, Sun D, Wang C, Qin H, Ding H, Li Y and Guo T, 2016. Silicon application alleviates drought stress in wheat through transcriptional regulation of multiple antioxidant defense pathways. Journal of Plant Growth Regulation, 35, 1-0.

Majid SA, Asghar R and Murtaza G, 2007. Yield stability analysis conferring adaptation of wheat to pre- and post-anthesis drought conditions. Pakistan Journal of Botany, 39, 1623-1637.

Matsunaka T, Takeuchi H and Miyawaki T, 1992. Optimum irrigation period for grain production in spring wheat. Soil Science and Plant Nutrition, 38, 269-279.

McDonald GK, Sutton BG and Ellison FW, 1984. The effect of sowing dates, irrigation on growth and yield of wheat in Namoi. River Vally. New South Wales, Irrigation Science, 2, 123-135.

McCree KJ and Davis SD, 1974. Effect of water stress and temperature on leaf size and on size and number of epidermal cells in Grain Sorghum 1. Crop Science, 14, 751-755. doi: 10.2135/cropsci1974.0011183X001400050041x

McDonald G and O'Leary R, 2016. Drought tolerance of wheat varieties. DRDC Update Papers, Department of Agriculture and Food, Western Australia. Available at: https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2016/02/drought-tolerance-fo-wheat-varieties (Accessed on: 02 December, 2021)

Mirbahar AA, Markhand GS, Mahar AR, Abro SA and Kanhar NA, 2009. Effect of water stress on yield and yield components of wheat (*Triticum aestivum* L.) varieties. Pakistan Journal of Botany, 41, 1303-1310.

Mitra J, 2001. Genetics and genetic improvement of drought tolerance in crop plants. Current Science, 80, 758-763.

Miyan MA, 2015. Droughts in Asian Least Developed Countries: Vulnerability and sustainability. Weather and Climate Extremes, 7, 8-23. doi: 10.1016/j.wace.2014.06.003.

Molnár I, 2002. The effects of drought stress on the photosynthetic processes of wheat and of *Aegilops biuncialis* genotypes originating from various habitats. Acta Biologica Szegediensis, 46,115-116.

Munns R, Brady CJ and Barlow EW, 1979. Solute accumulation in the apex and leaves of wheat during water stress. Functional Plant Biology, 6, 379-389.

Musaddique M, Hussain A, Wajid SA and Ahmad A, 2000. Growth, yield and components of yield of different genotypes of wheat. International Journal of Agriculture and Biology, 2, 242-244.

Mwadzingeni L, Shimelis H, Dube E, Laing MD and Tsilo TJ, 2016. Breeding wheat for drought tolerance, Progress and technologies. Journal of Integrative Agriculture, 15, 935-43.

Nagel M, Navakode S, Scheibal V**, Baum M, Nachit M, Roder MS and Borner A,** 2014. The genetic basis of durum wheat germination and seedling growth under osmotic stress. Biologia Plantarum, 58, 681-688. Doi: 10.1007/s10535-014-0436-3

Nezhadahmadi A, Prodhan ZH and Faruq G, 2013. Drought tolerance in wheat. The Scientific World Journal, 2013. Doi: 10.1155/2013/610721

Oppenheimer HR, 1960. Adaptation to drought, xerophytisim. Plant water relationships in Arid and Semi-arid conditions. Proc. Marid syp. UNESCO. Paris, pp. 105-138.

Pannu RK, Singh P, Singh DP, Chaudhary BD, Sangwan VP and Sharma HC, 1996. Ground water-table limits the irrigation requirement of tall and dwarf wheats (*Triticum aestivum* L.). Indian Journal of Agronomy, 41, 568-572.

Pellegrineschi A, Reynolds M, Pacheco M, Brito RM, Almeraya R, Yamaguchi-Shinozaki K and Hoisington D, 2004. Stress-induced expression in wheat of the Arabidopsis thaliana DREB1A gene delays water stress symptoms under greenhouse conditions. Genome, 47, 493-500.

Pereira-Netto AB, Magalhães AC and Pinto HS, 1999. Effects of soil water depletion on the water relations in tropical kudzu. Pesquisa agropecuária brasileira, 34, 1151-1157.

Pierce FJ and Rice CW, 1988. Crop rotation and its impact on efficiency of water and nitrogen use. Cropping strategies for efficient use of water and nitrogen, 51, 21-42.

Powell W, Morgante M, Andre C, Hanafey M, Vogel J, Tingey S and Rafalski A, 1996. The comparison of RFLP, RAPD, AFLP and SSR (microsatellite) markers for germplasm analysis. Molecular breeding, 2, 225-238.

Prasad PV, Pisipati SR, Momčilović I and Ristic Z, 2011. Independent and combined effects of high temperature and drought stress during grain filling on plant yield and chloroplast EF-F-Tu expression in spring wheat. Journal of Agronomy and Crop Science, 197, 430-441.

Qadir G, Saeed M and Cheema MA, 1999. Effect of water stress on growth and yield performance of four wheat cultivars. Pakistan Journal of Biological Sciences, 2, 236-239.

Quarrie SA, Gulli M, Calestani C, Steed A and Marmiroli N, 1994. Location of a gene regulating drought-induced abscisic acid production on the long arm of chromosome 5A of wheat. Theoretical and Applied Genetics, 89, 794-800.

Quarrie SA, Steed A, Calestani C, Semikhodskii A, Lebreton C, Chinoy C, Steele N, Pljevljakusić D, Waterman E, Weyen J and Schondelmaier J, 2005. A high-density genetic map of hexaploid wheat (*Triticum aestivum* L.) from the cross Chinese Spring× SQ1 and its use to compare QTLs for grain yield across a range of environments. Theoretical and Applied Genetics, 110, 865-80.

Rakshit A, Singh HB, Singh AK, Singh US and Fraceto L, 2020. New frontiers in stress management for durable agriculture. Springer Nature.

Reddy AR, Chaitanya KV and Vivekanandan M, 2004. Drought-induced responses of photosynthesis and antioxidant metabolism in higher plants. Journal of plant physiology, 161, 1189-202.

Richards RA, Rawson HM and Johnson DA, 1986. Glaucousness in wheat, its development and effect on water-use efficiency, gas exchange and photosynthetic tissue temperatures. Functional Plant Biology, 13, 465-473.

Rosielle AA and Hamblin J, 1981. Theoretical aspects of selection for yield in stress and non-stress environments. Crop Science, 21, 943-946.

Russell JR, Fuller JD, Macaulay M, Hatz BG, Jahoor A, Powell W and Waugh R, 1997. Direct comparison of levels of genetic variation among barley accessions detected by RFLPs, AFLPs, SSRs and RAPDs. Theoretical and Applied Genetics, 95, 714-722.

Sabra A, Daayf F and Renault S, 2012. Differential physiological and biochemical responses of three Echinacea species to salinity stress. Scientia Horticulturae, 135, 23-31.

Sairam RK, Deshmukh PS, Shukla DS and Ram S, 1990. Metabolic activity and grain yield under moisture stress in wheat genotypes. Indian Journal of Plant Physiology, 33, 226-231.

Sallam A, Alqudah AM, Dawood MFA, Baenziger PS and Börner A, 2019. Drought Stress Tolerance in Wheat and Barley: Advances in Physiology, Breeding and Genetics Research. International Journal of Molecular Sciences, 20, 3137. doi: 10.3390/ijms20133137.

Samyuni E and Purwanto dan S, 2015. Toleransi Varietas Padi Hitam (*Oryza sativa* L. Indica) Pada Berbagai Tingkat Cekaman Kekeringan EL-VIVO Journal Pascasarjana UNS, 3, 54-63

Sarwar A, 1994. Response of wheat to soil moisture stress at different stages of growth. J. Drainage and Reclamation, 4, 41-47.

Schneekloth J, Bauder T and Hansen N, 2009. Limited irrigation management, principles and practices. Thesis for DSc, Colorado State University.

Shamsi K and Kobraee S, 2011. Bread wheat production under drought stress conditions. Annals of Biological Research, 2, 352-358.

Shani U and Dudley LM, 2001. Field studies of crop response to water and salt stress. Soil Science Society of America Journal, 65, 1522-1528.

Sharif M, 1999. Effect of irrigation at different growth stages on growth and yield performance of wheat cultivars. Thesis for MSc, University of Agriculture, Faisalabad.

Shehzadi S, 1999. Effect of different water regimes on growth, yield and anatomy of wheat (*Triticum aestivum* L.). Thesis for MSc, University of Agriculture, Faisalabad.

Siddique MR, Hamid AI and Islam MS, 2000. Drought stress effects on water relations of wheat. Botanical Bulletin of Academia Sinica, 41, 35-39.

Singh G and Bhalla V, 1994. Differential response of wheat genotypes to moisture stress for seed germination and early seedling growth. Indian Journal of Agricultural Research, 28, 99-104.

Sivamani E, Bahieldin A, Wraith JM, Al-Niemi T, Dyer WE, Ho TH and Qu R, 2000. Improved biomass productivity and water use efficiency under water deficit conditions in transgenic wheat constitutively expressing the barley HVA1 gene. Plant Science, 155, 1-9.

Sokoto MB and Singh A, 2013. Yield and yield components of bread wheat as influenced by water stress, sowing date and cultivar in Sokoto, Sudan Savannah, Nigeria. American Journal of Plant Sciences, 4, 122-130.

Spielmeyer W, Hyles J, Joaquim P, Azanza F, Bonnett D, Ellis M, Moore C and Richards R A, 2007. A QTL on chromosome 6A in bread wheat (*Triticum aestivum* L.) is associated with longer coleoptiles, greater seedling vigour and final plant height. Theoretical and Applied Genetics, 115, 59-66.

Swati MS, Rahman H and Afsar J, 1985. Response of wheat (*Triticum aestivum* L.) cultivars to different levels of water stress. Sarhad Journal of Agriculture, 2, 295-303.

Tompkins DK, Fowler DB and Wright AT, 1991. Water use by no till winter wheat influence of seed rate and row spacing. Agronomy Journal, 83, 766-769.

Tuberosa R and Salvi S, 2006. Genomics-based approaches to improve drought tolerance of crops. Trends in plant science, 11, 405-412.

Tuberosa R, Salvi S, Sanguineti MC, Landi P, Maccaferri M, Conti S, 2002. Mapping QTLs regulating morpho-physiological traits and yield: Case studies, shortcomings and perspectives in drought-stressed maize. Annals of Botany, 89, 941-63.

Wajid SA, 2004. Modeling growth and yield of wheat under different sowing dates, plant populations and irrigation levels. Thesis for PhD, University of Arid Agriculture, Pakistan.

Wang Z, Li G, Sun H, Ma L, Guo Y, Zhao Z, Gao H, Mei L, 2018. Effects of drought stress on photosynthesis and photosynthetic electron transport chain in young apple tree leaves. Biology open, 7, bio035279. doi: 10.1242/bio.035279

Yang J and Zhang J, 2006. Grain filling of cereals under soil drying. New phytologist, 169, 223-236. Doi: 10.1111/j.1469-8137.2005.01597.x

Zhang HP and Oweis T, 1998. Water yield relation and optimal irrigation scheduling of wheat in Mediterranean regions. Agriculture Water Management, 38, 195-211.

Zhu, J-K,2002. Salt and drought stress signal transduction in plants. Annual Review of Plant Biology, 53, 247-273.