Review
20

Egypt. J. Agron. **Vol. 43**, No. 3, pp. 307-315 (2021)

Egyptian Journal of Agronomy
http://agro.journals.ekb.eg/

Effects of Water Stress on Cotton (*Gossypium* spp.) Plants and Productivity

Mashal Rehman[1], Ali Bakhsh[2], Muhammad Zubair[3]#, Muhammad Ishaq Asif Rehmani[4], Aqeel Shahzad[5], Syeda Fiza Nayab[5], Madiha Mobeen Khan[1], Wajiha Anum[1], Rubina Akhta[4], Natasha Kanwal[1], Nadia Manzoor [1], Imtiaz Ali[1]

[1]Regional Agricultural Research Institute, Bahawalpur, Pakistan; [2]Department of Plant Breeding and Genetics, Ghazi University, Dera Ghazi Khan, Pakistan; [3]Agricultural Research Station, Bahawalpur, Pakistan; [4]Department of Agronomy, Ghazi University, Dera Ghazi Khan, Pakistan; [5]Department of Plant Breeding and Genetics, University of Agriculture Faisalabad, Pakistan; [6]Maize and Millets Research Institute, Yusafwala Sahiwal, Pakistan.

THE WATER stress harshly influences the plant growth and development with considerable reductions in plant growth and biomass accumulates. It declines the number of bolls per plant, bolls weight, and seed cotton (*Gossypium* spp.) yield. Fiber length, fiber strength, seed index and boll weight are reduced dynamically. The relative leaf water contents, transpiration rate and leaf water potential are decreased while leaf and canopy temperature is increased under water stress conditions. Limited water availability restricts the total uptake of nutrients, thus deprecating their concentration in the plant tissues. The major effects of water stress on the plants are lowered photosynthesis stimulated by reduced leaf expansion, early leaf senescence, deteriorated photosynthetic machinery and reduction in food production.The Plant accomplishes escape from moisture stress by shortening its growing season which results in a reduction in yield. The plants cut down their water spending under water stress conditions by dercreasing the number and area of leaves to minimize the yield losses. The growth and development of tolerant genotypes are relatively fast because of retention of more moisture from soil earlier. Genes are induced by water stress, categorized into regulatory and functional genes; from them, functional genes produce functional proteins, whereas regulatory genes product regulatory proteins like transcriptional factors, they control a cluster of genes by regulating the expression of different targeted genes in their promoter region through specific binding of it with cis-acting elements. The development of stress-tolerant cotton varieties based on the stability of yield and yield components under water stress conditions should be the prime focus of breeders.

Keywords: Cotton (*Gossypium* spp.), Water stress, Yield and yield components.

Introduction

Over the years, consumers have raised the demand for cotton (*Gossypium* spp) consumption because it provides natural textile fiber with a considerable amount of edible oil (Zhang et al., 2017). For better cotton production, the availability of required amount of a moisture is necessary because deficiency of available moisture affects the photosynthetic rate which will increase or decrease the carbon uptake that ultimately lowers the boll maintenance on the cotton plant (Aujla et al., 2005). As a result maintenance of cotton bolls on the plant decreases the seed cotton yield. While the uncertainty in precipitation and awry increment in temperature extremes in crop growth period is another chasing problem, which will ultimately influence the world cotton productivity (Iqbal, 2010; Amin et al., 2018).

#Corresponding author email: mzf1483@gmail.com
Received 07/08/ 2021; Accepted 18/10/ 2021
DOI: 10.21608/agro.2021.89343.1272

Cotton an overview

Cotton (x= 2n= 26, or n= 13) is grown as a perennial shrub as well as a tree. It has been cultivated since the prehistoric times of human civilization (Azhar & Rehman, 2018). And, it is also cultivated as an annual crop in tropic and subtropical areas in the world. Taxonomically, the cotton plant (*Gossypium* spp.) belongs to the Malvaceae family, and it contains (5) allotetraploid species and more than (45) diploid species (Guan et al., 2014; Wang et al., 2017). These cotton species are classified into (9) different (genomic) groups contain as A, B, C, D, E, F, G, K and AD (Shang et al., 2015). These species are usually spread all over the diverse geographical areas of the world (Aslam et al., 2020). *Gossypium* spp. can be categorized into the primary gene pool, secondary gene pool and tertiary gene pool based on their usage in cotton breeding programs and their genetic hybridization properties. The primary gene pool of cotton species includes the (2) cultivated tetraploid species from the New World i.e. *G. hirsutum* L. and *G. barbadense* L. having AD genome. While remaining (3) wild tetraploid species, *G.tomentosum*, *G. mustelinum*and *G. darwinii* are placed in a secondary gene pool which including A, B, D and F genomes. The tertiary gene pool comprises diploid cotton species having C, E, G and K genomes (Campbell et al., 2010; Abdurakhmonov, 2013).

Water stress

Water stress occurs when the requirement for water exceeds the accessible amount during a specific period or when its utilization becomes confine due to its low quality. Crop plants are mostly affected by several abiotic stresses, which affect their growth and development resulting in the hindrance of crop productivity (Farooq et al., 2011; Seki et al., 2003). But it is thought to be the most destructive abiotic stress, which hampers its productivity more than any other abiotic stress (Lambers et al., 2008). Water stress harshly influences plant growth and development with considerable reductions in plant growth and biomass accumulates. The major adverse consequences of water stress on plant's growth are reduced rate of cell expansion, cell division, leaf size area, the proliferation of roots, elongation of the stem, fluctuation in stomatal oscillations, water relations and plant's nutrients uptake which ultimately reduced crop productivity and relative water use efficiency of plants (Farooq et al., 2009; Shahzad et al., 2016). Climatic fluctuation and its representations predicted that drought frequency and its severity have been increased under the continuous global environmental change conditions (Shahzad et al., 2021).

Water stress and cotton plant

Water stress is positioned highest among the world disasters influencing the substantial number of plants and individuals every year (Wilhite, 2000; Mishra & Singh, 2010). Water stress occurs due to unusually dry weather which gives rise to rigorous hydrological irregularity in a specific area. It may have distinctive definitions based on details of precipitation profile, dampness of soil and probable evapotranspiration or their diverse combinations (Heim, 2002; Homdee et al., 2016). Climatic, edaphic and agronomical variables influence it in different ways. Changing climatic conditions,especially decreasing precipitation and increasing evapotranspiration are caused by global warming. Consequently, global warming is expected to cause increased severity and frequency of drought stress in the future. Globally it is a restricting variable for plant development and yield efficiency and is more impairing than any other abiotic or biotic stress. It is a consistently developing stress which limits crop efficiency with more clear impacts in arid and semi-arid regions (Ghosh & Xu, 2014). Water stress is the most noteworthy factor, which restricts cotton production around the globe. Cotton yield and its fiber quality traits fluctuate according to the severity and duration of water stress. Water stress is also known as multidimensional stress that affects plant growth at different levels of plant organization. It may affect the plant's physiological, morphological and biochemical processes. The consequences of water stress are inhibition of plant growth, stomatal closure with diminished transpiration rate, lower chlorophyll contents and inhibition of photosynthesis. Thus water stress is said to be the major limiting factor to reduce the seed cotton yield around the globe (Anjum et al., 2011; Rejeb et al., 2016).

Effects of water stress on the cotton crop and seed cotton yield

Inadequate soil water content throughout the sensitive growth phases, for example, squaring, flowering, and fruit setting stageswill lead to the reduce plant height, decreasein fresh and dry matter content, the decline in the number of fruiting branches, number of seeds per boll, seed cotton yield and other yield-related attributes (Yazar et al., 2002). The squaring phase of thecotton plant is the initial stage for plant architecture development and any stress at this stage of thecrop may limit the overall performance of cotton genotypes. Usually, water stress imposes earliness under stressed conditions. Earliness slightly reduced in irrigated conditions because of increasing irrigation frequency which probably caused encouraging vegetative growth and delays the reproductive growth. Delayed squaring with water deficiency pushed diminished yield. Because delayed fruiting brought about more root development but didn't develop enough drought avoidance for stabilization of seed cotton yield under water stress (Dumka et al., 2004).

Water stress on the flowering stage decreases the overall plant biomas, bolls per plant, seed weight and seed cotton yield per plant because of decreasing trends in photosynthesis. While fiber length, strength and uniformity index decrease linearly with a decline in leaf water potential,on the other hand, fiber fineness value was increased with a decline in leaf water potential (Lokhande & Reddy, 2014). The imposition of water stress causes a significant reduction in main stem height owing to the decrease in intermodal length but the numbers of nodes per plant do not change significantly. Similarly, it was reported that a significant reduction in plant height in crop plants was due to water deficit stress (Saleem et al., 2015). A comparison among the water stress treatments indicated that the maximum reduction in main stem height was observed when water stress was imposed at squaring phase.

The adverse after-effects of water stress on plant growth, development and physiological phenomena were revealed in terms of reducing fruit production and seed cotton yield. Plants under dry spells developed smaller and less number of bolls as compared to normally-watered plants. Moreover, boll biomass dissemination and the number of seeds per boll may also change by a dry spell (Wang et al., 2016). Seed cotton yield decreases under water stress due to lessening the number of bolls per plant (Saleem et al., 2015). These outcomes are in correspondence to the preceding findings where decreased cotton lint yield was associated with more number of cotton boll abortions which decreases the boll production under moisture deficits during the reproductive growth (Pettigrew, 2004), because of increased levels of abscisic acid under stress condition (Borel & Simonneau, 2002). Its harvest decreases due to water shortage during the growing season. There is a significant interrelationship between the number of cotton bolls per plant and seed cotton yield underthe waterstress regime. This phenomenon suggested that boll retention is an essential determining factor of crop yield under water stress conditions (Rahman et al., 2008). The seed cotton yield and the other yield-related characteristics differed altogether among cultivars under watered-stressed conditions. Among cotton genotypes,significant differences were observed in boll numbers per plant, boll retention percentage and lint yield for two contrasting water treatments. There was a positive association in reducing boll retention, with a decline in yield with the water-stressed treatment (Bolek, 2007).

The lower water application level had a significantly negative impact on the number of buds, bolls, total dry weight and seed cotton production when compared with normal water application levels. The reduced water application level brought about a harvest before ten days. Seed quality was better in seeds from the lower water application system than in those from the normal water application level. Although the yield of cotton cultivars was higher under normal water application, but seed quality was lower as compared to lower water application levels (Zaxos et al., 2012). Under various irrigation levels, six cotton cultivars were assessed by Iqbal et al., (2011) to determined irrigation impacts on the distribution of bolls and seed cotton yield. With more irrigations, all genotypes increased boll formation on higher sympodial branches. Late maturing genotypes produced more bolls at the upper portion oftheplant; on the other hand, early maturing genotypes produced more bolls at the lower portion of the plant. With the increase in irrigation level, fiber fineness was also increased and also with a decrease in irrigation level the fiber fineness was also reduced. The findings proposed that with an increased in irrigation level the genotypes adjust for yield differently, and the decision for a particular genotype should be considered for boll distribution and its potential impact on fiber fineness concerning natural and management factors. Under irrigation conditions, it increases plant height, vegetative biomass, fiber yield, lint quality and reduced canopy temperature as compared to dryland cotton (Wiggins et al., 2014). While water stress declined number of bolls, bolls weight, and seed cotton yield. It was presumed that water stress diminished the yield by bringing down the number of bolls. The number of bolls per plant was less in water-constrained conditions than that in all around well-watered conditions (Ali & Ahmadikhah, 2009).

Effects of water stress on fiber yield and fiber quality traits

The amount and nature of the fiber produced on the cotton plant are directly associated with water accessibility amid the various phonological periods of advancement. Hereditarily identical cotton plant populaces, when submitted to water shortfalls, indicate decreases in yield of up to 50 percent as contrasted with those that have been well-irrigated, particularly when the stress is induced amid the period between flowering and boll forming stage (Saranga et al., 2004). Cotton fiber yield generally decreased as a result of diminished boll production, mainly due to less flowering and due to more boll abortions when the water stress is outrageous during the reproductive phase of growth (Wang et al., 2016). Drought stress decreased the lint yield of plants under stress conditions by about 25 %, because of a 19 % decline in the number of bolls (Pettigrew, 2004).

Mid-early and mid-late genotypes were more influenced by moisture deficit stress than early genotypes. Developing cotton under water-stressed conditions brought about the creation of weaker and shorter fibers. Lint properties of genotypes were incoherently influenced by water-stressed and inundated conditions, demonstrating unpredictability inherent in cotton fiber (Auge et al., 2001). Fiber length, fiber strength, seed index and boll weight are reduced dynamically with diminishing water accessibility. While no predictable impacts of a dry spell on fiber fineness were observed (Wang et al., 2016).

By increasing the irrigation frequency as compared to water stress fiber length and fiber strength increased eight percent but fiber fineness was decreased ten percent. Fiber length, fiber strength and fiber fineness value demonstrated significant differences with water availability (Attia & Rajan, 2016). The more irrigation water also produces the more fiber yield.Moisture deficit stress had not any impact on fiber yield but it increased the fiber fineness and decreased the fiber length value. Under deficit irrigation and high plant density, the seed cotton yield was higher due to more plant biomass with a high plant population and more harvest index. Finally, the results concluded that under water deficit stress or arid conditions, the use of high plant density is the best alternative without compromising on cotton seed yield (Zhang et al., 2017).

Effects of water stress on plant's mechanisms

Water stress effects appear in plants at any phonological stages of their growth. These effects are more prominent at various morphological, physiological and molecular levels. The first sign of water stress is reduced germination along with poor stand establishment. It retards germination as well as seedling stand. Reduced turgor pressure is the most sensitive physiological process which affects cell growth. Cell division, cell expansion and elongation are mostly restricted by water stress subsequently resulting in abridged leaf size, plant height and crop growth.Plant's water relations are mostly influenced by various characteristics i.e. leaf water potential, transpiration rate, relative water content, stomatal resistance, canopy and leaf temperature. At the initial stages of cotton leaf development, leaves have high relative water content which gradually decreases with the maturity of leaf and dry matter accumulates. The cotton stressed plants have lower relative water content as compared to non-stressed plants. When the plants are exposed to water stress their relative leaf water contents, transpiration rate and leaf water potential become decrease while its leaf and canopy temperature increase (Siddique et al., 2016).

Underwater stress conditions limited water availability restricts the total uptake of nutrients, thus deprecating their concentration in the tissues of crop plants. Water scarcity badly affects the nutrients uptake and their transportation from roots to various parts of the shoot. Interrupted uptake of nutrients, unloading mechanism and reduced flow of transpiration all lowers the absorption of inorganic nutrients (Jalota, 2006). Different plant species and even different genotypes belonging to a species respond contrarily to the uptake of minerals under moisture stress. The major effects of water stress on the plant are lowered photosynthesis stimulated by reduced leaf expansion, early leaf senescence, deteriorated photosynthetic machinery and lessen food production. Underwater stress conditions, the pigments and components of photosynthesis (Siddique et al., 2016) are altered which eventually harms the photosynthetic apparatus (Egilla et al., 2005) and lessening enzymatic activities which involved in the Calvin cycle, consequentially diminished crop yield (Noctor et al., 2002). For seed development transportation of assimilates is necessary towards the reproductive sink. Seed setting and its filling is mostly restricted due to limited assimilation either in source or sink (Shahzad et al., 2016). Water stress limits the size of tissues of the source as well as sinks. It also impairs the phloem loading, translocation of assimilates andpartitioning of dry matter contents. On the other hand, water stress effects are different in various plant species according to the phase of plant development, severity and time duration of water stress.Water stress tolerance is accomplished at the cost of the huge aggregate of energy which makes it a cost rigorous phenomenon. The efficiency of plant metabolic mechanisms is determined by the loss of carbohydrates through respiration. Water stress in the root zone area increases the respiration rate of roots, interrupts the carbon resources consumption balance and lessens adenosine triphosphate productivity and increments reactive oxygen species generation (ROS). They are produced in plants when plants are exposed to any environmental stress. ROS comprises alkoxy radicals, hydroxyl radicals, superoxide anion radicals, singlet oxygen and hydrogen peroxide. ROS reacts with lipids, proteins, and deoxyribonucleic acid bringing about oxidative impairment to cells by impeding its casual functions (Gill & Tuteja, 2010; Das & Roychoudhury, 2014; Choudhury et al., 2017).

Drought tolerance mechanism

A plant's ability to survive better and minimize the yield losses due to deficiency of water in the soil is known as drought resistance (Wimalasekera, 2016). More than a few morphological, physiological and molecular responses are encouraged in plants which empower them to better survive under such critical stress conditions (Iqbal et al., 2013).

Morphological mechanism

Plants deal with moisture stress by shortening the growing season as a result they complete their life cycle early before the onset of the water stress period. Flowering time is the most vital character that is linked with water stress adjustment and adaptations because it reduces the life cycle of the plant as a result leading it to prevent deadly drought effects (Araus et al., 2002). However, the crop yield under favorable environments is associated with the duration of crop length and any kind of decline in the length of crop duration will diminish yield.

Water stress avoidance mechanisms decrease the loss of water from the plant by a typical mechanism which includes uptake of adequate amount of water from the soil with the help of extensive, deep and prolific root system and it also controls the transpiration rate from the leaves (Kavar et al., 2008). Several root parameters i.e. root length, root density and biomass are the functional attributes for water stress avoidance and they also take part towards conclusive yield under terminal water stress conditions (Iqbal et al., 2011). A dense and deep root system helps the plant to extract water from the depth of soil (Kavar et al., 2008). While water stress-tolerant genotypes maintain the number of sympodial branches per plant, boll weight, plant height and seed cotton yield with a minute difference when contrasted with the controlled condition. It was additionally watched that water deficit stress altogether diminished the plant growth, yield and leaves water content. The growth and development of tolerant genotypes were relatively fast because of the retention of more moisture from soil earlier and leaving the soil slightly drier for others in this manner kept up the drought avoidance mechanism (Soomro et al., 2011). Plants show phenotypic adaptability under water stress. At the morphological level, the most influenced organs are the plant roots and shoots as both of these are key components for adjustment of plant functioning under water shortage conditions. Plants cut down their water spending under water stress conditions by decreasing number and area of leaves to minimize the yield losses (Homdee et al., 2016). Root growth, size, density and proliferation showed strategic response towards the water stress because obtaining water from the soil is get aceived through the root (Kavar et al., 2008; Rejeb et al., 2016).

Physiological mechanisms

The physiological tolerance mechanism of plants includes osmotic adjustments, Osmo-protectants, anti-oxidants and reactive oxygen species production which impart stress tolerance to the plant. The physiological basis of hereditary variation due to water scarcity is still indistinct as more complex mechanisms are suggested. In the mechanism of osmotic adjustment, cells reduce their osmotic potential as a result gradient for water influx is increased and it maintains the turgor pressure for the sake of conserving cell and tissue water contents. Immense cell water status can be gained through adjustment of osmotic potential or by changing the elasticity of the cell wall that will stabilize the physiological activity of the cell, if water stress will occur for a longer period (Kudoyarova et al., 2013). Cell's water balance is maintained through adjustment of osmotic potential by the accumulation of solutes inside the cytoplasm thus reducing harmful effects of moisture stress.

The antioxidant defense mechanism of crop plants contains enzymatic as well as non-enzymatic components. The enzymatic components of the antioxidant defense mechanism include catalase, glutathione reductase, dehydroascorbate reductase, ascorbate peroxidase, guaiacol peroxidase and monodehydroascorbate reductase (Sharma et al, 2012) While on the other hand, non-enzymatic components involve reduced glutathione, ascorbic acid, a-tocopherol, carotenoids, flavonoids osmolytes and proline (Gill & Tuteja, 2010; Das & Roychoudhury, 2014).

The first target sight of abiotic stress is the biological membranes. It is understood that under moisture stress conditions, stability maintenance and membrane's integrity is an essential component of water stress tolerance mechanism. Stability of cell membrane is correlated to cell membrane's injury and it is said to be physiological index, this phenomenon is utilized to evaluate water stress tolerance (Gerik et al., 1996). In segments of leaves, membrane stability is the most vital character to evaluate the germplasm for water stress tolerance (Hetherington & Woodward, 2003; Dhanda et al., 2004).

Molecular mechanisms

When soil's water contents become reduced, plants suffered from high water stress. The expression of genes may perhaps be altered under such stress conditions (Chen et al., 2017). Gene's expressions might be stimulated directly by stimuli of water stress or it may be indirectly influenced by injury response or secondary stresses. It is assumed that water stress tolerance is a complex phenomenon that contains severalgenes with rigorous activity (Cattivelli et al., 2008). With the use of micro-array technology, it is identified that the genes which are induced by water stress can be categorized into regulatory and functional genes; this categorization is based on the functioning of their products (Zhu, 2002). Functional proteins are produced by functional genes, these functional proteins include enzymes and membrane proteins, late embryogenesis abundant (LEA) proteins, antifreeze proteins, molecular chaperones and vital enzymes for osmolytes biosynthesis and also detoxification enzymes i.e. betaines and proline. While membrane transporters and water channel proteins are directly linked with the protection of plants from adverse effects of environmental stresses (Akhtar et al., 2012), whereas regulatory proteins are produced by regulatory genes like transcriptional factors (Zhou et al., 2010).

Transcriptional factors are known to be the "master regulators" because they control a cluster of genes by regulating the expression of different targeted genes in their promoter region through specific binding of it with cis-acting elements. More than one target gene is under the control of a single transcription factor. This type of regulation of transcriptional factor is termed as "regulon". Transcription factors are categorized into different groups based on the number of sequences and structure of DNA binding domains. Large families of transcription factors are NAC, MYC, bZIP, MYB, WRKY, Cys2His2, AP2/ERF and Zinc Finger (Qin et al., 2008).

Conclusion

Crop plants are mostly affected by several abiotic stresses, which affect their growth and development resulting in the hindrance of crop productivity. Water stress is also known as multidimensional stress that affects plant growth at different levels of plant organization. It may affect the plant's physiological, morphological and biochemical processes. The consequences of water stress are inhibition of plant growth, stomatal closure with diminished transpiration rate, lower chlorophyll contents and inhibition of photosynthesis. The early growth stages of the cotton plant are more critical regarding its survival. Growth and development of tolerant genotypes was relatively fast because of retention of more moisture from soil earlier and leaving the soil slightly drier for others in this manner kept up the drought avoidance mechanism. For increasing global cotton production it is essential to evolve the seed cotton varieties which will sustain their yield as well as quality under water stress conditions.

References

Abdurakhmonov, I.Y. (2013) Role of genomic studies in boosting yield. *Proceedings of International Cotton*

Advisory Board (ICAC), **20**, 7-22.

Akhtar, K.P., Saleem, M.Y., Asghar, M., Ali, S., Sarwar, N., Elahi, M.T. (2012) Resistance of *Solanum* species to *Phytophthora infestans* evaluated in the detached-leaf and whole plant assays. *Pakistan Journal of Botany,* **44**(3), 1141-1146.

Ali, S.O., Ahmadikhah, A. (2009) The effects of drought stress on improved cotton varieties in Golesatn Province of Iran. *International Journal of Plant Production,* **3**(1), 1735-6814.

Amin, A., Nasim, W., Mubeen, M., Sarwar, S., Urich, P., Ahmad, A., Hammad, H.M. (2018) Regional climate assessment of precipitation and temperature in Southern Punjab (Pakistan) using SimCLIM climate model for different temporal scales. *Theoretical and Applied Climatology,* **131**(1), 121-131.

Anjum, S.A., Xie, X.Y., Wang, L.C., Saleem, M.F., Man, C., Lei, W. (2011) Morphological, physiological and biochemical responses of plants to drought stress. *African Journal of Agricultural Research*, **6**(9), 2026-2032.

Araus, J., Slafer, G., Reynolds, M., Royo, C. (2002). Plant breeding and water relations in C3 cereals: What to breed for. *Annals of Botany,* **89**, 925-940.

Aslam, S. , Khan, S. , Ahmed, A., Dandekar, A. (2020) The Tale of Cotton Plant: From Wild Type to Domestication, Leading to Its Improvement by Genetic Transformation. *American Journal of Molecular Biology*, **10**, 91-127.

Attia, A., Rajan, N. (2016) Within season growth and spectral reflectance of cotton and their relation to lint yield. *Crop Science,* **56**(5), 2688-2701.

Auge, R.M. (2001) Water relations, drought and vesicular-arbuscular mycorrhizal symbiosis. *Mycorrhiza,* **11**(1), 3-42.

Aujla, M., Thind, H., Buttar, G. (2005) Cotton yield and water use efficiency at various levels of water and N through drip irrigation under two methods of planting. *Agricultural Water Management,* **71**(2), 167-179.

Azhar, M.T., Rehman, A. (2018) Overview on effects of water stress on cotton plants and productivity. In: "*Biochemical, Physiological and Molecular Avenues for Combating Abiotic Stress Tolerance in Plants*", pp. 297-316. Academic Press.

Bolek, Y. (2007) Yield and yield components of eight cotton genotypes under irrigated and non-irrigated conditions. *KSU Journal of Science and Engineering,* **10(**1), 126-133.

Borel, C., Simonneau, T. (2002) Is the ABA concentration in the sap collected by pressurizing leaves relevant for analyzing drought effects on stomata? Evidence from ABA fed leaves of transgenic plants with modified capacities to synthesize ABA. *Journal of Experimental Botany,* **53**(367), 287-296.

Campbell, B., Saha, S., Percy, R., Frelichowski, J., Jenkins, J.N., Park, W., Giband, M. (2010) Status of the global cotton germplasm resources. *Embrapa Recursos Genéticos e Biotecnologia-Artigo em Periódico Indexado (ALICE)*. **24**, 24-25 .

Cattivelli, L., Rizza, F., Badeck, F.W., Mazzucotelli, E., Mastrangelo, A.M., Francia, E., Stanca, A.M. (2008) Drought tolerance improvement in crop plants: an integrated view from breeding to genomics. *Field Crops Research,* **105**(1-2), 1-14.

Chen, Y., Feng, L., Wei, N., Liu, Z.H., Hu, S., Li, X.B. (2017) Overexpression of cotton PYL genes in *Arabidopsis*spp.enhances the transgenic plant tolerance to drought stress. *Plant Physiology and Biochemistry,* **115**, 229-238.

Choudhury, F.K., Rivero, R.M., Blumwald, E., Mittler, R. (2017). Reactive oxygen species, abiotic stress and stress combination. *The Plant Journal,* **90**(5), 856-867.

Das, K., Roychoudhury, A. (2014) Reactive oxygen species (ROS) and theresponse of antioxidants as ROS-scavengers during environmental stress in plants. *Frontiers in Environmental Science,* **2**, 53-58.

Dhanda, S., Sethi, G., Behl, R. (2004) Indices of drought tolerance in wheat genotypes at early stages of plant growth. *Journal of Agronomy and Crop Science,* **190(**1), 6-12.

Dumka, D., Bednarz, C.W., Maw, B.W. (2004) Delayed initiation of fruiting as a mechanism of improved drought avoidance in cotton. *Crop Science,* **44**(2), 528-534.

Egilla, J., Davies, F., Boutton, T. (2005) Drought stress influences leaf water content, photosynthesis, and water-use efficiency of *Hibiscusrosa-sinensis* L. at three potassium concentrations. *Photosynthetica,* **43**(1), 135-140.

Farooq, M., Wahid, A., Kobayashi, N., Fujita, D., Basra, S. (2009) Plant drought stress: Effects, mechanisms and management. *Agronomy for Sustainable Development*, **29**, 185-212.

Gerik, T.J., Faver, K.L., Thaxton, P.M., El-Zik, K.M. (1996) Late season water stress in cotton: I. Plant growth, water use, and yield. *Crop Science*, **36**(4), 914-921

Ghosh, D., Xu, J. (2014) Abiotic stress responses in plant roots: a proteomics perspective. *Frontiers in Plant Science,* **5**, 6-10.

Gill, S.S., Tuteja, N. (2010) Reactive oxygen species and antioxidant machinery in abiotic stress tolerance in crop plants. *Plant Physiology and Biochemistry,* **48**(12), 909-930.

Guan, X., Song, Q., Chen, Z.J. (2014) Polyploidy and small RNA regulation of cotton fiber development. *Trends in Plant Science,* **19**(8), 516-528.

Heim Jr, R.R. (2002) A review of twentieth-century drought indices used in the United States. *Bulletin of the American Meteorological Society,* **83(**8), 1149-1166.

Hetherington, A.M., Woodward, F.I. (2003) The role of stomata in sensing and driving environmental change. *Nature,* **424**(6951), 901-908.

Homdee, T., Pongput, K., Kanae, S. (2016) Comparative performance analysis of three standardized climatic drought indices in the Chi River basin, Thailand. *Agriculture and Natural Resources,* **50**(3), 211-219.

Iqbal, A.R. (2010) Water Shortage in Pakistan-A Crisis around the Corner. *Institute for Strategic Studies, Research & Analysis (ISSRA) Papers,* **2**(2), 1-13.

Iqbal, K., Azhar, F.M., Khan, I.A. (2011) Variability for drought tolerance in cotton (*Gossypium hirsutum* L.) and its genetic basis. *International Journal of Agriculture and Biology,* **13**(1), 61-66.

Iqbal, M., Khan, M.A., Naeem, M., Aziz, U., Afzal, J., Latif, M. (2013) Inducing drought tolerance in upland cotton (*Gossypium hirsutum* L.), accomplishments and prospects. *World AppliedScience Journal,* **21**(7), 1062-1069.

Jalota, S.K., Sood, A., Chahal, G.B.S., Choudhury, B.U. (2006) Crop water productivity of cotton (*Gossypium hirsutum* L.) wheat (*Triticum aestivum* L.) system as influenced by deficit irrigation, soil texture and precipitation. *Agricultural Water Management*, **84**(1-2), 137-146.

Kavar, T., Maras, M., Kidric, M., Sustar-Vozlic, J., Meglic, V. (2008) Identification of genes involved in the response of leaves of *Phaseolus vulgaris* L. to drought stress. *Molecular Breeding,* **21**(2), 159-172.

Kudoyarova, G., Kholodova, V., Veselov, D. (2013) The current state of the problem of water relations in plants under water deficit. *Russian Journal of Plant Physiology,* **60**(2), 165-175.

Lambers, H., Chapin, F.S., Pons, T.L. (2008) Ecological biochemistry: allelopathy and defense against herbivores. In: "*Plant Physiological Ecology*", pp. 445-477. Springer, New York, NY.

Lokhande, S., Reddy, K.R. (2014) Reproductive and fiber quality responses of upland cotton to moisture deficiency. *Agronomy Journal,* **106**(3), 1060-1069.

Mishra, A.K., Singh, V.P. (2010) A review of drought concepts. *Journal of Hydrology,* **391**(1-2), 202-216.

Noctor, G., Jovanovic, S., Driscoll, S., Novitskaya, L., Foyer, C.H. (2002) Drought and oxidative load in the leaves of C3 plants: a predominant role for photorespiration. *Annals of Botany,* **89**(7), 841-850.

Pettigrew, W. (2004) Moisture deficit effects on cotton lint yield, yield components, and boll distribution. *Agronomy Journal*, **96**(2), 377- 383.

Qin, F., Sakuma, Y., Tran, L.-S. P., Maruyama, K., Kidokoro, S., Fujita, Y., Miyazono, K.I. (2008) Arabidopsis DREB2A-interacting proteins function as RING E3 ligases and negatively regulate plant drought stress-responsive gene expression. *The Plant Cell,* **20**(6), 1693-1707.

Rahman, M., Ullah, I., Ahsraf, M., Stewart, J., Zafar, Y. (2008) Genotypic variation for drought tolerance in cotton. *Agronomy for Sustainable Development,* **28**(3), 439-447.

Rejeb, K.B., Benzarti, M., Debez, A., Savouré, A., Abdelly, C. (2016) Water stress in plants. In: "*Water*

Stress and Crop Plants", pp. 142-149.

Saleem, M.A., Malik, T.A., Shakeel, A., Amjad, M.W., Qayyum, A. (2015) Genetics of physiological and agronomic traits in upland cotton under drought stress. *Pakistan Journal of Agriculture Sciences*, **52(**2), 317-324.

Saranga, Y.E., Jiang, C.X., Wright, R., Yakir, D., Paterson, A. (2004) Genetic dissection of cotton physiological responses to arid conditions and their inter relationships with productivity. *Plant, Cell & Environment,* **27**(3), 263-277.

Seki, M., Kamei, A., Yamaguchi-Shinozaki, K., Shinozaki, K. (2003) Molecular responses to drought, salinity and frost: common and different paths for plant protection. *Current Opinion in Biotechnology,* **14**(2), 194-199.

Shahzad, A., Ullah, S., Dar, A.A., Sardar, M.F., Mehmood, T., Tufail, M.A., Haris, M. (2021) Nexus on climate change: Agriculture and possible solution to cope future climate change stresses. *Environmental Science and Pollution Research*, **28**(5), 1-22.

Shahzad, M.A., Jan, S.U., Afzal, F., Khalid, M., Gul, A., Sharma, I., Ahmad, P. (2016) Drought stress and morphophysiological responses in plants. *Water Stress and Crop Plants: A Sustainable Approach,* **2**, 452-467.

Shang, L., Liang, Q., Wang, Y., Wang, X., Wang, K., Abduweli, A**.,** Hua, J. (2015) Identification of stable QTLs controlling fiber traits properties in multi-environment using recombinant inbred lines in Upland cotton (*Gossypium hirsutum* L.) *Euphytica,* **205**(3), 877-888.

Sharma P., Jha, A.B., Dubey, R.S., Pessarakli, M. (2012) Reactive oxygen species, oxidative damage, and antioxidative defense mechanism in plants under stressful conditions. *Journal of Botany*. Doi. org/10.1155/2012/217037

Siddique, Z., Jan, S., Imadi, S.R., Gul, A., Ahmad, P. (2016) Drought stress and photosynthesis in plants. In: "*Water stress and crop plants: A Sustainable Approach*,"Parvaiz Ahmad (Ed.), pp. 1-11.

Soomro, M.H., Markhand, G.S., Soomro, B.A. (2011) Screening Pakistani cotton for drought tolerance. *Pakistan journal of Botany,* **44(**1), 383-388.

Wang, R., Ji, S., Zhang, P., Meng, Y., Wang, Y., Chen, B., Zhou, Z. (2016) Drought effects on cotton yield and fiber quality on different fruiting branches. *Crop Science,* **56**(3), 1265-1276.

Wang, W.W., Tan, Z.Y., Xu, Y.Q., Zhu, A.A., Li, Y., Yao, J., Tian, Y.M. (2017) Chromosome structural variation of two cultivated tetraploid cottons and their ancestral diploid species based on a new high-density genetic map. *Scientific Reports,* **7**(1), 1-6.

Wiggins, M., Leib, B., Mueller, T.C., Main, C.L. (2014) Cotton growth, yield, and fiber quality response to irrigation and water deficit in soil of varying depth to a sand layer. *Journal of Cotton Science,* **18**(2), 145-152.

Wilhite, D.A. (2000) Drought as a natural hazard: Concepts and definitions. In: "*Drought: A Global Assessment*", Vol. I, Chap. **1**, pp. 3–18.

Wimalasekera, R. (2016) Breeding crop plants for drought tolerance. In: "*Water Stress and Crop Plants: A Sustainable Approach*". Vol. 2, pp. 543-557.

Yazar, A., Sezen, S.M., Sesveren, S. (2002) LEPA and trickle irrigation of cotton in the Southeast Anatolia Project (GAP) area in Turkey. *Agricultural Water Management,* **54**(3), 189-203.

Zaxos, D., Kostoula, S., Khah, E., Mavromatis, A., Chachalis, D., Sakellariou, M. (2012) Evaluation of seed cotton (*Gossypium hirsutum* L.) production and qualitywith the different irrigation levels and two-row spacings. *International Journal of Plant Production,* **6**(1), 129-148.

Zhang, D., Luo, Z., Liu, S., Li, W., Dong, H. (2017) Effects of deficit irrigation and plant density on the growth, yield and fiber quality of irrigated cotton. *Field Crops Research,* **197**, 1-9.

Zhou, G.A., Chang, R.Z., Qiu, L.J. (2010) Overexpression of soybean ubiquitin-conjugating enzyme gene GmUBC2 confers enhanced drought and salt tolerance through modulating abiotic stress-responsive gene expression in *Arabidopsis*spp. *Plant Molecular Biology,* **72**(4), 357-367.

Zhu, J.K. (2002) Salt and drought stress signal transduction in plants. *Annual Review of Plant Biology,* **53**(1), 247-273.