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Effect of heat stress on developmental stages, yield and fibre traits of cotton (*Gossypium hirsutum*)

Sadia Kanwal[1], Muhammad Rafiq Shahid[1]*, Wajid Nazir[3], Muhammad Usama Khan[2], Nadia Hussain[1], Amna Bibi[1], Muhammad Farooq[1], Taj Muhammad[1] and Muhammad Ramzan[4]

[1]Cotton Research Institute, Multan
[2]Department of Agronomy, Ghazi University, D.G. Khan
[3]Department of Plant Breeding & Genetics, Ghazi University, D.G. Khan
[4]Arid Zone Research Institute, Bhakkar

*Corresponding author: Muhammad Rafiq Shahid (shahid1364@yahoo.com)

Abstract

Cotton is taken as white gold for the economy of Pakistan. However, heat stress is the most crucial factor that drastically affects its yield right from germination to maturity. Optimum temperature for root development is 30-35°C but at 40°C root development stops. Extremes of high temperature are harmful that hinders the photosynthetic rate of the crop. For fruiting 27-32°C temperature is required but an increase in temperature from optimum range reduces time for synthate accumulation resulting in fruit shedding. Higher temperature stress decreases pollen viability and the anther indehiscence, which results in a lower seed setting rate and causes significant reductions in final yield. At 40°C Rubisco activity is also inhibited thus results in photosynthesis hindrance. In the case of the cotton crop, an increase in 1°C of temperature, 110kg/ha lint yield is reduced. Heat stress along with water stress also affects potassium and soluble sugar that contribute 80% of total fiber sap resulting in the shortening of fiber length. High temperature can cause roughness of fiber, increasing the micronaire of lint. Lint index, lint percentage, and lint per boll decreased when temperature exceeds 37°C. Therefore, this review article demonstrates the effects of heat stress on different crop stages, productivity, and fiber quality of cotton. Cotton breeders should focus on development of climate resilient cultivars of cotton. © 2021 Department of Agricultural Sciences, AIOU

Keyword: Climate change, cotton, effect of heat stress, developmental stages, yield parameter and fiber quality

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Introduction

Cotton is one of the major crops in Pakistan which covers more than two Mha area accounting for 79% in Punjab, while 20% in Sindh province. Cotton crop contributes about 0.8% in Pakistan's total GDP and values 4.1% in total agriculture addition (Shuli, et al., 2018). Pakistan is the fourth largest producer and the third major consumer of cotton in the world. Approximately 1.6 Million farmers grow cotton in Pakistan, while 10 Million people are linked to the cotton industry (Anjum & Zia, 2020). Pakistan is regarded as a country that is extremely vulnerable to disasters caused by climate change. Due to climate change, Pakistan is facing a rapid rise in annual mean temperature. By the year 2050, there will be a rise in temperature by 2.5 °C (Ahmad et al., 2016a). The poor and underdeveloped countries will suffer the most (Stern, 2006). Due to increased temperature, the agriculture sector will be more susceptible and more vulnerable, since around 60% of total agricultural production is determined by the suitability of the climatic conditions (Deshmukh, 2012). Research findings indicate that the production of major crops in Pakistan would be drastically affected by the rise in temperature (Arshad et al., 2020; Khan et al., 2019). The average cotton production in Pakistan has been around 10 million bales per annum but from the year 2020-21, the expected production is 6.3 million bales,21% less than last year (Anjum & Zia, 2020). Besides other problems for yield reduction in Pakistan, Climate change is the key factor for this serious lag. This study reviews the impacts of high temperature due to climate change on cotton plant growth and physiological attributes.

Temperature affecting cotton crop

For the last few decades, cotton has been the most affected crop to high temperature in Pakistan causing rapid decrease in quantity and quality of the production. Extreme temperature changes are directly affecting the cotton crop that causes change in physiological and morphological functions while indirectly manipulating environmental factors (Zulfiqar et al., 2017). The rapid change in environmental conditions and rise in annual temperature would result in decreased number of bolls per plant, fiber quality, and dry matter (Wang et al., 2014; Wang et al., 2017).

In the growth of the cotton plant, the primary environmental factor influencing growth and maturity is the temperature (Bibi et al., 2004). A plant can be sustained to a high temperature by two different mechanisms of genetics and non-genetics (Klueva et al., 2001). The future of the cotton crop now mainly depends upon the abiotic stresses predominately on high-temperature stresses (Timothy & Michael, 2014). The temperature requirements of the cotton crop can be varied from its physiological periodvariations.

The cotton crop is attributed to the temperate climatic conditions but an adverse increase in temperature can be harmful to its growth and germination (Oosterhuis, 2002). Cotton plants require a high temperature 30/20°C day and night for dry matter accumulation. Different Stress conditions can badly affect the height of the plant, number of internodes per plant, number of sympodial and monopodial branches, and the total number of seeds per boll on a cotton plant depending on stress duration and intensity. From the extensive studies, it has been proved that the root and shoot growth, flowering, and the quality. of fiber traits are strongly influenced by rapid increase in temperature (Saifullah et al., 2015).

Table 1 Effect of abiotic factors on physiological traits of cotton

Abiotic Factors	Effects	References
Heat Stress	Prohit seed imbibition, seed germination percentage and plant populations per unit area. Reduced branching, yield decrease and lint quality reduction	(Rahman, 2006)
Heat-Induced Drought	Stomatal closure, Turgor loss, low photosynthesis, Photo-oxidation, protein denaturing, ROS production, leaf abscission and boll shedding	(Santhosh & Yohan, 2019)
Quality of Solar Radiations	Low quality solar radiation causes sterile flowers and fewer bolls. Quality of solar radiation and interception directly effects P/S rate, CHOS assimilation and source-sink relationships.	(Pettigrew, 2001; Chapea, 2020)
Wind	Wind modifies the temperature and humidity level which directly influences the cotton physiological attributes. 2Extreme winds can cause damage to cotton leaves by 30% and 50% to mature fruits.3Slightly higher winds can increase the number of bolls and their retention.	(Freeland et al., 2006; Cetin & Basbag, 2010; Abdullaev, 2020)
Water Logging Stress	Waterlogging induces Anoxic and Hypoxic conditions in cotton plants. Reduce Mitochondrial and increase fermentation. Terminated growth and root apices death.	(Hassan et al., 2020)
Salinity Stress	Salinity disturbs the soil and plant water relations hinders the water uptake. Reduction in seed emergence, root growth, respiration, photosynthesis, and protein synthesis. Salinity also induces ROS production.	(Wang et al., 2013)
Rainfall	1 Cotton requires 50-100 cm annual rainfall. A little deviation from average rainfall can cause dry and fresh weight reduction, increased secondary metabolites and oxidation. 2 Changing in annual rainfall quantity can alter the growth and development of cotton plant.	(Zulfiqar et al., 2017; Jiang, 2020)

Table 2 Optimum climatic conditions required for cotton

Growth Stage	Average daily temperature	Daily water requirement (mm)	Daily water requirement (in)
Planting Soil	Minimum 18 °C	0	0
Planting Air	More than 21 °C		
Vegetative Growth	21-27 °C	1-2	0.04-0.08
First Square		2-4	0.08-0.16
Reproductive Growth	27-32 °C	3-8	0.12-0.31
Peak Bloom		8	0.31
First Boll Opening		8-4	0.31-0.16
Maturation	21-31 °C	4	0.16

Source: Erie et al. (1981); Abdulmumin & Misari (1990); Hake et al. (1996).

Influence of temperature on seed germination of cotton

Maximum cotton seeds germination can be obtained at optimum temperature. High or low temperature from optimum temperature can influence the germination percentage. Optimum seed germination is required to get the required plant population. From various studies, it has been proved that the seedling germination potential and growth was lowered under the 18 °C and 37 °C, along with the different levels of water stress conditions (Lauxen et al., 2016). The seedling stage is the first and highly prone to be affected by high temperature (Dabbbert and Gore, 2014). The effects of high temperature on germination, seedling growth, vegetative growth, and crop development have been well documented. Extreme weather events are causing more than 50% yield reduction in cotton crop all over the world (Ahmad et al., 2017). The required temperature for seed germination is ranging from 28-30 °C (Rishi et al., 2007). From different experiments, it was observed that the seed germination was satisfactory at 20-25 °C but relatively slow at 25°C. High temperature affects growth stages of cotton including germination, seedling development, stand establishment (Burke & Wanjura 2010). When different tests were conducted, the higher percentage of seed germination was observed at 30 °C and the germination was earlier from 2 to 5 days than at 20 °C. The basal temperature required for seed germination is above 12 °C (Rishi et al., 2007).The recommended soil temperature at proper seeding depth should be above 18 °C to ensure healthy uniform stands (Oosterhuis, 2001). It was reported that a rapid increase in temperature is affecting the mean germination time as well as the mean germination percentage. (Derick et al., 2011).

Influence of temperature on root growth of cotton

When seed is germinated the protrusion of plumule and radicle is initiated and the plant starts to establish its roots in the soil for support, nutrients, and water uptake. Root growth of cotton is much faster than the shoot growth at the initial stages and is most susceptible to temperature and moisture indices. Many studies have suggested that the optimum temperature for maximum root growth of a cotton crop is 35 °C (Schrier et al., 2000). The studies shows that the optimal thermal requirements for cotton root growth is 30/35 °C while maximum temperature at which root development will be extremely affected is 40 °C where roots are contained to shallow depth, this might be done due to reduction in roots hydraulic conductivity caused by water shortage, stomatal closing and abscission (Farooq et al., 2015 ; Saifullah et al., 2015). Stress at roots by high temperature can cause an alteration in hydraulic conductivity of the roots to nutrients and water uptake (Burke, 2001). High temperature can cause a rapid decrease in soil moisture which can disturb the downward root movement causing the containment of root to the top of the soil (Lather et al., 2001). Temperature-induced low moisture conditions cause poorly developed root systems (Burke, 2001). Roots have generally lower temperature requirements ranging up to 30 °C for optimal growth (Snider et al., 2009). Different studies have shown that the root growth increases at optimal temperature or below the optimal temperature. The optimum temperature for root growth is 30/22 °C and gradually decreases when temperature increases more than optimal(Zafar et al., 2018). Roots generally have a lower optimum temperature range for growth than shoots, with optimum temperatures reported to be 30°C. Different studies have shown that root growth of cotton crop was maximum at optimum or below the optimum temperature.Root elongation rate increased rather gradually as temperature increased, reaching a maximum at 32°C, and then falling sharply as the temperature was increased further.

Influence of temperature on vegetative growth of cotton

Vegetative growth in cotton plants includes leaf area development, monopodial and sympodial branches, and canopy establishment. All these characteristics are influenced by climatic conditions predominately temperature. The temperature has two main implications on cotton growth and development. At first, it determines the rates of morphological development and crop growth which includes node development, internodal distance, photosynthesis rate, accumulation of synthates, and respiration. At the second stage, temperature determines the start and end of a growing season (Bange, 2007). Spells of higher temperature couples with water stress affect the photosynthesis rate and hinders the leaf development and leaf area expansion (Snider, 2009). It has been reported the temperature fluctuations can cause adverse effects on uptake of macro and micro nutrients thus resulting in retardation of root shoot growth, branching and leave area expansion (Shakoor et al., 2017). Leaf area development is strictly prohibited during heated environments (Zhao et al., 2017). Cotton plants have an indeterminate growth pattern and require warm days and cool nights (Zeeshan et al., 2010). Cotton plant is of warm climate, but it is directly affected by extreme temperatures. The optimum temperature requirements for Asian Cotton plants is 21/27°C (Oosterhuis, 2002). Past studies show that leaf area development is highly sensitive to temperature. Required temperature for optimum leaf growth is 26 °C. Higher temperature than optimum (>32 °C) will retard vegetative and reproductive growth at different stages (Loka, 2010). The temperature range for leaf expansion and stem elongation was 30-32°C. (Rishi et al., 2007). The length of fruiting branches can be increased at 30 °C temperature but rapidly reduces the growth at 40 °C as the maximum temperature for cotton protection threshold level is 40°C (Rishi et al., 2007). With the rise in temperature the length of the fruiting branches can be increased with increase in fruiting node distance, but at 40 °C, the increase will be down to zero. The high temperature thus resulting in slow growth in leaf and branches, thus resulting in reduced plant canopy (Burke et al., 2004). The optimum temperature for head formation, boll production and retention can be achieved at maximum level at 30 °C. The temperature 40°C or more can cause stoppage of many physiological functions in cotton plants (Mohamed & Hamid, 2013).

Influence of temperature on fruiting and retention of cotton

Timely fruiting and retention of maximum fruits or bolls on the cotton plant are the main yield contributing factors. Fruiting and retention percentage is a genetic character of specific species, but these attributes are highly sensitive to fluctuation in temperature. Extreme temperature in plant flowering and boll development stage has caused severe abortion in Punjab Pakistan (Statista, 2017; Iqbal et al., 2017). Temperature alteration will modify the flowering percentage, boll retention and even seed numbers in boll (Sarwar et al., 2017). Every single function in a cotton plant is directly or indirectly affected by temperature (Mohamed & Hamid, 2013). 27-32 °C temperature is required for maximum fruiting. (Thomas et al 2006). Temperature higher than the optimum can boost up the fruit development, but reduce the time for synthates to accumulate thus causing a fall in fruits. From fruit branching to flowering, pollination and boll formation and retention temperature decides directions of the plant (Bibi et al., 2004). Thermal conductivity and tolerance are the key factors for deciding fruit retention or shedding on cotton plants (Ekinci et al., 2017). Higher temperatures than optimal can induce the (Snider et al., 2009), square and boll shedding and decreased boll size leading to lower cotton yield. At the end High temperature stress is reported to affect the pollen viability and the anther indehiscence, resulting in lower fruiting rate and causing significant reductions in final yields (Zahid et al., 2016).

Fig. 1 Flower shedding in cotton due to high temperature

Fig. 2 Boll shedding and decreased boll size of cotton due to high temperature

Fig. 3 Dehydrated bolls of cotton due to high temperature

Fig. 4 Dissection view of dehydrated bolls exhibiting 2 shrinkled out of total 5 locules (both fiber and seeds remained un-developed

Influence of temperature on yield of cotton

The main objective of a better crop stand is to obtain the maximum yield in available resources. As discussed earlier, all the yielding parameters of the cotton crop are highly sensitive to temperature. Heat stress has potentially affected the cotton yield in Pakistan for the past few decades(Amin et al., 2018; Iqbalet al., 2017) The rise in temperature causes poor mineral nutrition to shoot, leave boarding and boll developing resulting in low yield in near future (Huang 2015; Amin et al., 2018). An increase in even 1°C of temperature than optimal can cause a yield reduction up to 110 kg/ha lint (Singh et al., 2007). Temperature is one of the most important climatic parameters which can affect the growth, development, and yield of the crop (Ghosh et al., 2014). Environmental factors, mainly temperature are the main driver of the yield (Brown et al., 2003). Temperature effect on yield is resulted due to its impact on critical growth stages of the cotton plant (Thakare et al., 2014). Optimum temperature will enhance flowering capacity, net P/S rate and accumulation, thus higher boll weight and yield (Xiao et al., 2017). High temperature caused a disruption in photosynthesis and accumulation resultantly lowered the yield (Oosterhuis, 2002). The cotton plant requires relatively cool nights for better fruiting, but during the monsoon periods, there can be a rise in 4-5 °C temperature which can cause a decrease in dry matter production and lint yield (Brown et al., 1995). Heat stress coupled with water deficiency during the boll filling stage can cause shortening in the fiber length and weight (Haigler et al., 2005).

Influence of temperature on fiber quality of cotton

Besides other factors, the quality of fiber could be contrived due to temperature-induced impingement on the growth and production of the cotton plant. Cotton fiber quality traits such as length, strength, elongation, and micronaire are negatively impacted under higher temperature (Pettigrew, 2008). The fiber quality and lint characteristics highly anticipate the air temperature and agronomic practices (Zhou et al., 2014; Wang et al., 2017; Gu et al., 2018). Fiber strength and qualities are dependent upon the accumulation of photosynthates which is directly affected by high temperature(Pettigrew, 2016). Higher temperature impedes cellulose synthesis, thus compromising the fiber length and strength (Loka, 2010).The optimum temperature for fiber uniformity and micronaire is around 16°C while fiber strength is 18-22 °C (Lokhande, 2014).Temperature extreme can also cause constraints in fiber quality (Dong et al., 2006). Potassium, soluble sugar, and malate contribute to 80% total fiber sap, and these components are extensively affected by the rise in temperature (Pfugler & Zambryski, 2001). High temperature can cause roughness of fiber, increasing the micronaire of lint (Haigler et al., 2005). Heat stress at fiber development can cause alteration in fiber wall deposition and cross-sectional growth of micronaire (Bradow et al., 2001). An increase of 1 °C from optimal temperature, fiber yield can be reduced up to 110 kg ha^{-1} (Singh et al., 2007).

Effect of temperature on physiology of cotton

Different stress conditions, especially heat stress can induce a wide number of physiological changes in plant cell mechanisms. Heat stress can cause multiple alterations in plant systems from stomatal closure, causing photosynthesis reduction, lower transpiration rates, and protein malfunction. Cotton plant defense mechanism is functional at 40°C and beyond it can cause a rapid reduction in photosynthetic pigment dysfunction, reduction in proline content, and total soluble sugars (Mohamed & Hamid, 2013). Chlorophyll fluorescence is also reduced under higher temperature conditions (Bibiet al., 2004). Photosystem(II) or PSII is considered to be the most sensitive component under heat stress conditions (Salvucci & Craft, 2004). Higher temperature stress causes pollen viability and the anther indehiscence, resulting in a lower boll/seed setting rate and causing significant reductions in final yields (Zahid et al., 2016). At 40°C Rubisco activity is also inhibited thus resulting in photosynthesis hindrance (Crafts & Law, 2000). Changes in plant water relationship, photosynthates accumulation, chlorophyll pigments synthesis, and enzymatic activities were altered in heat stress conditions (Kamal et al., 2017). Heat stress at 40 °C is reported to cause significant reductions in photosynthetic pigments, proline contents and total soluble sugars along with decreased morphological attributes (Mohamed & Hamid, 2013). It is evaded that with increased temperature with elevated concentration, only rise in CO_2 concentration can increase the photosynthetic activity and assimilation, while temperature and CO_2 coupled can cause a loss in water relations and photorespiration (Broughton et al., 2017). In a study conducted on 16 different cultivars, dry weight, leaf pigment, and cellular respiration was affected by elevated temperature (Demirel et al., 2016). In an experiment, it was observed that heat stress can cause a delay in reproductive stage initiation in late maturity cultivars as compared to short-duration cultivars (Ahmad et al., 2016b).

Effect of temperature on plant biochemistry of cotton

Suboptimal temperature conditions at the critical reproductive stage can cause tremendous qualitative and quantitative losses inboll production and fiber formation. Due to heat stress at the fiber development stage, carbohydrates assimilation which is more than 60% direct comes from the leaf of the boll, and the responsible leaf is affected by heat stress spells, thus disrupting the photosynthesis rate and mis-balancing the carbohydrates assimilation in the leaf (Snider, 2009). Water stress induced by heat stress inhibits the cell elongation due to influenced osmolyte compositions, activation of growth inhibitory enzymes, and low turgidity (Chen et al. 2017). It is proved that under severe heat stress conditions, protein dysfunctioning can be held thus activating heat shock protein (Sarwaret al., 2017). Different cotton genotypes under heat stress,during their evolution in stress tolerance,have induced heat shock proteins in response to stress as compared to sensitive ones (Mohamed & Hamid 2013; Kumar et al., 2011).In arid and semi-arid conditions followed by high temperature, the plant has accumulated HSP as a defense mechanism. HSPs are implicated in acquiring thermotolerance in heat stress, maintaining cell integrity, preventing the cell from denaturing, and protecting PSII. PSII is regarded as the most sensitive site of the photosynthetic apparatus sensitive to heat stress, while the CO_2 fixation is also considered to be affected at high temperatures (Salvuci & Crafts, 2004). The elevated temperature of 38-41°C causes HSP to be inducted in laboratory-grown cotton plants . From an experiment, it was clearly shown that during high temperature, CMT or cell membrane thermostability mechanism was activated. This mechanism was highly active in heat stress from 44-49°C and lower in 37-39 °C in a Pakistani cultivar MNH-886 (Kamal et al., 2017). More than 35 °C, inhibition of pollen tube growth was more pronounced at the boll formation stage resulting in lowering end products. During an experiment on cotton cultivars conducted in Pakistan, plants under extreme heat stress conditions 38-45 °C failed to protect cellular membranes. Besides the heat stress, temperatures below 15 °C can cause severe damage to plant cells at the cellular and molecular level due to oxidative effects (Holadayet al., 2016).

Table 3 Growth stages indicated by degree day heat units

Growth stage	DD15.5 °C	DD60 °F
Planting to emergence	25-35	50-60
Emergence to first fruiting branch	165-190	300-340
From emergence to 1st square	235-265	425-475
Square to white bloom	165-195	300-350
Emergence to full bloom	770-795	1385-1435
White bloom to boll opening	415-610	750-1100
Emergence to crop maturity	1165-1250	2100-2250

Source modified from Boyd et al. (2004).

Conclusion

Temperature extremes both maximum and minimum are important, because seed germination, root development, photosynthetic response, boll and fiber development are also influenced with respect to change in environmental temperature. Range of 30-35 °C is the ideal temperature for root development, and at 40 °C, root development typically ceases. Both vegetative and reproductive stages are affected by temperature extremes and spells of high temperature modifies metabolic activity and induced water stress. It was concluded that the optimum temperature for boll production, and retention was at 30 °C. Above 40 °C square initiation, root, fiber and seed development is nearly stopped. Maximum temperature stress reduces pollen viability and the anther indehiscence. Therefore, this review article demonstrates the effects of heat stress on different crop stages, productivity, and fiber quality of cotton. Cotton breeders should focus on development of climate resilient cultivars of cotton.

References

Abdullaev, S. F., & Sokolik, I. N. (2020). Assessment of the influences of dust storms on cotton production in Tajikistan. *Landscape Dynamics of Drylands across Greater Central Asia: People, Societies and Ecosystems, 17*, 83-87.

Ahmad, A., Wajid, A., Hussain, M., Akhtar, J., & Hoogenboom, G. (2016b). Estimation of temporal variation resilience in cotton varieties using statistical models. *Pakistan Journal Agricultural Sciences, 53*(4), 787-807.

Ahmad, S., Abbas, Q., Abbas, G., Fatima, Z., Naz, S., Younis, H., Khan, R. J., Nasim, W., Rehman, M. H., Ahmad, A., & Rasul, G. (2017). Quantification of climate warming and crop management impacts on cotton phenology. *Plants, 6*(1), 7. doi: 10.3390/plants6010007

Ahmad, S., Nadeem, M., Abbas, G., Fatima, Z. Z., Khan, R. J., Ahmed, M., Ahmad, A., Rasul, G. A., & Khan, M. A. (2016a). Quantification of the effects of climate warming and crop management on sugarcane phenology. *Climate Research 71*, 47–61.

Amin, A., Nasim, W., Mubeen, M., Sarwar, S., Urich, P., Ahmad, A., Wajid, A., Khaliq, T., Rasul, F., Hammad., & Rehmani, M. I. A. (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*(1-2), 121-131.

Anjum, A., & Zia, U. (2020). Unravelling water use efficiency in Sugarcane and Cotton production in Pakistan. *The Pakistan Development Review, 59*(2), 321-326.

Arshad, A., Ashraf, M., Sundari, R. S., Qamar, H., Wajid, M., & Hasan, M. (2020). Vulnerability assessment of urban expansion and modelling green spaces to build heat waves risk resiliency in Karachi. *International Journal of Disaster Risk Reduction, 46*, 101-468.

Bange, M. (2007). Effects of climate change on cotton growth and development. *The Australian Cotton Grower, 28*(3), 41-45.

Bibi, A. C., Oosterhuis, D. M., Gonias, E. D., & Bourland, F. M. (2004). Screening a diverse set of cotton cultivars for high temperature tolerance. *Summaries of Arkansas Cotton Research, 533*, 39-43.

Boyd, M. L., Phipps, B. J., Wrather, J. A., Newman, M., & Sciumbato, G. (2004). Cotton pests scouting and management. Plant Protection Programs College of Food, Agriculture and Natural Resources. *University of Missouri*, 1-98.

Bradow, J. M., Johnson, R. M., Bauer, P. J., & Sassenrath-Cole, G. F. (2001). Variability in micronaire: Sources and significance. In ‘‘Proceeding of the Beltwide Cotton Conferences’’. *National Cotton Council of America, Memphis, TN*, 477–478.

Broughton, K. J., Smith, R. A., Duursma, R. A., Tan, D. K., Payton, P., Bange, M. P., & Tissue, D. T. (2017). Warming alters the positive impact of elevated CO2 concentration on cotton growth and physiology during soil water deficit. *Functional Plant Biology, 44*(2), 267-278.

Brown, R. S., Oosterhuis, D. M., Coker, D. L., & Fowler, L. (2003). The dynamis of drymatter partitioning in the cotton boll of modern and obsolete cultivars. In ‘‘Proceeding of the Beltwide Cotton Conferences’’. *National Cotton Council of America, Memphis, TN.* 1886–1889.

Burke, J. J. (2001). Opportunities for improving cotton’s tolerance to high temperature. In ‘‘Proceeding of the Beltwide Cotton Conferences’’ (C. P. Dugger and D. A. Richter, Eds.) *National Cotton Council of America, Memphis, TN, 1453*.

Burke, J. J., & Wanjura, D. F. (2010). Plant responses to temperature extremes. In J. M. Stewart, D. M. Oosterhuis, J. J. Heitholt, J. R. Mauney (Eds.), *Physiology of cotton* (pp. 123-128). New York: Springer.

Burke, J. J., Velten, J., & Oliver, M. (2004). *In vitro* analysis of cotton pollen germination. *Journal of Agronomy, 96*(2), 359-368.

Cetin, O., & Basbag, S. (2010). Effects of climatic factors on cotton production in semi-arid regions. *Research on Crops, 11*(3), 785-791.

Chapea, B., Mudada, N., & Mapuranga, R. (2020). The impact of plant density and spatial arrangement on light interception on cotton crop and seed cotton yield: An overview. *Journal of Cotton Research, 3*(1), 1-6.

Chen, Y., Wang, H., Hu, W., Wang, S., Wang, Y., Snider, J. L., & Zhou, Z. (2017). Combined elevated temperature and soil waterlogging stresses inhibit cell elongation by altering osmolyte composition of the developing cotton (*Gossypium hirsutum* L.) fiber. *Plant Science, 256*, 196-207.

Crafts-Brandner, S., & Law, R. D. (2000). Effect of heat stress on the inhibition and recovery of the ribulose-1, 5-bisphosphate carboxylase/oxygenase activation state. *Planta*, *212*(1), 67-74.

Dabbert, T. A., & Gore, M. A. (2014). Challenges and perspectives on improving heat and drought stress resilience in cotton. *Journal of Cotton Science, 18*(3), 393-409.

Demirel, U., Copur, O., & Gur, A. (2016). Early-stage screening for heat tolerance in cotton. *Plant Breeding, 135*(1), 80-89.

Deshmukh, D. T., & Lunge, H. S. (2012). Impact of global warming on rainfall and cotton lint with vulnerability profiles of five districts in Vidarbha, India. *International Journal of Scientific & Technology Research, 1*(11), 77-85.

Dong, H., Li. W., Tang. W., Li. Z., Zhang. D., & Niu. Y. (2006). Yield, quality and leaf senescence of cotton grown at varying planting dates and plant densities in the Yellow Rive Valley of China. *Field Crops Research, 98*(2–3), 106-115

Erie, L. J., French, O. F., Bucks, D. A., & Harris, K. (1981). Consumptive Use of Water by Major Crops in the Southwestern United States. *United States Department of Agriculture.*

Farooq, J., Mahmood, K., Rehman, A. U., Javaid, M. I., Petrescu-Mag, V., & Nawaz, B. (2015). High temperature stress in cotton *Gossypium hirsutum* L. *Extreme Life, Biospeology & Astrobiology, 7*(1), 34-44.

Freeland Jr, T. B., Pettigrew, B., Thaxton, P., & Andrews, G. L. (2006). Agrometeorology and cotton production. *World Meteorological Organization.*

Ghosh, K., Rajavel, M., Samui, R. P., Singh, G. P., & Karmakar, C. (2014). Forewarning incidence of American boll worm (*Heliothis armigera* H.) of cotton at Akola in Vidarbha region of Maharashtra. *Mausam, 65*(1), 73-82.

Gu, S., Zhang, L., Yan, Z., VanDerWerf, W. & Evers, J. B. (2018). Quantifying within-plant spatial heterogeneity in carbohydrate availability in cotton using a local-pool model. *Annals of Botany, 121*(5), 1005-1017.

Haigler, C. H., Zhang. D., & Wilkerson, C. G. (2005). Biotechnological improvement of cotton fiber maturity. *Physiologia Plantarum, 124*(3), 285–294.

Hake, S. J., Grimes, D. W., Hake, K. D., Kerby, T. A., Munier, D. J., & Zelinski, L. J. (1996). Irrigation scheduling. In: J. S. Hake, T. A. Kerby & K. D. Hake (Eds.), *Cotton production manual* (pp. 228-247). Los Angeles, Californai: *University of California, Division of Agriculture and Natural Resources*.

Hassan, A., Ijaz, M., Sattar, A., Sher, A., Rasheed, I., Saleem, M. Z., & Hussain, I. (2020). Abiotic stress tolerance in cotton. In *Advances in Cotton Research*; IntechOpen: London, UK, 2020; ISBN 978-1-78984-354-5.

Holaday, A. S., Mahan. J. R., & Payton, P. (2016). Effects of chilling temperatures on photosynthesis. *Journal of Cotton Science, 20*(3), 220-231.

Huang, J., & Ji, F. (2015) . Effects of climate change on phenological trends and seed cotton yields in oasis of arid regions. *International Journal of Biometerology, 59*(7), 877-888.

Iqbal, M., Ul-Allah, S., Naeem, M., Ijaz, M., Sattar, A., & Sher, A. (2017). Response of cotton genotypes to water and heat stress from field to genes. *Euphytica, 213*(6), 1-11.

Kamal, M., Saleem, M. F., Wahid, M. A., & Shakeel, A. (2017). Effects of ascorbic acid on membrane stability and yield of heat-stressed BT cotton. *Journal of Animal and Plant Sciences, 27*(1), 192-199.

Khan, N., Shahid, S., Bin Ismail, T., & Wang, X. J. (2019). Spatial distribution of unidirectional trends in temperature and temperature extremes in Pakistan. *Theoretical and Applied Climatology,136*(3), 899–913.

Klueva, N. Y., Maestri, E., Marmiroli, N., & Nguyen, H. T. (2001). Mechanism of thermotolerance in crops. In A. S. Basra (Ed.), *Crops responses and adaptations to temperature stress* (pp. 177–217). Binghamton, NY: Food Products Press

Kumar, R. R., Goswami, S., Kumar, N., Pandey, S. K., Pandey, V. C., Sharma, S. K., Pathak, H., & Rai, R. D. (2011). Expression of novel ascorbate peroxidase isoenzymes of wheat (*Triticum aestivum* L.) in response to heat stress. *International Journal of Plant Physiology and Biochemistry, 3*(11), 188-194.

Lather, B. P. S., Saini, M. L., & Punia, M. S. (2001). Hybrid cotton retrospect and prospects in Indian context. *National Journal of Plant Improvement, 3*, 61–68.

Loka, D. A., & Oosterhuis, D. M. (2010). Effect of high night temperatures on cotton respiration, ATP levels and carbohydrate content. *Environmental and Experimental Botany, 68*(3), 258-263.

Lokhande, S., & Reddy, K. R. (2014). Quantifying temperature effects on cotton reproductive efficiency and fiber quality. *Agronomy Journal, 106*(4), 1275-1282.

Mohamed, H. I., & Abdel-Hamid, A. M. E. (2013) . Molecular and biochemical studies for heat tolerance on four cotton genotypes. *Romanian Biotechnological Letters, 18*(6), 8823-8831.

Oosterhuis, D. M., & Bourland, F. M. (2001). Development of a cotton plant. In R. Seagull & P. Alspaugh (Eds.), *Cotton fiber development and processing: An illustrated overview*. Texas USA: International Textile Center, Texas Tech. University, Lubbock.

Oosterhuis, D. M. (2002). Day or night high temperatures: A major cause of yield variability. *Cotton Grower, 46*(9), 8-9.

Pettigrew, W. (2008). The effect of higher temperatures on cotton lint yield production and fiber quality. *Crop Science, 48*(1), 278-285.

Pettigrew, W. (2016). Cultivar variation in cotton photosynthetic performance under different temperature regimes. *Photosynthetica, 54*(4), 502-507.

Pettigrew, W. T. (2001). Environmental effects on cotton fiber carbohydrate concentration and quality. *Crop Science, 41*, 1108-1113.

Rahman, H. U. (2006). Number and weight of cotton lint fibres: variation due to high temperatures in the field. *Australian Journal of Agricultural Research, 57* (5), 583-590.

Rishi, P. S., VaraPrasad, P. V., Sunita, S. N. G., & Reddy, R. K. (2007). Influence of high temperature and breeding for heat tolerance in cotton: *A Review: Advances in Agronomy,* (93), 313-385.

Saifullah, A., Rajput, M. T., Khan, M. A., Sial, M. A., & Tahir, S. S. (2015). Screening of cotton (*Gossypium hirsutum* L.) genotypes for heat tolerance. *Pakistan Journal of Botany, 47*(6), 2085-2091.

Salvucci, M. E., & Crafts-Brandner, S. J. (2004). Mechanism for deactivation of Rubisco under moderate heat stress. *Physiologia Plantarum, 122*(4), 513-519.

Santhosh, B., & Yohan, Y. (2019). Abiotic stress responses of cotton: A review. *International Joual of Chemical Sciences, 7*(6), 795-798.

Sarwar, M. B., Sadique, S., Hassan, S., Sania, R. I. A. Z., Rashid, B., Mohamed, B. B., & Husnain. T. (2017). Physio-biochemical and molecular responses in transgenic cotton under drought stress. *Journal of Agricultural Sciences, 23*(2), 157-166.

Schrier, A. A., Hoffmann-Thoma, G., & van Bel, A. J. (2000). Temperature effects on symplasmic and apoplasmic phloem loading and loading-associated carbohydrate processing. *Functional Plant Biology, 27*(9), 769-778.

Shakoor, A., Saleem, M. F., Anjum, S. A., Wahid, M. A., & Saeed, M. T. (2017). Effect of heat stress and benzoic acid as foliar application on earliness and nutrients uptake in cotton. *Journal of Agricultural Research, 55*(1), 15-28.

Shuli, F., Jarwar, A. H., Wang, X., Wang L., & Ma, Q. 2018. Overview of the cotton in Pakistan and its future prospects. *Pakistan Journal of Agricultural Research, 31*(4), 396-407

Singh, R. P., Prasad, P. V., Sunita, K., Giri, S. N., & Reddy, K. R. (2007). Influence of high temperature and breeding for heat tolerance in cotton: A review. *Advances in Agronomy, 93,* 313-385.

Snider, J. L., Oosterhuis, D. M., Skulman, B. W., & Kawakami, E. M. (2009). Heat stress-induced limitations to reproductive success in (*Gossypium hirsutum*). *Physiologia Plantarum, 137*(2), 125-138.

Statista. (2017). World Cotton Production by Country; Statista: Hamburg, Germany.

Stern, N. (2006). The economics of climate change, The Stern review. *Cambridge University Press.*

Thakare, H. S., Shrivastava, P. K., & Bardhan, K. (2014). Impact of weather parameters on cotton productivity at Surat (Gujarat), India. *Journal of Applied Natural Sciences, 6*(2), 599-604.

Timothy, A., & Michael, A. (2014). Challenges and perspectives on improving heat and drought stress resilience in cotton. *Journal of Cotton Science, 18,* 393-409.

Wang, S. L., Heisey, P. W., Huffman, W. E., & Fuglie, K. O. (2013). Public R&D, private R&D, and US agricultural productivity growth: Dynamic and long-run relationships. *American Journal of Agricultural Economics, 95*(5), 1287-1293.

Wang, X., Zhang, L., Evers, J. B., Mao, L., Wei, S., Pan, X., Zhao., X., van der Werf, W., & Li, Z. (2014). Predicting the effects of environment and management on cotton fiber growth and quality: A functional-structural plant modelling approach. *AoB Plants*, *6*, plu040; doi:10.1093/ aobpla/plu040

Wang, Z., Chen, J., Xing, F., Han, Y., Chen, F., Zhang, L., Li, Y., & Li. C. (2017). Response of cotton phenology to climate change on the North China Plain from 1981 to 2012. *Scientific Reports, 7*(1), 1-10.

Xiao, F., Yang, Y., Wang, Y., Ma, H., & Zhang, W. (2017). Effects of low temperature on PSI and PSII photoinhibition in cotton leaf at boll stage. *Acta Agronomica Sinica*, *43*(9), 1401-1409.

Zafar, S. A., Noor, M. A., Waqas, M. A., Wang, X., Shaheen, T., Raza, M., & Rahman, M. U. (2018). Temperature extremes in cotton production and mitigation strategies. *In: Past, present and future trends in cotton breeding,* IntechOpen, doi: 10.5772/intechopen.74648.

Zahid, K. R., Ali, F., Shah, F., Younas, M., Shah, T., Shahwar, D., Hassan, W., Ahmad, Z., Qi, C., Lu, Y., & Iqbal, A. (2016). Response and tolerance mechanism of cotton *Gossypium hirsutum* L. to elevated temperature stress: *A review. Frontiers in Plant Science,* 7, 937. doi: 10.3389/fpls.2016.00937

Zeeshan, A., Khan, T. M., & Noorka, I. R. (2010). Diallel analysis to determine gene action for lint percentage and fibre traits in upland cotton. *International Journal of Agricultural and Applied Sciences, 2*(1), 11-14.

Zhao, W., Du, M., Xu, D., Lu, H., Tian, X., & Li, Z. (2017). Interactions of single mepiquat chloride application at different growth stages with climate, cultivar, and plant population for cotton yield. *Crop Science, 57*(3), 1713-1724.

Zhou, X., Bi, S., Yang, Y., Tian, F., & Ren, D. (2014). Comparison of ET estimations by the three-temperature model, SEBAL model and eddy covariance observations. *Journal of Hydro-environment Research, 519,* 769-776.

Zulfiqar, F., Datta, A., & Thapa, G. B. (2017). Determinants and resource use efficiency of “better cotton”: An innovative cleaner production alternative. *Journal of Cleaner Production, 166,* 1372-1380.

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