

Research Article



Evaluation of Spring Wheat Genotypes for Climatic Adaptability using Canopy Temperature as Physiological Indicator

Muhammad Sohail^{1*}, Imtiaz Hussain², Maqsood Qamar², Sikander Khan Tanveer², Syed Haider Abbas², Zeshan Ali¹ and Muhammad Imtiaz³

¹Plant Physiology Program, Crop Sciences Institute, National Agricultural Research Center, Islamabad Pakistan; ²Wheat Program, Crop Sciences Institute, National Agricultural Research Center, Islamabad Pakistan; ³International Maize and Wheat Improvement Centre (CIMMYT), Islamabad Office Pakistan.

Abstract | Temperature and drought stresses are generally considered main wheat yield limiting factors in rainfed environment, especially during reproductive growth stages. However, variability might exist among wheat genotypes in response to stressful conditions. The objective of the study was to test the climatic adaptability potential of the wheat genotypes using canopy temperature measurement as physiological indicator. The trial was comprised of forty spring wheat genotypes which were sown on normal and late planting dates to create variable growing environments under field conditions. Wheat genotypes showed significant variation ($p < 0.05$) under both normal and late planting dates. The genotypes showed a strong correlation among canopy temperature, spike sterility and grain yield under both planting dates. The canopy temperature and grain yield correlated negatively under both normal ($r^2 = -0.943$) and late planting ($r^2 = -0.957$). However, the canopy temperature and spike sterility showed strong positive correlations under both normal ($r^2 = 0.920$) and late ($r^2 = 0.937$) planting dates, respectively. The results indicate that genotypes viz; Pakistan-2013, DN-93, SRN-09111, PR-103, NR-409, NR-421 (now approved wheat variety in the name of Zincol-2016), Galaxy and NARC-2011 maintained low crop canopy temperature during grain filling period showed lower spike sterility and produced higher grain yields. The genotypes with higher canopy temperature during grain filling period showed higher spike sterility which is linked to lower grain yield. The wheat genotypes identified with better climatic adaptability are potentially useful sources for improving drought and heat tolerance in wheat. Moreover, canopy temperature measurement proved to be a useful phenotyping tool in selection of drought and heat tolerant wheat germplasm under field conditions.

Received | March 26, 2019; **Accepted** | October 23, 2019; **Published** | January 22, 2020

***Correspondence** | Muhammad Sohail, Plant Physiology Program, Crop Sciences Institute, National Agricultural Research Center, Islamabad 45500, Pakistan; **Email:** sohail.parc@gmail.com

Citation | Sohail, M., I. Hussain, M. Qamar, S.K. Tanveer, S.H. Abbas, Z. Ali and M. Imtiaz. 2019. Evaluation of spring wheat genotypes for climatic adaptability using canopy temperature as physiological indicator. *Pakistan Journal of Agricultural Research*, 33(1): 89-96.

DOI | <http://dx.doi.org/10.17582/journal.pjar/2020/33.1.89.96>

Keywords | Wheat, Climate adaptability, Canopy temperature, Grain yield, Spike sterility

Introduction

Climate change is cumulative accepted as a worldwide phenomenon with possibly significant consequences (IPCC, 2007b) and accompanying with recurrent extreme weather events (Stern, 2006; Karl et al., 2009). Global average annual temperature has

increased by ~0.4 °C since 1980, with some extreme changes in different parts of the world (IPCC, 2001). Many studies have indicated the impacts of upcoming climate changes on food security (Rosenzweig and Parry, 1994; Edmonds and Rosenberg, 2005). Third world countries are only contributing 10% to the annual global carbon dioxide emissions but are most

susceptible to climate change (Maskrey et al., 2007) because they are reliant on mainly agriculture-based rural livelihood (World Bank, 2009). Crops cultivation in Pakistan are mainly dominated in arid and semi-arid regions (Janjua et al., 2010) and changes in rainfall pattern and increase in temperature would adversely impact crop productivity.

Shift in seasonal temperature and rainfall patterns forecast the global climate variability. There is high level of uncertainty about the nature of micro climate change. High temperature and limited soil moisture adversely affect physio-agronomic traits of the crop under rainfed conditions, which ultimately led to lower grain yield (Sohail et al., 2013). Reduced grain yield under rainfed conditions might be linked to grain mortality (spike sterility) due to high temperature injury at reproductive growth stages of the crop (Calderini et al., 1999; Khan et al., 2007). Terminal heat stress shortens grain filling period, disrupt synthesis of starch in the endosperms of the kernels, induce early maturity which cause shrinking of kernels, reduce grain weight (Rawson, 1987; Nageswara et al., 2001) and quality (Sohail et al., 2018).

Wheat occupies the largest rainfed area among all the crops (Portmann et al., 2010). Significant variations exist among wheat genotypes in terms of their adaptability to stressful environment (Khan et al., 2007; Mehboob et al., 2005; Okuyama et al., 2005). The ability of the wheat genotypes to withstand high temperature stress is associated with various physiological adaptability traits (Lopes and Reynolds, 2010; Reynolds et al., 1994). Adapted genotypes can play important role to enhance wheat productivity under rainfed conditions.

It is a daunting task for the wheat breeders to increase the productivity under stress environment. Selection for tolerance to temperature and drought under field conditions is complicated due to unavailability of quick screening techniques to evaluate large number of genotypes. Many physiological and agronomic indices to assess yield loss under drought and heat tolerance have been used for evaluation of tolerant genotype. However, Infrared thermometry (canopy temperature measurements) have been widely used in recent years to study genetic variation among genotypes under field conditions in response to temperature and drought. Crop canopy temperature

within and near the surface of canopy is more or less different from the air temperature. Canopy temperature can be warmer and cooler than the surrounding air depending upon the prevailing micro environmental factors (Sohail et al., 2014). During transpiration process, a significant amount of energy is needed to transform liquid water into vapour, and this energy is consumed by evaporating water from the leaf which lowers the leaf temperature and surrounding air which links canopy temperature with crop water stress and evapotranspiration. Canopy temperature measurement can be a good indicator of abiotic stress and metabolic functioning of plant (Colaizzi et al., 2012).

Infrared thermometer (measuring crop canopy temperature) is used as remote sensing tool which is also named as thermometry, thermal sensing or thermography. These spectral reflectance techniques are found to be very convenient and robust to estimate abiotic stresses in plants (Renold, 1998; Mahan and Yeater, 2008; Vadivambal and Jayas, 2011). A hand-held infrared thermometer is a non-destructive, quick and robust tool to measure canopy temperature (CT) which is related to the amount of transpiration resulting in evaporative surface cooling (Renold, 1998). Researchers have reported a strong correlation among canopy temperature measurement with many physiological factors: stomatal conductance, transpiration rate, plant water status, water use, leaf area index and crop yield (Khan et al., 2007; Sohail et al., 2013). Variation in canopy temperature of plant species in contrast to prevailing air temperature has been documented as indicators of overall plant water status (Blum et al., 1982; Jackson et al., 1981) and used in evaluation of plant species for drought stress tolerance (Blum et al., 1989; Royo et al., 2002; Rashid et al., 1999). Canopy temperature measurement is also used as physiological tool for screening large populations of wheat against heat stress. (Amani et al., 1996; Reynolds et al., 1998). Fischer et al. (1998) observed strong association of cool crop canopy temperature maintenance under stressful environment with grain yield increase in wheat genotypes.

The study was conducted to evaluate temperature and drought stress adaptability potential of wheat genotypes in rainfed environment using canopy temperature measurement as physiological indicator. The research work is a step towards generation of useful information for crop improvement under

abiotic stresses.

Materials and Methods

A field trial was carried out in 2013-14 growing season, at the experimental area of Crop Sciences Institute, National Agricultural Research Centre (NARC), Islamabad, Pakistan situated at coordinates of latitude 33° 42' N and longitude 73° 10' E. The trial involved adaptability evaluation of forty (40) spring bread wheat genotypes Viz (1 to 40 correspondingly); 109384, 99172, 99346, 99114, DN-93, CT09137, SRN09111, V-09082, V-09087, V-10104, V-10110, V-11160, SKD-11, NN-GANDUM 1, NN-GANDUM 2, TW96010, TW96018, SD-998, NIA-MN-08, CIM-04-10, ESW-9525, PR-103, PR-106, PR-107, RCA-1, V-11005, NR-413, NR-421, NR-409, NR-419, UAF-9452, GUARD-C, SAWSN-02-102, PAKISTAN-13, TD-1, PIRSABAK-13, SEHAR-06, GALAXY-13, AAS-11 and NARC-11. Plantation was done on November 15, 2013 (normal) and December 15, 2013 (late). The late sowing was used to expose the crop to more extreme weather conditions. Experimental site comprised clay type soil with low organic matter (0.8%) and low amounts of N and P. The pH was 7.7 without any salinity problems.

Land preparation was done by using disc plow (primary tillage) and planking (secondary tillage). The crop was planted with self-propelled wheat planter at seed rate of 120 kg ha⁻¹. Sowing for each genotype was done in 6-row plots, 5 m long, with a 25 cm row spacing. Nitrogen and phosphate fertilizers were applied in ratio of 120: 85 respectively, in form of Urea and DAP. Full dose of nitrogenous and phosphate fertilizers were applied at planting, which is regular practice under rainfed conditions. Daily mean, minimum and maximum temperatures at the experimental site were recorded along with relative humidity (RH) (Table 1).

A hand-held Infrared Thermometer (Model AG- 42, Telatemp Crop, Fullerton, CA.) was used to measure canopy temperature. Canopy temperature (°C) reading were recorded at boot (Feekes 10), Kernel watery ripe (Feekes 10.5.4) and mealy ripe (Feekes 11.2) growth stages of the crop. Measurements were taken by holding the Infrared Thermometer at an appropriate angle (30° from the horizontal and approximately 50 cm above the canopy) and 1 m distance from the

edge of the plot to avoid the effect of soil temperature. One measurement per plot was taken between 11:00 and 14:00 hours under calm air conditions (Reynold et al., 1998). Spike sterility (%) in the field was observed visually as gaping glume, transparent florets and calculated as average percentage of randomly selected 15 spikes per plot (not clear). Grain yield was measured after harvesting, threshing and weighing of grains of 2 m² sample area which was converted into kg ha⁻¹. The data were tested for analysis of variance using Statistix v. 7.0 package. Treatment means were compared using Tukey's HSD test at P ≤ 0.05. Correlations among grain yield, spike sterility and canopy temperature (°C) were determined using MS Excel 2007.

Table 1: Mean monthly minimum and maximum temperature, relative humidity and solar radiation at the experimental site growing season 2013-14.

Month	Mean temperature (°C)			RH (%)	Radiations (MJm ⁻² d ⁻¹)
	Daily	Max.	Min.		
November	18.1	26.2	9.9	56	14.35
December	11.7	20.3	3.4	57	9.72
January	9.8	16.8	2.8	65	10.08
February	12.4	17.9	6.8	68	8.73
March	19.2	26.5	11.9	57	17.30
April	22.6	29.6	15.5	42	18.99

Results and Discussion

Interactive study of sowing dates and genotypes showed significant variation (p<0.05) in terms of canopy temperature, spike sterility and grain yield. A negative correlation was observed between crop canopy temperature and grain yield under both normal (r² = -0.943) and late (r² = -0.957) growing conditions. At the same time, significant variation was noticed within the entries tested. Under normal growing conditions, the group of entries that maintained mean canopy temperature (CT) less than 23 °C during grain filling period produced grain yield more than 4500 kg ha⁻¹, on other hand, the entries that showed mean canopy temperature higher than 25 °C produced grain yield less than 4000 kg ha⁻¹ (Figure 1). In case of late planting, which exposed crop to more adverse growing conditions at grain filling period as compared to normal sowing, the group of entries which maintained canopy temperature below 24.5 °C during grain filling period produced more than 3000 kg ha⁻¹ while entries with mean canopy temperature

higher than 24.5 °C produced grain yield less than 3000 Kg ha⁻¹ (Figure 2).

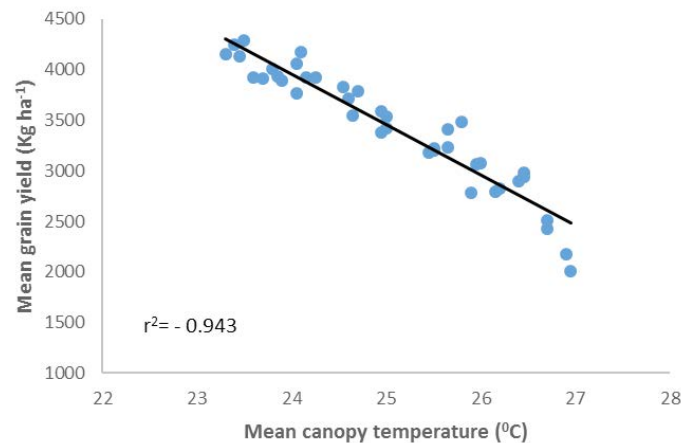


Figure 1: Correlation between mean canopy temperature and grain yield of wheat genotypes under normal sowing conditions.

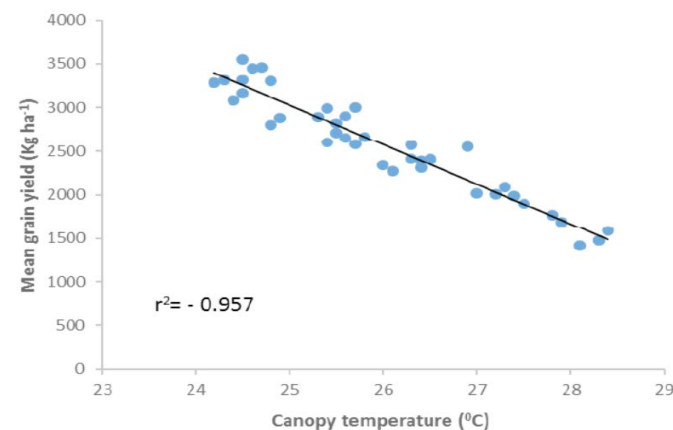


Figure 2: Correlation between mean canopy temperature and grain yield of wheat genotypes under late sowing conditions.

A positive correlation was also observed between canopy temperature and spike sterility under both normal ($r^2 = 0.920$) and late sowing ($r^2 = 0.937$). Under normal growing conditions, the entries which maintained mean canopy temperature less than 24 °C during grain filling period showed sterility percentage less than 10 %. The genotypes that showed mean canopy temperature higher than 24 °C showed more than 10% spike sterility (Figure 3). Spike sterility percentage increased in the late plantation. However, variation was observed among the tested genotypes. The group of genotypes which maintained mean canopy temperature less than 25 °C showed spike sterility percentage less than 15%. While, entries with canopy temperature higher than 25 °C showed more than 15% spike sterility (Figure 4).

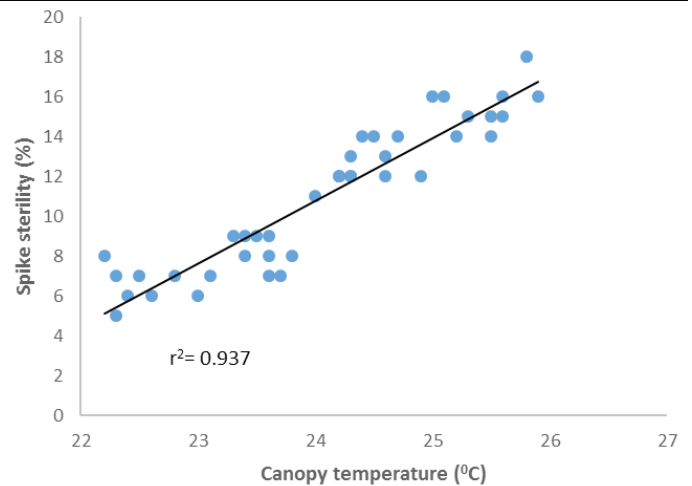


Figure 3: Correlation between mean canopy temperature and spike sterility (%) of wheat genotypes under normal sowing conditions.

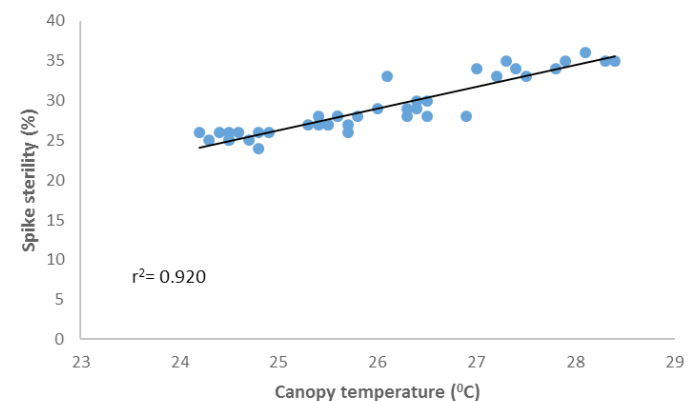


Figure 4: Correlation between mean canopy temperature and spike sterility (%) of wheat genotypes under late sowing conditions.

All genotypes showed lower grain yield and higher spike sterility percentage under late plantation. The higher spike sterility among late sowing genotypes was due to the exposure to more adverse weather conditions.

Results of this study clearly showed that the entries which managed to maintain low mean canopy temperature contributed to higher grain yield. Post-anthesis high temperature stress and drought seems responsible for higher floret sterility and grain mortality (Sikder and Paul, 2010). Abortion of kernels at high temperature may be due to reduced photosynthetic activity and decreased supply of carbohydrates which leads to increased spike sterility. Reduced growth period and increased spike sterility significantly lowered grain yield of wheat genotypes under late growing conditions than normal planting (Reference?).

However, significant variation among genotypes

in relation to spike sterility and grain yield under both normal and late plantation indicated that some genotypes were more adapted to rainfed conditions. Crop canopy temperature has been shown to be well correlated to spike sterility and grain yields of wheat genotypes. For instance, entries with lower mean canopy temperature showed less spike sterility and higher grain yields as compared to others, which may be their inherent character to tolerate temperature and drought stress especially under late planting conditions. Significant variation among genotypes was observed by many researchers under variable growing conditions (Jain et al., 1992; Okuyama et al., 2005; Kumar et al., 1994).

Maintenance of low canopy temperature by genotypes under stressful rainfed conditions may be linked to their ability to extract water through better root system (Lopes and Reynolds, 2010) and larger stomatal conductance (Reynolds et al., 2005). Low canopy temperature of random wheat lines was associated with higher grain yields in hot environments (Lopes and Reynolds, 2010; Sohail et al., 2013). Variation in canopy temperature maintenance among wheat genotypes might be due to their genetic differences which are also mentioned by Reynolds et al. (1994) that genotypic variations existed for canopy temperature among the wheat germplasms under climatic stress condition.

Cool canopy maintenance of wheat genotypes during grain filling duration is an important physiological indication for terminal heat stress tolerance (Munjal and Rena, 2003). These findings showed that increase in crop canopy temperature at grain filling period in susceptible genotypes reduced biomass accumulation and grain yield. Similar results were also reported by Munjal and Rena (2003) that cool canopy during grain filling time is a vital physiological principle for heat stress tolerance in wheat. Canopy temperature measurement has been used as effective selection criteria for evaluating screening wheat cultivars for heat tolerance and proved most potential screening (Reynolds et al., 2001).

So, wheat breeders can opt crop canopy temperature measurement as efficient selection criteria for heat tolerant wheat genotypes which will provide basis for developing climate resilient wheat varieties.

Conclusions and Recommendations

Wheat crop under late sowing condition was more exposed to high temperature stress during grain filling period which caused grain mortality and lead to reduced grain yield among all genotypes. However, genotypes showed variability under stressful rainfed conditions. Some genotypes i.e. Pakistan-2013, DN-93, SRN-09111, PR-103, NR-409, NR-421 showed higher grain yields under both normal and late growing conditions and proved to be more climate adapted than others. The study generated useful information to be utilized in wheat improvement programs with the aim of developing drought and heat tolerant wheat material. Moreover, this study revealed crop canopy temperature as a pretty useful physiological trait to estimate drought and temperature stress tolerance potential of wheat genotypes.

Acknowledgments

The authors acknowledge financial support from Wheat Production Enhancement Program (WPEP) CIMMYT office Pakistan, as part of the U.S. Government's assistance to Pakistan.

Author's contribution

Muhammad Sohail, Principal investigator, conceived the idea, Executed the trial and written manuscript. Imtiaz Hussain, Supervised the research work and given technical input and reviewed the manuscript before submission. Maqsood Qamar, Assisted in methodology and review of literature. Sikander Khan Tanveer, Crop management and data compilation. Syed Haider Abbas, Crop management and data collection. Zeshan Ali, Statistical analysis of the data. Muhammad Imtiaz, Acquisition of the financial support for the project leading to this publication.

References

- Amani, I., R.A. Fischer and M.P. Reynolds. 1996. Canopy temperature depression association with yield of irrigated spring wheat cultivars in hot climate. *J. Agron. Crop Sci.* 176: 119–129. <https://doi.org/10.1111/j.1439-037X.1996.tb00454.x>
- Al-Khatib, K. and G.M. Paulsen. 1984. Mode of high temperature injury to wheat during grain development. *Physiol. Plan.* 61:363–368.

- <https://doi.org/10.1111/j.1399-3054.1984.tb06341.x>
- Blum, A., J. Mayer and G. Gozlan. 1982. Infrared thermal sensing of plant canopies as a screening technique for dehydration avoidance in wheat. *Field Crops Res.* 5: 137-146. [https://doi.org/10.1016/0378-4290\(82\)90014-4](https://doi.org/10.1016/0378-4290(82)90014-4)
- Blum, A., L. Shipiler, G. Golan and J. Mayer. 1989. Yield stability and canopy temperature of wheat genotypes under drought stress. *Field Crops Res.* 22: 289-296. [https://doi.org/10.1016/0378-4290\(89\)90028-2](https://doi.org/10.1016/0378-4290(89)90028-2)
- Calderini, D.F., L.G. Abedelo, R. Savin and G.A. Slafer. 1999. Final grain weight in wheat as affected by short period of high temperatures during pre and post-anthesis under field conditions. *Aust. J. Plant Physiol.* 26: 452-458. <https://doi.org/10.1071/PP99015>
- Colaizzi, P.D., S.A. Shaughnessy, S.R. Evett and T.A. Howell. 2012. Using plant canopy temperature to improve irrigated crop management. *Proc. 24th Annu. Cent. Plains Irrig. Conf.*, Colby, KS.
- Edmonds, J.A. and N.J. Rosenberg. 2005. Climate change impacts for the conterminous USA: An integrated assessment summary *Clim. Change.* 69: 151-162. <https://doi.org/10.1007/s10584-005-3613-8>
- Evans, L.T., F.T. Wardlaw and R.A. Fischer. 1975. Wheat in: Evans LT. (ed.) *Crop Physiology: Some Case Histories*. Cambridge University Press. Cambridge.
- Fischer, R.A., D. Rees, K.D. Sayre, Z.M. Lu, A.G. Condon and A. Larque Saavedra. 1998. Wheat yield progress associated with higher stomatal conductance and photosynthetic rate, and cooler canopies. *Crop Sci.* 38: 1467-1475. <https://doi.org/10.2135/cropsci1998.0011183X003800060011x>
- Gutiérrez-Rodríguez, M., M.P. Reynolds, J.A. Escalante-Estrada and M.T. Rodríguez-González. 2004. Association between canopy reflectance indices with yield and physiological traits in bread wheat under drought and well-irrigated conditions. *Aust. J. Agric. Res.* 55: 1139-1147. <https://doi.org/10.1071/AR04214>
- IPCC. 2001. Climate change 2001: Impacts, adaptation and vulnerability IPCC working group 2.
- IPCC. 2007b. Climate change impacts, adaptation and vulnerability-working group II contribution to the intergovernmental panel on climate change: Summary for policymakers. IPCC Secretariat, Geneva, Switzerland.
- Jain, M.P., J.P. Dixit, P.V.A. Pillai and R.A. Khan. 1992. Effect of sowing date on wheat varieties under late sown irrigated condition. *Indian J. Agric. Res.* 62: 669-671.
- Jackson R.D., S.B. Idso, R.J. Reginato and P.J. Pinter. 1981. Canopy temperature as a crop water stress index. *Water Resour. Res.* 17: 1133-1138. <https://doi.org/10.1029/WR017i004p01133>
- Janjua, P.Z., G. Samad, N.U. Khan. 2010. Impact of climate change on wheat production: A case study of Pakistan, *Pak. Dev. Rev.* 49(4): 799-822. <https://doi.org/10.30541/v49i4IIpp.799-822>
- Jenner, C.F. 1994. Starch synthesis in the kernel of wheat under high temperature conditions. *Aust. J. Plant Physiol.* 21(6): 791- 806. <https://doi.org/10.1071/PP9940791>
- Karl, T., J. Melillo, T. Peterson and S. Hassol. 2009. *Global climate change impacts in the United States*. Cambridge Univ. Press, New York.
- Khan, M.I, M. Tila, F. Subhan, M. Amin and S.T. Shah. 2007. Agronomic evaluation of different bread wheat (*Triticum aestivum* L.) genotypes for terminal heat stress. *Pak. J. Bot.* 39(7): 2415-2425.
- Kumar, R., S. Madam and M. Yunus. 1994. Effect of planting date on yield and quality in durum varieties of wheat. *Haryana Agric. Univ. J. Res.* 24:186-188.
- Kurukulasuriya, P. and S. Rosenthal. 2003. Climate change and agriculture: A review of impacts and adaptations, June 2003. *Environ. Dep. World Bank*, Washington, DC, USA.
- Lopes, M.S. and M.P. Reynolds. 2010. Partitioning of assimilates to deeper roots is associated with cooler canopies and increased yield under drought in wheat. *Funct. Plant Biol.* 37(2): 147-156. <https://doi.org/10.1071/FP09121>
- Mahan, J.R. and K.M. Yeater. 2008. Agricultural applications of a low-cost infrared thermometer. *Comput. Electron. Agric.* 64: 262-267. <https://doi.org/10.1016/j.compag.2008.05.017>
- Mahboob, A.S., A. Arain, S. Khanzada, H. Mazhar, M. Naqvi, D. Umar and N.A. Nizamani. 2005. Yield and quality parameters of wheat genotypes as affected by sowing dates and high temperature stress. *Pak. J. Bot.* 37(3): 575-584.
- Maskrey, A., G. Buescher, P. Peduzzi and C. Schaerpf. 2007. Disaster risk reduction: 2007 Global review. Consultation edition. Prepared

- Glob. Platform Disaster Risk Reduction First Session, Geneva, Switzerland, pp. 5–7.
- Munjal, R. and R.K. Rana. 2003. Evaluation of physiological traits in wheat (*Triticum aestivum* L.) for terminal high temperature tolerance. Proc. Tenth Int. Wheat Genet. Symp. Poestum, Italy, Class. Mol. Breed. 2(3): 804–805.
- Nageswara, R.C., H.S. Talwar and G.C. Wright. 2001. Rapid assessment of specific leaf area and leaf nitrogen in Peanut (*Arachis hypogaea* L.) using a chlorophyll meter. J. Agron. Crop Sci. 186(3): 175–182. <https://doi.org/10.1046/j.1439-037X.2001.00472.x>
- Okuyama, L.A., F.L. Carlos and B.N.J. Fernandes. 2005. Grain yield stability of wheat genotypes under irrigated and non-irrigated conditions. Braz. Arch. Biol. Technol. 48(5): 697–704. <https://doi.org/10.1590/S1516-89132005000600004>
- Portmann, F.T., S. Siebert and P. Döll. 2010. MIRCA2000–Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling. Glob. Biogeochem. Cycles (Journal abbreviation) 24(1): GB1011. <https://doi.org/10.1029/2008GB003435>
- Rashid, A., J.C. Stark, A. Tanveer and T. Mustafa. 1999. Use of canopy temperature measurements as a screening tool for drought tolerance in spring wheat. J. Agron. Crop. Sci. 182: 231–237. <https://doi.org/10.1046/j.1439-037x.1999.00335.x>
- Reynolds, M.P., M. Balota, M.I.B. Delgado, I. Amani and R.A. Fischer. 1994. Physiological and morphological traits associated with spring wheat yield under hot, irrigated conditions. Aust. J. Plant Physiol. 21: 717–730. <https://doi.org/10.1071/PP9940717>
- Reynolds, M.P., J.I. Ortiz-Monasterio and A. McNab. 2001. Application of physiology in wheat breeding. CIMMYT, El Batan, Mexico.
- Reynolds, M.P., R.P. Singh, A. Ibrahim, O.A.A. Ageeb, A. Larque-Saavedra and J.S. Quick. 1998. Evaluating the physiological traits to complement empirical selection for wheat in warm environments. Euphytica. 100: 85–94. <https://doi.org/10.1023/A:1018355906553>
- Reynolds, M.P., A. Mujeeb-Kazi and M. Sawkins. 2005. Prospects for utilizing plant-adaptive mechanisms to improve wheat and other crops in drought and salinity-prone environments. Ann. Appl. Biol. 146: 239–259. <https://doi.org/10.1111/j.1744-7348.2005.040058.x>
- Rawson, H.M., P.A. Gardner and M.J. Long. 1987. Sources of variation in specific leaf area in wheat grown at high temperature. Aust. J. Plant Physiol. 14(3): 287–298. <https://doi.org/10.1071/PP9870287>
- Rosenzweig, C. and M.L. Parry. 1994. Potential impact of climate-change on world food-supply Nature. 367: 133–138. <https://doi.org/10.1038/367133a0>
- Royo, C., D. Villegas, F.L. Garcia Del Moral, S. Elhani, N. Aparicio, Y. Rharrabti and J.L. Araus. 2002. Comparative performance of carbon isotope discrimination and canopy temperature depression as predictors of genotypes differences in durum wheat yield in Spain. Aust. J. Agric. Res. 53: 561–569. <https://doi.org/10.1071/AR01016>
- Shahzad, K., J. Bakht, S.W. Ali, M. Shafi and N. Jabeen. 2002. Yield and yield components of various wheat genotypes as affected by different sowing dates. Asian J. Plant Sci. 1(5): 522–525. <https://doi.org/10.3923/ajps.2002.522.525>
- Sikder, S. and N.K. Paul. 2010. Effects of post-anthesis heat stress on stem reserves mobilization, canopy temperature depression and floret sterility of wheat genotypes. Bangladesh J. Bot. 39(1): 51–55. <https://doi.org/10.3329/bjb.v39i1.5526>
- Schuster, W.S. and R.K. Monson. 1990. An examination of the advantages of C₃–C₄ intermediate photosynthesis in warm environments. Plant Cell Environ. 13: 903–912. <https://doi.org/10.1111/j.1365-3040.1990.tb01980.x>
- Sohail, M., I. Hussain, Riaz-ud-din, S.H. Abbas, M. Qamar and M. Noman. 2013. Effect of split N fertilizer application on physioagronomic traits of wheat (*Triticum aestivum* L.) under rainfed conditions. Pak. J. Agric. Res. 26(2): 71–78.
- Sohail, M., I. Hussain, Riaz-ud-din, S.K. Tanveer, M. Qamar and S.H. Abbas. 2014. Physio-agronomic traits evaluation of wheat genotypes for adaptability under rainfed conditions. Sarhad J. Agric. 30(2): 151–156.
- Sohail, M., I. Hussain, S.K. Tanveer, S.H. Abbas, M. Qamar, M.S. Ahmed and S. Waqar. 2018. Effect of nitrogen fertilizer application methods on wheat yield and quality. Sci. Technol. Dev. 37(2): 89–92.

- Stern, N. 2006. What is the economics of climate change? *World Econ. -Henley On Thames* 7 (2): 1.
- Subhan, F., A. Nazir, M. Anwar, H.S. Nazir, M. Siddiq, J. Rahman and S. Tahir. 2004. Response of newly developed wheat genotypes/advance lines to planting dates in the central agro-ecological zone of NWFP. *Asian J. Plant Sci.* 3(1): 87-90. <https://doi.org/10.3923/ajps.2004.87.90>
- Vadivambal, R. and D.S. Jayas. 2011. Applications of thermal imaging in agriculture and food industry-a review. *Food Bioprocess Technol.* 4: 186-199. <https://doi.org/10.1007/s11947-010-0333-5>
- Wardlaw, I.F. and C.W. Wrigley. 1994. Heat tolerance in temperate cereals: an overview. *Aust. J. Plant Physiol.* 21: 695-703. <https://doi.org/10.1071/PP9940695>
- World Bank. 2009. South Asia: Shared views on development and climate change. World Bank, S. Asia Reg. Sustainable Dev. Dep. 1818 H Street NW, Washington DC, 20433, U.S.A.