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EVALUATION OF ADVANCE WHEAT LINES FOR AGRONOMIC TRAITS IN RAINFED ENVIRONMENT

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ABSTRACT:- Wheat under rainfed conditions of Pothwar region of Pakistan is usually exposed to limited soil moisture during early growth period and high temperature stress during reproductive growth stage. Better yield under stressful environment is the main objective while evaluating genotypes for rainfed ecologies. A field study was conducted at National Agricultural Research Centre (NARC), Islamabad, Pakistan to evaluate the agronomic traits of three advance lines (NR-397, NR-379 and NR-400) in comparison to released variety (NARC-09) under rainfed conditions during crop season 2010-2011. Crop was sown on normal (November 15) and late (December 15) planting times to create variable growing conditions especially during reproductive growth period. The adverse effect of the late planting was significant ($P<0.05$) on grain yield of the crop. Late planting produced 29% lower grain yield than normal planting. Genotypes also showed significant variation ($P<0.05$) regarding grain yield production under both normal and late sowing dates. Under more stressful growing conditions (late planting), minimum grain yield reduction was noticed in line NR-397 (19%) followed by NARC-09 (20%), NR-400 (30%) and NR-379 (35%). Late planting conditions also significantly reduced days to maturity, spikes m^{-2} and 1000-grain weight in all genotypes as compared to normal sowing; however, the reduction in these parameters were significantly less ($P<0.05$) in wheat lines NR-397 and NARC-09 as compared to other two genotypes. Results showed that comparatively higher grain yields of lines NR-397 and NARC-09 were correlated to their better leaf chlorophyll retention and maintenance of low canopy temperature during grain filling periods particularly under late planting conditions. Findings of this study have indications that wheat sowing up to November 15 is more appropriate time and advance lines NR-397 and NARC-09 have the genetic potential to tolerate adverse rainfed growing conditions under agro-ecological conditions of Pothwar region, Pakistan.

Key Words: Wheat; Triticum aestivum; Planting Dates; Genotypes Evaluation; Rainfed Conditions; Agronomic Characteristics; Pakistan.

INTRODUCTION

About 70% of the world's wheat is cultivated under rainfed condition (Portmann et al., 2010). Wheat crop under rainfed conditions often suffers from heat and drought which usually occurs simultaneously (Shah and

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Paulsen, 2003) and cause significant reduction in yield (Sohail et al., 2013). The yield loss may reach up to 70% (Trethowan and Pfeiffer, 1999; Bruce et al., 2002) in different parts of the world. In Pakistan, wheat under rainfed conditions is cultivated on more than 20% of the total wheat area mainly concentrated in Pothwar plateau where average farmer yield is about 1.5 t ha^{-1} which is 50% less than national average wheat yield.

Optimum temperature range for better wheat growth falls between 15° and 25°C. Low wheat yield under tropical rainfed conditions is generally associated with low soil moisture at planting and high temperature stress at reproductive growth stages of the crop (Khan et al., 2007; Martell, 2011). High temperature stress accompanied with limited soil moisture considerably decreases wheat productivity. Yield potential of wheat genotypes has been associated with different physiological and agronomic traits. High temperature injury at reproductive growth stages may cause grain mortality (Calderini et al., 1999; Wardlaw, 2002). Heat stress adversely affects photosynthetic activities through markedly reducing the leaf chlorophyll (Paulsen, 1994). Abortion and shrinking of kernels, might be due to decreased supply of carbohydrates to the grain (Saini and Westgate, 2000). High temperature stress results in forced maturity and reduction in growth duration (Al-Khatib and Paulsen, 1984) which cause low grain weight due to a short grain-filling period (Wardlaw and Wregley, 1994)

However, differences among wheat genotypes exist to tolerate abiotic stresses to variable extent through different physiological adaptability traits which may be used as screening criteria. For instance, premature leaf chlorosis is related with heat stress (Al-Khatib and Paulsen, 1984). Sohail et al. (2013) found a positive correlation between leaf chlorophyll content and grain yield of wheat genotypes during grain filling period under rainfed environment. Stressful environment significantly reduces grain yield (Guendouz et al., 2012), crop canopy temperature has been shown to be associated with heat tolerance (Reynolds et al., 1994).

The objective of present study was to evaluate advance wheat lines for adaptability in rainfed environment under late and normal growing conditions by using infrared thermometer (canopy temperature measurements) and leaf chlorophyll (SPAD value).

MATERIALS AND METHOD

A field trial, comprising two planting dates and four wheat genotypes, was carried out at National Agricultural Research Centre (NARC), Islamabad during 2010-11. Three advance wheat lines (NR-379, 397 and 400) and one existing wheat cultivar (NARC-09) developed by Wheat Programme, NARC, Islamabad, Pakistan, were included in the study. The experiment was laid out in a randomized complete block design (RCBD) with three replications in split plot arrangement where two planting dates were placed in main plots and four cultivars were assigned to the subplots. Experimental site comprised clay type Alfisols 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 through using disc plow

Table 1. Mean squares for yield contributing parameters of wheat genotypes

Source of variation	Days taken to maturity (No.)	Spikes m^{-2} (No.)	1000 Grain weight (g)	Spike sterility (%)	Grain yield (kg ha^{-1})
Replication	0.87	65	3.87	5.29	42778
Sowing date	5581.50**	252971**	198.37**	1504.17**	6917634**
Cultivars	13.50**	1229*	37.37**	52.50**	364234**
Sowing date x Cultivar	29.50**	141*	1.37*	17.17**	6234*
Error	4.02	164	1.87	3.58	15207

* = $P < 0.05$ ** = $P < 0.01$

(primary tillage) followed by two cultivators and planking (secondary tillage). The crop was sown on November 15, 2010 (normal planting) and December 15, 2010 (late planting) with self propelled wheat planter at seed rate of 120 kg ha^{-1}. Each subplot consisted of six 5 m long rows at 25 cm spacing. Recommended doses of N and P fertilizers @120:85 kg ha^{-1} were applied as single basal N at planting in form of urea and DAP which is regular practice under rainfed conditions. The weather data during the growing season was recorded at weather station located at the experimental site (Figure 1).

Days to physiological maturity were measured when 50% of the spikes showed complete absence of green color. Spike sterility (%) in the field was observed visually as gaping glumes and transparent florets and calculated as average percentage of randomly selected 15 spikes per plot. Grain yield was measured after harvesting, threshing and weighing of grains of 2 m^2 sample area which is then converted into kg ha^{-1}. Samples for 1000 grain weight were taken from the grain yield of each plot. Prior to harvest, the exact number of spike-bearing culms m^{-2} were counted from the sample area. A hand-held Infrared Thermometer (Model AG- 42, Telatemp Crop, Fullerton, CA.) was used to measure canopy temperature. One measurement per plot was taken between 1100 and 1400 hours under calm air conditions (Reynolds et al., 1998). SPAD values of 15 flag leaves per plot were measured for successive three weeks after anthesis by using chlorophyll meter (model SPAD 502). Measurements of leaf chlorophyll and canopy temperature were taken for three successive weeks after anthesis on March16, 23 and

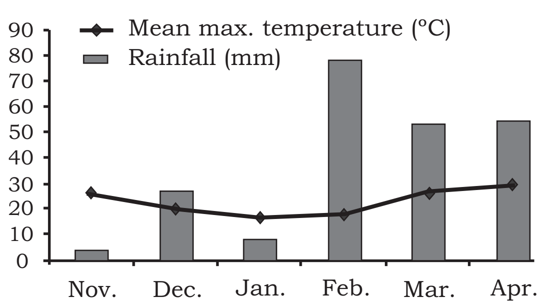

Figure 1. Mean monthly maximum temperature and rainfall at the experimental site during growing season 2010-11

30. For analysis of variance, the data were analyzed by using Statistix v. 7.0 packages, and the treatment means were further separated and compared using Tukey HSD test at $P \leq 0.05$.

RESULTS AND DISCUSSION

Days to Maturity

All the genotypes under study took more mean days to physiological maturity (164 days) under normal growing conditions as compared to late sowing (134 days). Mean values for days to maturity were significantly (P<0.05) different among genotypes. Genotypes NR-397 and NARC-09 took significantly (P<0.05) more mean days to reach physiological maturity (152 and 153 days, respectively) as compared to NR-379 and NR-400 (147 days each) (Table 2). Reduced life span of the genotypes under late planting conditions indicated forced maturity driven by high temperatures at later growth stages. Under normal growing conditions, the grain filling period of genotypes lasts from 45 to 58 days, more than under late planting (30-38 days). However, variation among cultivars exists to prolong its grain filling duration under high temperatures of late planting, as NR-397 and NARC-09 took 5-7 more days to reach physiological maturity as compared to rest of cultivars which may have inherent character to tolerate high temperature stress at grain filling period. Hossain et al. (2011) also observed significant reduction in days to physiological maturity from early to late sowing and also noticed that wheat variety Shatabdi took more days to reach physiological maturity in all sowing conditions as compared to rest of the tested genotypes. Inherent differences among wheat genotypes were also reported by Shahzad et al. (2002) regarding days to physiological maturity under variable growing conditions. Late sown crop was more exposed to high temperature which shortened the duration of development phases (Spink et al., 2000) however; genotypic variation exists to tolerate adverse growing conditions (Khan et al., 2007). Favorable climatic conditions at tiller formation stage significantly increased numbers of spikes m^2; however significant genotypic variation was also noticed among cultivars (Spink et al., 2000). The most plausible reason for genetic variation among cultivars might be their different response to variable growing conditions to which the crop was exposed (Hakim et al., 2012). Hossain et al. (2011) observed adverse effect of low temperature at tiller formation which ultimately reduced number of spikes per unit area.

Spike Sterility

The spike sterility percentage was significantly (P<0.05) influenced by genotype and planting date. Mean sterility was higher in the late sown crop (30%) as compared to normal sowing (14%). Among genotypes, NARC-09 showed less mean sterility (19%) followed by NR-397 (21%), NR-379 (24%) and NR-400 (26%) (Table 2). Post-anthesis high temperature stress seems the most plausible reason for higher floret sterility (Rawson, et al., 1987) and grain mortality (Sikder and Paul, 2010) under late planting conditions. Abortion of kernels at high temperature may be due to reduced photosynthetic activity and decreased supply of carbo-

Table 2. Effect of normal and late growing conditions on different yield contributing parameters of wheat genotypes

Treatments		Days taken to maturity (No.)	Spikes m^{-2} (No.)	1000-grain weight (g)	Spike sterility (%)	Grain yield (kg ha^{-1})
Sowing dates						
Normal		164^{a}	409^{a}	39^{a}	14^{a}	3714^{a}
Late		133^{b}	203^{b}	33^{b}	30^{b}	2640^{b}
Genotypes						
NR-400		147^{b}	303^{ab}	38^{a}	26^{a}	3025^{b}
NR-397		152^{a}	316^{a}	39^{a}	21^{b}	3395^{a}
NR-379		147^{b}	287^{b}	35^{b}	24^{a}	2910^{b}
NARC -09		153^{a}	319^{a}	34^{b}	19^{b}	3377^{a}
Sowing date x Genotype						
Normal	NR-400	162^{a}	407^{ab}	37^{b}	16^{c}	3550^{b}
	NR-397	165^{a}	417^{a}	42^{a}	14^{c}	3950^{a}
	NR-379	164^{a}	385^{b}	36^{b}	15^{c}	3480^{b}
	NARC-09	165^{a}	428^{a}	41^{a}	13^{c}	3875^{a}
Late	NR-400	131^{d}	200^{cd}	32^{c}	35^{a}	2500^{d}
	NR-397	137^{c}	215^{c}	35^{b}	28^{b}	2840^{c}
	NR-379	130^{d}	190^{d}	31^{c}	33^{a}	2340^{d}
	NARC-09	136^{c}	210^{cd}	35^{b}	25^{b}	2880^{c}

Means followed by same letter(s) do not differ significantly at 5 % level of probability.

hydrates which leads to increased spike sterility. Floret sterility variation among cultivars was also found by Rawson et al. (1987) in wheat.

Spikes m^{-2}

Significant ($P<0.05$) adverse effect of late sowing was observed on spikes m^{-2} for all the genotypes under late planting conditions as compared to normal planting. Overall, about 25% reduction in spike m^{-2} was noticed in late planted crop as compared to normal. Mean values of spikes m^{-2} were also varied among genotype. Again the genotypes NR-397 and NARC-09 produced maximum productive tillers under both normal and late sowing conditions (Table 2). Khan et al. (2007) and Shahzad et al. (2002) also reported variations about reduced fertile tillers in late planted wheat cultivars. High temperature stress induces forced maturity and reduces numbers of days to maturity. Nahar et al. (2010) reported up to 15% reduction in maturity period of wheat genotypes due to the effect of heat stress under late planted conditions.

1000-Grain Weight

Significant ($P<0.05$) reduction was observed for 1000-grain weight in all the genotypes when sowing was delayed from mid November to mid December; however the extent of reduction was different among genotypes. Genotype NR-397 and NARC-09 produced significantly ($P<0.05$) higher grain weight under both normal and late planting conditions as compared to rest of the genotypes (Table 2). Variability among some genotypes exists for production of higher grain weight as compared to other genotypes under stressed environment. Some genotypes have the ability to produce higher seed weight as compared to others under high temperature stress of late sowing (Mahboob et al., 2005; Khan et al., 2007). Reduction in grain weight of some genotypes under stress condition may be attributed to grain mortality due to high temperature injury at reproductive growth stages (Al-Khatib and Paulsen, 1984; Calderini et al., 1999; Wardlaw, 2002). In late sowing, comparatively high temperature shortens the grain filling duration, which ultimately reduces grain weight. Delayed sown crop tolerated high temperature stress at reproductive growth stages which induced forced maturity and shortened the duration of grain filling with reduction in kernel growth (Hossain et al., 2011) leading to losses in kernel density and weight by up to 7% in spring wheat (Guilioni et al., 2003). Wahid et al. (2007) reported adverse effect of radiation and high temperatures on wheat yield and yield components. Heat stress caused decline in photosynthesis and leaf area, grain mass as well as weight and sugar content of kernels (Shah and Paulsen, 2003). Post-anthesis high temperature stress adversely affects formation and supply of photosynthates to the developing kernels and resulting in reduced kernels weight (Mohammadi et al., 2004).

Grain Yield

Normal planting time produced significantly ($P<0.05$) higher grain yield (3714 kg ha^{-1}) as compared to late planted crop (2640 kg ha^{-1}) (Table 2). Mean values for grain yields of both sowing dates were also observed significantly ($P<0.05$) different among genotype. The mean grain yields of NR-397 (3395 kg ha^{-1}) and NARC-09 (3370 kg ha^{-1}) were consistently higher ($P<0.05$) as compared to NR-400 (3050 kg ha^{-1}) and NR-379 (2910 kg ha^{-1}). Under late planting conditions, the genotype NARC-09 produced maximum yield (2840 kg ha^{-1}) followed by NR-397 (2840 kg ha^{-1}), NR-400 (2500 kg ha^{-1}) and NR-379 (2340 kg ha^{-1}). According to present results, significantly ($P<0.05$) higher grain yields of NR-397 and NARC-2009 under variable rainfed growing conditions may be attributed to the maintenance of their low canopy temperature, higher flag leaf chlorophyll retention, lower spike sterility and better grain weight especially in more stressful late sowing conditions at reproductive growth stages (Sohail et al., 2013). Reduction in grain yield of genotype and significant variation among them was also observed by many other researchers (Jain et al., 1992; Kumar et al., 1994; Arain, 1999; Okuyama et al., 2005) under late planting as compared to normal planting (Mahboob et al., 2005; Khan et al., 2007).

Results showed negative correlation (-0.936) between canopy temperature and average grain yield. Genotypes with low average canopy temperatures at grain filling stages produced higher grain yields (Figure 2). Canopy temperature has been shown to be well correlated to grain yields of wheat genotypes under heat and drought stressed environments (Reynolds et al., 1994). Low canopy temperatures of random wheat lines were associated with higher grain yields in hot environments (Lopes and Reynolds, 2010; Sohail et al., 2013). Maintenance of low canopy temperatures of better performing genotypes (NR-397 and NARC-09) under stressful rainfed conditions may be linked to their ability to extract water through better root system (Lopes and Reynolds, 2010) and with larger stomata conductance (Reynolds et al., 2005). At the same time, a positive correlation (0.856) was observed between mean flag leaf chlorophyll and grain yields of genotypes. Genotypes with higher leaf chloro-phyll values produced maximum average grain yields (Figure 3). Significantly low leaf chlorophyll degradation in NR-397 and NARC-09 have the indication of more stable photo system which ultimately lead to better photosynthetic activity, more dry matter accumulation and ultimately higher grain yields as compared to other two tested genotypes. Sohail et al. (2013) reported high yield of wheat genotypes linked with better mean flag leaf chlorophyll maintenance in rainfed environment. A positive correction between grain yields and better leaf chlorophyll retention of wheat genotypes was also observed by Gutiérrez-Rodríguez et al. (2004) under stressed environment.

The late sown wheat crop, therefore, was more exposed to high temperature stress during grain filling period which caused grain mortality and lead to reduced grain yields of all genotypes, therefore the wheat planting up to November 15 is

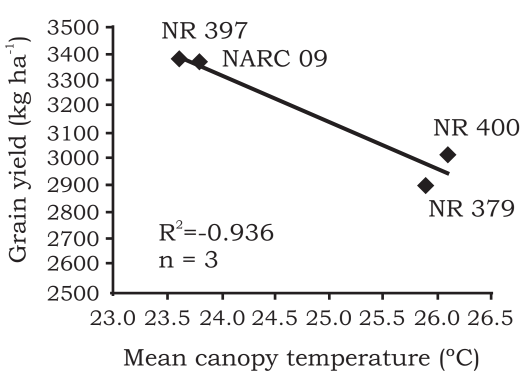

Figure 2. Correlation between mean canopy temperature and average grain yield of wheat genotypes

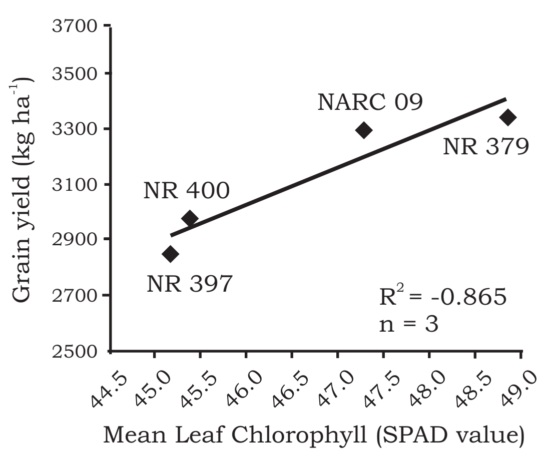

Figure 3. Correlation between mean leaf chlorophyll (SPAD value) and average grain yield of wheat genotypes

more appropriate as all genotypes produced significantly higher yields than late planting. However, the genotypes NR-397 and NARC-09 produced significantly higher grain yields under both environments. These two genotypes might have inherent tolerance against temperature stress under rainfed conditions and proved to be more adapted to rainfed environment.

LITERATURE CITED

Al-Khatib, K., and G.M. Paulsen. 1984. Mode of high temperature injury to wheat during grain development. Physiol. Plant, 61: 363-368.

Arain, M.A., M. Ahmad, and M.A., Rajput. 1999. Evaluation of wheat genotypes under varying environments induced through changing sowing dates. Proc. Symp. New Genetical Approaches to Crop Improvement-III. Nuclear Institute of Agriculture, Tando Jam, Pakistan. p.163-173.

Bruce, W.B., G.O. Edmeades, and T.C. Barker. 2002. Molecular and physiological approaches to maize improvement for drought tolerance. J. Exptl. Bot. 53:13-25.

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.

Guendouz, A., S. Guessoum, K. Maamari, and M. Hafsi. 2012. The effect of supplementary irrigation on grain yield, yield components and some morphological traits of durum wheat (*Triticum durum* desf.) cultivars. Adv. Environ. Biol. 6(2): 564-572.

Guilioni L., J. Wery, and J. Lecoeur. 2003. High temperature and water deficit may reduce seed number in field pea purely by decreasing plant growth rate. Functional Pl. Biol. 30: 1151-1164.

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.

Hakim, M.A., A. Hossain, A. Jaime, Teixeira da Silva, V. P. Zvolinsky, and M. M. Khan. 2012. Yield, protein and starch content of twenty wheat (*Triticum aestivum* L.) genotypes exposed to high temperature under late sowing conditions. J. Sci. Res. 4 (2): 477-489.

Hossain, A., M.A.Z. Saker, M.A. Hakim, M.V. Lozovskaya, and V.P. Zvolisky. 2011. Effect of temperature on yield and some agronomic characters of spring wheat. Int. J. Agric. Res. Innov. Tech. 1(1&2): 44-54.

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. Sci. 62: 669-671.

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. Pakistan 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.

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.

Mahboob, A. S., M.A. Arain, S.K. Mazhar, H. Naqvi, M.U. Dahot, and N.A. Nizamani. 2005. Yield and quality parameters of wheat genotypes as affected by sowing dates and high temperature stress. Pakistan J. Bot. 37 (3): 575-584.

Martell. 2011. Crop worries from weather stress in Russia, China and Australia: Stressful hot finish in Russian grain belt'. Available online at: http://www.martellcropprojections.com/CropProductionReports/CropWorries-From-Weather-Stress-in-Russia-China-and-Australia.

Mohammadi, V., M.R. Qannadha, A.A. Zali, and B. Yazidi-Samadi. 2004. Effect of post anthesis heat stress on head traits of wheat. Intern. J. Agric. Biol. 6: 42-44.

Nahar, K., K. Ahmad, and M. Fujita, 2010. Phenological variation and its relation with yield in several wheat (*Triticum aestivum* L.) cultivars under normal and late sowing mediated heat stress conditions. Not. Sci. Biol. 2 (3): 51-56.

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.

Paulsen, G.M. 1994. High temperature responses of crop plants. In: Boote, K.J., Bennett J.M., Sinclair, T.R., and Paulsen, G.M. (eds.). Physiology and determination of crop yield. American Society of Agronomy, Madison, WI. p. 365-389.

Portmann, F.T., S. Siebert, and P. Doll. 2010. Mirca-2000-global monthly irrigated and rainfed crop areas around the year 2000: A new high resolution data set for agricultural and hydrological modeling. Global Biogeochem. Cycles, 24: 1-24.

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.

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

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.

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.

Saini, H.S., and M.E. Westgate. 2000. Reproductive development in grain crops during drought. Adv. Agron. 68: 59-96.

Shah, N.H., and G.M. Paulsen. 2003. Interaction of drought and high temperature on photosynthesis and grain-filling of wheat. Plant Soil, 257: 219-226.

Shahzad, K., J. Bakht, S.W. Ali, M. Shafi, and N. Jabeen. 2002. Yield and yield components of various wheat cultivars as affected by different sowing dates. Asian J. Plant Sci. 1(5): 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 cultivars. Bangladesh J. Bot. 39(1): 51-55.

Sohail, M., I. Hussain, Riaz-ud-din, S.H. Abbas, M. Qamar, and M. Noman. 2013. Effect of split N fertilizer application on physio-agronomic traits of wheat (*Triticum aestivum* L.) under rainfed conditions. Pakistan J. Agric. Res. 26(2): 71-78.

Spink, J.H., T. Semere, D.L. Sparkes, J.M. Wahley, M.J. Foulkes, R.W. Calre, and R.K. Scatt. 2000. Effect of sowing dates and planting density of winter wheat. Ann. Appl. Biol. 137(2): 179-188.

Trethowan, R., and W.H. Pfeiffer. 1999. Challenges and future strategies in breeding wheat for adaptation to drought stressed environments: A CIMMYT wheat program perspective. In: Ribaut, J.M., and D. Poland (eds.) Molecular approaches for the genetic improvement of cereals for stable production in water limited environments. A strategic planning workshop held at CIMMYT, Mexico. June 21-25, 1999. CIMMYT, Mexico, p. 45-48.

Wahid, A., S. Gelani, M. Ashraf, and M.R. Foolad. 2007. Heat tolerance in plants: An overview. Environ. Exptl. Bot. 61: 199-233.

Wardlaw, I.F. 2002. Interaction between drought and chronic high temperature during kernel filling in wheat in a controlled environment. Ann. Bot. 90: 469-476.

Wardlaw, I.F., and C.W. Wrigley. 1994. Heat tolerance in temperate cereals: An overview. Aust. J. Plant Physiol. 21: 695-703.