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LATE PLANTING INDUCED HEAT STRESS TOLERANCE IN WHEAT

IQRA TAHIR[1], NAQIB ULLAH KHAN[1*], SAMRIN GUL[2], SHERAZ AHMED[1], YUSRA ANDLEEB[1], AMINA HABIB[3], SARDAR ALI[4], SHER ASLAM KHAN[4], NAUSHAD ALI[4] AND IZHAR HUSSAIN[4]

[1]*Department of Plant Breeding and Genetics, University of Agriculture, Peshawar, Pakistan*
[2]*Department of Plant Breeding and Genetics, University of Sargodha, Sargodha, Pakistan*
[3]*Department of Agricultural Chemistry, University of Agriculture, Peshawar, Pakistan*
[4]*Department of Plant Breeding and Genetics, University of Haripur, Haripur, Pakistan*
[*]*Corresponding author's email: nukmarwat@yahoo.com, nukmarwat@aup.edu.pk*

Abstract

Wheat crop with late planting is rapidly subjected to stress due to high temperature which severely affects crop growth, grain filling, and eventually grain yield. Present studies aim to recognize the heat stress tolerant wheat genotypes by using stress selection indices, principal components, and biplot analyses. Hence, 24 wheat genotypes (including six advanced lines and 18 commercial wheat cultivars) were evaluated through genotype by environment interactions. Wheat genotypes were grown in a randomized complete block design with a factorial arrangement under normal (non-stress) and late (stress) planting environments with three replications. Stress selection indices i.e., tolerance index (TOL), mean productivity (MP), stress tolerance index (STI), trait stability index (TSI), trait index (TI), and the principal component (PCA) and biplot analyses were used to assess the response of wheat genotypes. Significant ($p<0.01$) variations were observed between environments, while genotypes and genotype by environment interactions revealed significant ($p<0.01$) differences for the majority of the traits. Because of reduced heat stress emphasis and sufficient growth period, genotypes with optimum planting performed better compared to late planting. Under the late planting environment, cultivars Khaista-2017, Shahkar-2013 and Zincol-16 performed better for grain yield and its components. With non-stress and stress (Yn and Ys) conditions, the grain yield was found significantly and positively correlated with stress selection indices i.e., MP, STI, TSI, and TI whereas the yield relationship was negative with TOL. Genotypes Zincol-16, Pakistan-13, and Khaista-2017 were identified as stress-tolerant and high yielding under both environments indicating their potency to tackle late planting and heat stress. Traits with indirect positive effects could be used as selection criteria, and the promising genotypes could be used as a source population in the development of heat stress-tolerant wheat cultivars in the future breeding program.

Key words: Normal and late planting; G × E interaction; Stress selection indices; Principal component analysis; Biplot analysis; *Triticum aestivum* L.

Introduction

Wheat (*Triticum aestivum* L.) is a cereal grain that is widely cultivated for its seed and is worldwide known as a staple food. The wheat crop was evolved in Fertile Crescent and its domestication was started over 10,000 years ago, and later became one of the most important food crops of the entire globe (Sabit *et al.*, 2017). Being a staple food for over 36% of the world population, wheat fulfills the protein and caloric needs of one-third world's population (Khan & Mohammad, 2018). In Pakistan, during 2019-20 an area of 8.805 million hectares was occupied by wheat crop and the production was 25.248 million tons with an average grain yield of 2867 kg ha^{-1} (Pakistan Economic Survey, 2020-2021).

Wheat is an elegant source of nutrients and energy containing major constituents of the food i.e., vitamins particularly riboflavin, thiamin, niacin, and vitamin E. Wheat is enriched by protein and carbohydrates and vital minerals such as phosphorus, magnesium, copper, iron, and zinc (Bhanu *et al.*, 2018). It is a chief source of human diet and way of earning for millions of farmers so its vitality cannot be denied. Special attention and greater investment are needed in wheat production to come across the food demand of the ever-growing population. The enhanced wheat production can be achieved by genotypes with a wider genetic base, adaptation, and having improved performance across different agro-climatic conditions (Khan & Mohammad, 2018).

Late planting wheat crop abruptly exposes to high temperature stress at the flowering stage causing the reduction in yield and it is one of the major reasons for the yield gap. Global warming may further amplify the problem in the future. Therefore, efforts should be made to lessen the late sown yield reduction by screening and developing high temperature stress tolerant wheat genotypes and also by remodeling agronomic approaches to minimize the heat stress effects (Rahman *et al.*, 2018; Hossain *et al.*, 2019). With recent changes in agro-climatic conditions and the unpredictable rainfall pattern, there is a dire need for wheat genotypes to be tested with different sowing times with different planting densities for yield optimization (Kaur & Behl, 2010; Prasad *et al*., 2020). Therefore, wheat genotypes evaluation for optimum planting period and seed rate for irrigated and rainfed areas is also important for setting a proper cropping pattern in wheat-growing regions.

The genotype-by-environment relationship is an alteration in the response of wheat genotypes across test environments (Khazratkulova *et al.*, 2015; Bacha *et al.*, 2017). The role of environmental conditions and their interaction with wheat genotypes has a crucial influence on crop yield. Sufficient effects of GE interaction were noted in the past studies on quantity and quality related parameters of bread wheat (Montesinos-López *et al.*, 2018). The development of stable cultivars with improved yield and quality traits under different environments is the ultimate goal of wheat breeding (Mehari & Workineh, 2018).

Genotype-environment interaction, therefore, showed a vital role in determining the strength of genotypes across a wide range of environments (Tulu & Wondimu, 2019).

To enhance the effectiveness of selection for improvement in grain yield, selection indices are mostly used by the breeders (Raiyani *et al*., 2015). Smith (1936) first developed the theory of selection indices to improve the genetic values of traits in crop plants. The yield differences among non-stress (Yn) and stress (Ys) planting environments are termed as stress tolerance (TOL), while the mean yield of a crop under non-stress (Yn) and stress (Ys) conditions is denoted as mean productivity (Rosielle & Hamblin, 1981). The stress tolerance index (STI) is used to select high yielding genotypes under non-stress and stress conditions (Fernandez, 1992). In wheat breeding for critical stress conditions, the sensitivity drought index (SDI), and stress susceptibility index (SSI) were suggested, while for lower stress state the applicable indices were stress tolerance index (STI), mean productivity (MP), and geometric mean productivity (GMP) (Lepekhov & Khlebova, 2018). Several studies have advocated the use of principal component (PCA) and biplot analyses in multi-environment trials (METs) (Yan, 2001; Yan *et al.*, 2007). The PCA and biplot analyses are the graphical approaches to visualize the response of genotypes under varying environments (Yan & Holland, 2010). Therefore, in the elucidation of the above discussion, the present study was carried out to identify the wheat genotypes with tolerance to late planting induced heat stress by using stress selection indices, principal components, and biplot analyses through genotype-environment interaction effects under both planting environments.

Materials and Methods

Wheat germplasm and procedure: Wheat germplasm was evaluated under normal and late planting environments during crop season 2018-19 at the University of Agriculture, Peshawar, Pakistan (Table 1). For this research, 24 wheat genotypes (including six advanced lines and 18 commercial wheat cultivars) were assessed in a randomized complete block design with a factorial arrangement under normal (non-stress) and late (stress) planting environments with three replications. Each genotype was grown in a sub-plot comprised of six rows, with a five-meter length in each replication. The spacing between two adjacent rows was kept 25 cm. The optimum sowing was performed on November 05, 2018; whereas the delayed sowing was made after one month on December 05, 2018. Monthly metrological data regarding agro-climatic conditions are presented in Fig. 1.

Table 1. Wheat genotypes evaluated in the present study.

S. No.	Genotypes	Institution	S. No.	Genotypes	Institution
Advanced lines			12.	Shahkar-2013	CCRI, Pirsabak
1.	PR-123	CCRI, Pirsabak	13.	Pakistan-13	NARC, Islamabad
2.	PR-125	CCRI, Pirsabak	14.	Anaj-2017	AARI, Faisalabad
3.	PR-128	CCRI, Pirsabak	15.	Kohat-2000	BARS, Kohat
4.	PR-129	CCRI, Pirsabak	16.	NIFA Lalma-2013	NIFA, Peshawar
5.	HPYT-48	CCRI, Pirsabak	17.	Pirsabak-2013	CCRI, Pirsabak.
6.	HPYT-47	CCRI, Pirsabak	18.	Pirsabak-2008	CCRI, Pirsabak.
Existing cultivars			19.	Pirsabak-15	CCRI, Pirsabak.
7.	Janbaz	AUP, Peshawar	20.	Khaista-2017	CCRI, Pirsabak.
8.	Faislabad-2008	AARI, Faisalabad	21.	Atta Habib	AUP, Peshawar
9.	Zincol-16	NARC, Islamabad	22.	Ghanemat	AUP, Peshawar
10.	Waadan-2017	CCRI, Pirsabak	23.	Paseena-2017	CCRI, Pirsabak
11.	NIFA-Aman	NIFA, Peshawar	24.	NARC-2011	NARC, Islamabad

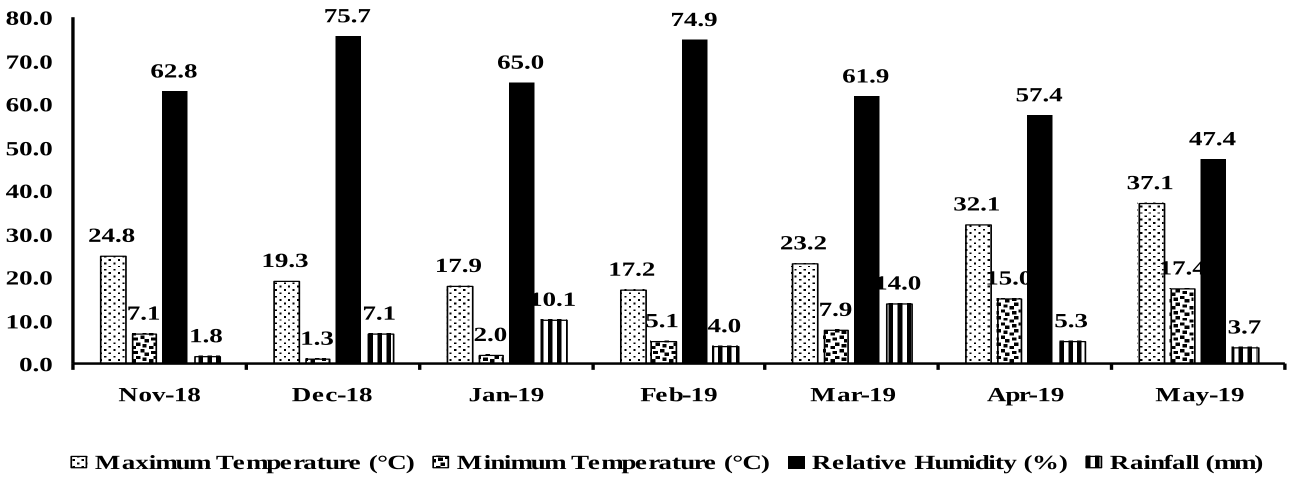

Fig. 1. Agro-climatic conditions i.e., temperature, relative humidity, and rainfall during 2018-19 at the University of Agriculture, Peshawar, Pakistan.

Crop husbandry: Before sowing, the field was well irrigated to create conditions conducive for seedbed preparation. The field was ploughed with deep plough then harrowed with planking each time to make the soil loose, fine, leveled, and pulverized. The fertilizers were used at the rate of 120:90:60 NPK kg ha^{-1}, respectively. The full dose of fertilizers i.e., P_2O_5, K_2O, while the half dose of N fertilizer was applied at sowing time while the remaining half N was applied in two split doses with first and second irrigation. Overall, four irrigations have been given to the crop until maturity. For sowing, three to four seeds per hill were used for all the genotypes to get the required plant population, and after germination thinning was performed. The dominant weeds were *Avena fatua, Chenopodium album, Chenopodium murale, Convolvulus arvensis, Cynodon dactylon, Phalaris minor,* and *Rumex dentatus*. All the weeds were controlled with broad and narrow leaf herbicides i.e., Buctril Super (*Bromoxynil* - 750 mL ha^{-1}) and Puma Super (*Fenoxaprop-P-ethyl* 69 g - 1250 mL ha^{-1}), respectively. However, the leftover weed plants were removed manually.

Data recorded: Ten randomly selected wheat plants were used for recording the data on various traits in each genotype and replication among both the planting environments. The spike length was deliberated by the ruler after the crop maturity. The spikelets in each spike were considered as the number of fertile spikelets in randomly selected spikes other than basal sterile ones. Biological and grain yield were calculated with electric balance after harvesting each sub-plot when the crop was fully matured. The harvest index (%) was measured as the ratio of grain yield to biological yield for each genotype.

Stress selection indices: The tolerance index (TOL), mean productivity (MP) (Rosielle & Hamblin, 1981; Lepekhov & Khlebova, 2018), stress tolerance index (STI), trait stability index (TSI), and trait index (TI) were used for assessing the response of wheat genotypes under non-stress (optimum) and stress (delayed) planting environments (Bouslama & Schapaugh, 1984; Hossain *et al*., 1990; Fernandez, 1992; Gavuzzi *et al*., 1997).

$$\text{Tolerance (TOL)} = Y_n - Y_S$$

$$\text{Mean Productivity (MP)} = \frac{Y_n + Y_s}{2}$$

$$\text{Stress Tolerance Index (STI)} = \frac{Y_n - Y_s}{(\bar{Y}_n)^2}$$

$$\text{Trait Index (TI)} = \frac{Y_s}{\bar{Y}_s}$$

$$\text{Trait Stability Index (TSI)} = \frac{Y_s}{\bar{Y}_n}$$

Where;
Y_n = Genotype means for that trait within optimum planting.
Y_s = Genotype means for that trait within late planting.
$\bar{Y}_n$ = Grand mean of a specific trait within optimum planting.
$\bar{Y}_s$ = Grand mean of a specific trait within late planting.

Biometrical analyses: All the data were analyzed according to the analysis of variance (ANOVA) using the proper paradigm for genotype-environment interaction (GEI) (Yang *et al*., 2006; Yang, 2007). After analysis, the means for each category and parameter were further evaluated by using $LSD_{0.05}$. The analysis of the correlation coefficient for yield and its attributes was carried out according to Kwon and Torrie (1964).

Principal component and biplot analyses: Data calculated for various stress selection indices were standardized before subjecting to principal component analysis to reduce the wide ranges in the data and get a credible relationship among variables. The correlation coefficient of grain yield under non-stress (Yn) and stress (Ys) conditions with various stress selection indices, principal component analysis, dendrogram tree, and biplot were constructed using STATISTICA ver. 10 and MINITAB ver. 16 (Mohammadi *et al*., 2012).

Results

A total of 24 wheat genotypes were evaluated through their response to non-stress (normal) and stress (delayed) planting environments and stress selection indices during 2018-19 at The University of Agriculture, Peshawar, Pakistan (Table 1). In a pooled analysis of variance, planting environments revealed significant ($p \leq 0.01$) differences for all the studied traits (Table 2). Genotypes also showed significant ($p \leq 0.01$) variations for traits i.e., spikelets per spike, grain yield, while significant ($p \leq 0.05$) for spike length under both planting environments. However, genotypes exhibited nonsignificant variation for biological yield and harvest index. Genotype by environment interaction (GEI) values were significant ($p \leq 0.01$) for all the traits under both planting environments. The trait-wise results are present as under:

Spike length: Regarding spike length, the genotypes ranged from 9.12 to 13.73 cm, while for genotype by environment interaction the means varied from 7.63 to 14.80 cm (Table 3). However, a decrease of 2.21 cm in the spike length was seen in the comparison of genotype averages over both the planting environments where optimum planting had more spike length (12.39 cm) than delayed planting (10.18 cm). On average, the utmost spike length was recorded in genotype PR-128 (13.73 cm), pursued by genotypes Zincol-16 (12.17 cm), PR-123 (11.82), and HPYT-47 (11.82). However, cultivar Pirsabak-2008 (9.12 cm) achieved minimum spike length and it was found at par with genotypes HPYT-48 (10.15 cm) and NARC-2011 (10.56 cm). In genotype by environment interaction, advanced line PR-128 was topmost ranked for spike length (14.80 cm), followed by cultivars Zincol-16 and Pakistan-13, and lines HPYT-47 and PR-123 ranged from 13.00 to 13.63 cm with non-stress planting environment. Cultivar Pirsabak-2008 produced the lowest spike length (7.63 cm) and it was found similar in performance with genotype HPYT-48 (8.23 cm) under a stress planting environment. Among both the planting environments, the cultivar PR-128 showed maximum spike length.

Table 2. Mean squares for various traits in bread wheat genotypes evaluated under optimum and late plantings.

Variables	Mean squares					CV %
	Environments	Replications	Genotypes	G × E Interactions	Error	
d.f.	1	4	23	23	92	-
Spike length	176.23**	0.61	3.88*	1.55**	0.215	4.02
Spikelets spike^{-1}	164.05**	0.99	8.33**	1.37**	0.37	2.97
Biological yield	1502415121**	162128	4993445.9^{NS}	2804148**	382492	6.08
Grain yield	70013661.67**	4569.05	1170367**	293172.69**	11115.4	3.07
Harvest Index	2491.67**	1.32	32.59^{NS}	17.73**	2.23	4.25

*,**: Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively, NS: Non-significant

Table 3. Mean performance and stress selection indices in bread wheat genotypes for spike length evaluated under optimum and late planting environments.

Genotypes	Spike length (cm)							
	Optimum	Late	Means	TOL	MP	STI	TSI	TI
Advanced lines								
PR-123	13.20	10.43	11.82	2.77	11.82	0.90	0.79	1.02
PR-125	12.27	9.70	10.98	2.57	10.99	0.78	0.79	0.95
PR-128	14.80	12.67	13.73	2.13	13.74	1.22	0.86	1.24
PR-129	12.40	10.83	11.62	1.57	11.62	0.87	0.87	1.06
HPYT-48	12.07	8.23	10.15	3.84	10.15	0.65	0.68	0.81
HPYT-47	13.33	10.30	11.82	3.03	11.82	0.89	0.77	1.01
Commercial cultivars								
Janbaz	11.47	10.47	10.97	1.00	10.97	0.78	0.91	1.03
Faislabad-2008	12.27	10.33	11.30	1.94	11.30	0.83	0.84	1.01
Zincol-16	13.63	10.70	12.17	2.93	12.17	0.95	0.78	1.05
Waadan-2017	12.60	9.30	10.95	3.30	10.95	0.76	0.74	0.91
NIFA-Aman	12.33	10.57	11.45	1.76	11.45	0.85	0.86	1.04
Shahkar-2013	12.33	10.93	11.63	1.40	11.63	0.88	0.89	1.07
Pakistan-13	13.00	8.77	10.88	4.23	10.89	0.74	0.67	0.86
Anaaj-2017	12.20	10.33	11.27	1.87	11.27	0.82	0.85	1.01
Kohat-2000	12.87	10.07	11.47	2.80	11.47	0.84	0.78	0.99
NIFA Lalma-2013	12.13	10.57	11.35	1.56	11.35	0.84	0.87	1.04
Pirsabak-2013	11.97	10.23	11.10	1.74	11.10	0.80	0.85	1.01
Pirsabak-2008	10.60	7.63	9.12	2.97	9.12	0.53	0.72	0.75
Pirsabak-15	12.80	10.57	11.68	2.23	11.69	0.88	0.83	1.04
Khaista-2017	12.00	10.63	11.32	1.37	11.32	0.83	0.89	1.04
Atta Habib	11.70	10.43	11.07	1.27	11.07	0.79	0.89	1.02
Ghaneemat	12.27	10.17	11.22	2.10	11.22	0.81	0.83	1.00
Paseena-2017	12.80	9.60	11.20	3.20	11.20	0.80	0.75	0.94
NARC-2011	10.33	10.80	10.57	-0.47	10.57	0.73	1.05	1.06
Means	12.39	10.18	-					
$LSD_{0.05}$ Genotypes	149	-	-					
$LSD_{0.05}$ Environments	0.36	-	-					
$LSG_{0.05}$ G x E	0.74	-	-					

The stress selection indices and the wheat genotypes average values across the planting environments for spike length are shown in Table 3. For tolerance index (TOL), the most talented cultivar was NARC-2011 with the least desirable value (-0.47 cm), resembling three other cultivars i.e., Janbaz (1.00 cm), Atta Habib (1.27 cm), and Khaista-2017 (1.37 cm). Nevertheless, the genotype Pakistan-13 (4.23 cm), followed by three genotypes i.e., HPYT-48 (3.83 cm), Waadan-2017 (3.30 cm), and Paseena-2017 (3.20 cm) were found as least tolerant genotypes with maximum values of TOL. Based on mean productivity (MP) values, the genotype PR-128 was identified as the most favorable genotype with the highest MP value (13.73 cm), followed by genotypes Zincol-16 (12.17 cm), and PR-123 and HPYT-47 with the same value (11.82 cm). Nonetheless, Pirsabak-2008 was observed as an unfavorable genotype by holding the bottom value of MP (9.12 cm), parallel to three genotypes i.e., HPYT-48 (10.15 cm), NARC-2011 (10.57 cm), and Pakistan-13 (10.88 cm).

According to the stress tolerance index (STI), line PR-128 was figured as a desirable genotype with increased STI value (1.22 cm), followed by four other genotypes viz., Zincol-16, PR-123, HPYT-47 and Pirsabak-15 ranged from 0.95 to 0.88 cm (Table 3). Similarly, the lowest STI value was shown by cultivar Pirsabak-2008 (0.26 cm), pursued by three other genotypes i.e., Pirsabak-2008 (0.53 cm), HPYT-48 (0.65 cm), and NARC-2011 (0.73 cm). The most stable genotype with the maximum value of trait stability index (TSI) was NARC-2011 (1.05 cm), followed by three cultivars i.e., Janbaz (0.91 cm), and Khaista-2017 and Atta Habib with the same TSI value (0.89 cm). Conversely, the genotype with minimum value of TSI was Pakistan-13 (0.67 cm), pursued by Pirsabak-2008 (0.72 cm), Waadan-2017 (0.74 cm), and Paseena-2017 (0.75 cm). For trait index (TI), the genotype PR-128 expressed the highest TI value (1.24 cm), followed by three other cultivars i.e., Shahkar-2013 (1.07 cm), NARC-2011 (1.06 cm), and Zincol-16 (1.05 cm). Though, the least TI value was shown by cultivar Pirsabak-2008 (0.75 cm), followed by genotypes HPYT-48 (0.81 cm), Pakistan-13 (0.86 cm) and Waadan-2017 (0.91 cm).

Spikelets per spike: For spikelets per spike, the genotypes mean values over normal and late planting environments ranged from 18 to 24, whereas for genotype-environment interaction (GEI), the average values varied from 16 to 26 (Table 4). On average, the genotypes with optimum planting had increased spikelets per spike (22) than late planting (19) with a net difference of three spikelets. Overall, cultivar Kohat-2000 (24) had the maximum number of spikelets, proceeded by Khaista-2017 (22). However, genotype Pirsabak-2008 (18) yielded minimum spikelets per spike and it was equitable with genotype NARC-2011 (19). For G × E interactions, genotype Kohat-2000 (26) expressed the highest number of spikelets per spike, ensued by genotypes Paseena-2017 (24), and Pirsabak-15 (23) with optimum planting. Nonetheless, the genotype Pirsabak-2008 (16) had the least number of spikelets per spike, followed by four genotypes NARC-2011, HPYT-48, Pakistan-13, and NIFA-Aman ranged from 18 to 19 with delayed planting. In both planting environments, genotype Kohat-2000 resulted in the highest number of spikelets per spike while genotypes Pirsabak-2008 and NARC-2011 produced the least number of spikelets per spike.

According to TOL, the genotype Faislabad-2008 was known for minimal desirable value (0.43), ensued by three other tolerant genotypes PR-129 (0.87), Khaista-2017 (0.97), and Pirsabak-2013 (1.20) (Table 4). Nevertheless, in terms of maximum TOL value, the least tolerant genotype was Paseena-2017 (4.03), pursued by three other cultivars i.e., Pirsabak-15 (3.43), Kohat-2000 (3.33), and Pirsabak-2008 (3.07). In terms of MP, the superlative genotype was Kohat-2000 having an ample value (24.20) and in proceeding the desirable cultivars were Khaista-2017 (21.88), Paseena-2017 (21.65), and NIFA Lalma-2013 (21.30). In contrast, genotype Pirsabak-2008 had the lowest MP value (17.73), followed by three other cultivars i.e., NARC-2011 (18.77), Pirsabak-2013 (19.70), and Pakistan-13 (19.88).

For STI, the highest requisite value was exposed by cultivar Khaista-2017 (1.02), proceeded by three other genotypes i.e., Paseena-2017 (0.99), NIFA Lalma-2013 (0.97), and PR-129 (0.95) (Table 4). Though, the lowest STI value was shown by cultivar Pirsabak-2008 (0.67), resembling three other genotypes i.e., NARC-2011 (0.75), Pirsabak-2013 (0.83), and Pakistan-13 (0.84). Regarding the TSI, the noteworthy genotypes with more TSI values were PR-129 and Khaista-2017 with the same value (0.96), ensued by five other genotypes i.e., Pirsabak-2013, Ghaneemat, PR-128, NIFA Lalma-2013, and Atta Habib ranged from 0.94 to 0.93. However, the lowest TSI value was obtained by the genotype HPYT-48 (0.82), followed by three other genotypes i.e., Paseena-2017 (0.83), Pirsabak-2008 (0.84), and Pirsabak-15 (0.85). The best genotype with the highest TI value was Kohat-2000 (1.16), pursued by Khaista-2017 (1.10), PR-129 (1.06), and NIFA Lalma-2013 (1.05). Conversely, the least TI value was shown by cultivar Pirsabak-2008 (0.83), followed by three other genotypes i.e., NARC-2011 (0.91), HPYT-48 (0.94), and Pakistan-13 (0.95).

Biological yield: Genotypes ranged from 8595 to 12452 kg ha^{-1} while in genotype by environment interactions the range was 4358 to 15611 kg ha^{-1} for biological yield (Table 5). On average, the genotypes with early planting delivered the highest biological yield (13403 kg ha^{-1}) than late sowing environment (6924 kg ha^{-1}), and there was almost a 50% reduction in biological yield with late planting. Genotype Zincol-16 showed the utmost value in terms of biological yield (12452 kg ha^{-1}), and it was observed similar to ten other genotypes ranging from 11028 to 10538 kg ha^{-1}. However, cultivar NARC-2011 exhibited minimal biological yield (8595 kg ha^{-1}), and it was likely at par with 13 other genotypes varied from 8609 to 10538 kg ha^{-1}. In the genotype-environment relationship, the maximum biological yield was noted in genotype Zincol-16 (15611 kg ha^{-1}) and it was the same in performance with two other genotypes i.e., Faislabad-2008 (14999 kg ha^{-1}), and PR-123 (14672 kg ha^{-1}) with normal planting. Nonetheless, the least biological yield was observed in genotype HPYT-48 (4358 kg ha^{-1}) and it was found the same in performance with two other genotypes Kohat-2000 (5122 kg ha^{-1}) and Ghaneemat (5207 kg ha^{-1}) with delayed sowing.

Table 4. Mean performance and stress selection indices in bread wheat genotypes for spikelets per spike evaluated under optimum and late planting environments

Genotypes	Spikelets per spike (#)							
	Optimum	**Late**	**Means**	**TOL**	**MP**	**STI**	**TSI**	**TI**
Advanced lines								
PR-123	21	19	20	2	19.95	0.85	0.92	0.98
PR-125	22	19	20	3	20.40	0.88	0.87	0.97
PR-128	22	20	21	2	20.87	0.93	0.93	1.03
PR-129	21	21	21	1	21.04	0.95	0.96	1.06
HPYT-48	22	18	20	4	20.27	0.87	0.82	0.94
HPYT-47	22	20	21	2	20.73	0.92	0.89	1.00
Commercial cultivars								
Janbaz	21	19	20	2	20.03	0.86	0.89	0.97
Faislabad-2008	21	20	20	1	20.28	0.88	0.98	1.03
Zincol-16	21	19	20	2	20.20	0.87	0.91	0.99
Waadan-2017	22	20	21	2	20.97	0.94	0.90	1.02
NIFA-Aman	21	19	20	2	19.80	0.84	0.90	0.96
Shahkar-2013	22	20	21	2	20.84	0.93	0.91	1.02
Pakistan-13	21	19	20	3	19.89	0.84	0.88	0.95
Anaaj-2017	22	20	21	2	21.08	0.95	0.91	1.03
Kohat-2000	26	23	24	3	24.20	1.25	0.87	1.16
NIFA Lalma-2013	22	21	21	2	21.30	0.97	0.93	1.05
Pirsabak-2013	20	19	20	1	19.70	0.83	0.94	0.98
Pirsabak-2008	19	16	18	3	17.74	0.67	0.84	0.83
Pirsabak-15	23	19	21	3	21.05	0.94	0.85	0.99
Khaista-2017	22	21	22	1	21.89	1.02	0.96	1.10
Atta Habib	21	20	21	1	20.65	0.91	0.93	1.02
Ghaneemat	21	20	20	1	20.22	0.87	0.94	1.00
Paseena-2017	24	20	22	4	21.65	0.99	0.83	1.01
NARC-2011	20	18	19	2	18.77	0.75	0.91	0.91
Means	22	20	-					
$LSD_{0.05}$ Genotypes	1.40	-	-					
$LSD_{0.05}$ Environments	0.46	-	-					
$LSG_{0.05}$ G x E	0.99	-	-					

In the case of TOL, the reduced and desirable value was shown by cultivar Janbaz (4056 kg ha^{-1}), followed by three other cultivars i.e., Shahkar-2013 (4191 kg ha^{-1}), NIFA-Aman (4586 kg ha^{-1}), and Khaista-2017 (4832 kg ha^{-1}) (Table 5). However, the highest and undesirable value of TOL was calculated for genotype HPYT-48 (9404 kg ha^{-1}), pursued by three other cultivars i.e., Ghaneemat (8469 kg ha^{-1}), Faislabad-2008 (8466 kg ha^{-1}), and Anaaj-17 (7812 kg ha^{-1}). According to MP, cultivar Zincol-16 was identified as a prominent cultivar with maximum MP value (12452 kg ha^{-1}), followed by three other genotypes viz., Khaista-2017 (11028 kg ha^{-1}), PR-123 (11016 kg ha^{-1}), and Pakistan-13 (10928 kg ha^{-1}). Nonetheless, the cultivar NARC-2011 showed the lowest MP value (8597 kg ha^{-1}), followed by three other genotypes i.e., Kohat-2000 (8609 kg ha^{-1}), Atta Habib (9039 kg ha^{-1}), and HPYT-48 (9060 kg ha^{-1}).

Genotype Zincol-16 showed the greater STI value (0.81 kg ha^{-1}), pursued by three other genotypes i.e., Khaista-2017 (0.64 kg ha^{-1}), Pakistan-13 (0.62 kg ha^{-1}), and PR-123 (0.60 kg ha^{-1}) (Table 5). However, the least value of STI was shown by genotype HPYT-48 (0.33 kg ha^{-1}), ensured by three other cultivars Kohat-2000 (0.34 kg ha^{-1}), NARC-2011 (0.36 kg ha^{-1}), and Ghaneemat (0.40 kg ha^{-1}). Regarding the TSI, the notable genotype with the largest TSI value was Janbaz (0.67 kg ha^{-1}), followed by three other genotypes i.e., Shahkar-2013 (0.65), Khaista-2017 (0.64 kg ha^{-1}), and NIFA-Aman (0.61 kg ha^{-1}). Conversely, the least value of TSI was obtained by genotype HPYT-48 (0.32 kg ha^{-1}), accompanied by Ghaneemat (0.38 kg ha^{-1}), Kohat-2000 (0.42 kg ha^{-1}), and Faislabad-2008 (0.44 kg ha^{-1}). In concern with TI, genotype Zincol-16 (1.34 kg ha^{-1}) was of great significance, succeeded by genotypes i.e., Khaista-2017 (1.24 kg ha^{-1}), Janbaz (1.20 kg ha^{-1}), and Pakistan-13 (1.17 kg ha^{-1}). Nevertheless, the genotype HPYT-48 was noted with a minimum TI value (0.63 kg ha^{-1}), followed by three other genotypes i.e., Kohat-2000 (0.74 kg ha^{-1}), Ghaneemat (0.75 kg ha^{-1}), and NARC-2011 (0.79 kg ha^{-1}).

Table 5. Mean performance and stress selection indices in bread wheat genotypes for biological yield evaluated under optimum and late planting environments.

Genotypes	Biological yield (kg ha^{-1})							
	Optimum	Late	Means	TOL	MP	STI	TSI	TI
Advanced lines								
PR-123	14672	7360	11016	7312	11016	0.60	0.50	1.06
PR-125	14222	7320	10771	6902	10771	0.58	0.51	1.06
PR-128	14345	6878	10611	7467	10612	0.55	0.48	0.99
PR-129	14235	7312	10773	6923	10774	0.58	0.51	1.06
HPYT-48	13762	4358	9060	9404	9060	0.33	0.32	0.63
HPYT-47	12578	5833	9206	6745	9206	0.41	0.46	0.84
Commercial cultivars								
Janbaz	12342	8286	10314	4056	10314	0.57	0.67	1.20
Faislabad-2008	14999	6533	10766	8466	10766	0.55	0.44	0.94
Zincol-16	15611	9292	12452	6319	12452	0.81	0.60	1.34
Waadan-2017	12600	7420	10010	5180	10010	0.52	0.59	1.07
NIFA-Aman	11904	7318	9611	4586	9611	0.48	0.61	1.06
Shahkar-2013	12011	7820	9916	4191	9916	0.50	0.65	1.08
Pakistan-13	13732	8123	10927	5609	10928	0.62	0.59	1.17
Anaaj-2017	14444	6632	10538	7812	10538	0.53	0.46	0.96
Kohat 2000	12096	5122	8609	6974	8609	0.34	0.42	0.74
NIFA Lalma-2013	14167	7356	10761	6811	10762	0.58	0.52	1.06
Pirsabak-2013	14412	7348	10880	7064	10819	0.58	0.51	1.04
Pirsabak-2008	12944	7552	10248	5392	10248	0.54	0.58	1.09
Pirsbak-15	12778	6530	9654	6248	9654	0.46	0.51	0.94
Khaista-2017	13444	8612	11028	4832	11028	0.64	0.64	1.24
Atta Habib	11830	6247	9039	5583	9039	0.41	0.53	0.90
Ghaneemat	13676	5207	9441	8469	9442	0.40	0.38	0.75
Paseena-2017	13121	6716	9918	6405	9919	0.49	0.51	0.97
NARC-2011	11744	5449	8597	6295	8597	0.36	0.46	0.79
Means	13403	6943	-					
$LSD_{0.05}$ Genotypes	-	-	-					
$LSD_{0.05}$ Environments	186.32	-	-					
$LSD_{0.05}$ G × E	1002.9	-	-					

Grain yield: Genotypes varied from 2709 to 4147 kg ha^{-1} while for genotype into environment interaction, the range was 1689 to 4739 kg ha^{-1} for grain yield (Table 6). Overall, the optimum planting was a top-yielding environment (4135 kg ha^{-1}) as compared to late sowing (2740 kg ha^{-1}) with a significant difference of 1395 kg ha^{-1}. Genotype Zincol-16 (4147 kg ha^{-1}) was top-yielding and it was found at par with 11 other genotypes varied from 4133 to 3563 kg ha^{-1}. However, genotype NARC-2011 (2709 kg ha^{-1}) showed the least grain yield and was alike with nine more genotypes ranged from 2778 to 3353 kg ha^{-1}. For genotype by environment interaction, genotypes Zincol-16 (4739 kg ha^{-1}), PR-128 (4707 kg ha^{-1}), Pakistan-13 (4703 kg ha^{-1}), PR-123 (4697 kg ha^{-1}), and Khaista-2017 (4600 kg ha^{-1}) were superior genotypes in displaying maximum grain yield with non-stress conditions. Nonetheless, the genotype HPYT-48 expressed the minimum grain yield (1689 kg ha^{-1}), followed by three other genotypes i.e., NARC-2011 (1891 kg ha^{-1}), Ghaneemat (1908 kg ha^{-1}), and Kohat-2000 (1956 kg ha^{-1}) with late planting environment.

For TOL, the enduring genotype with the least value was Shahkar-2013 (559 kg ha^{-1}), pursued by three other genotypes i.e., Pirsabak-2008, NIFA-Aman and Pirsabak-2013 ranged from 830 to 850 kg ha^{-1} (Table 6). However, the highest and undesirable TOL value was noted in genotype HPYT-48 (2435 kg ha^{-1}), succeeded by three other genotypes i.e., PR-128, Paseena-2017, and Ghaneemat varied from 2036 to 1902 kg ha^{-1}. The highest MP value was observed in genotypes i.e., Zincol-16 (4148 kg ha^{-1}), Khaista-2017 (4134 kg ha^{-1}), and Pakistan-13 (4105 kg ha^{-1}). However, the minimum MP value was obtained by genotype NARC-2011 (2710 kg ha^{-1}), followed by three other genotypes i.e., Kohat-2000 (2779 kg ha^{-1}), Ghaneemat (2859 kg ha^{-1}), and HPYT-48 (2907 kg ha^{-1}).

Table 6. Mean performance and stress selection indices in bread wheat genotypes for grain yield evaluated under optimum and late planting environments.

Genotypes	Grain yield (kg ha^{-1})							
	Optimum	Late	Means	TOL	MP	STI	TSI	TI
Advanced lines								
PR-123	4698	3291	3995	1407	3995	0.90	0.70	1.20
PR-125	4159	2793	3476	1366	3476	0.68	0.67	1.02
PR-128	4707	2671	3689	2036	3689	0.74	0.57	0.97
PR-129	4242	2978	3610	1264	3610	0.74	0.70	1.09
HPYT-48	4124	1689	2907	2435	2907	0.41	0.41	0.62
HPYT-47	3610	2249	2929	1361	2930	0.47	0.62	0.82
Commercial cultivars								
Janbaz	4247	2878	3563	1369	3563	0.71	0.68	1.05
Faislabad-2008	3978	2241	3110	1737	3110	0.52	0.56	0.82
Zincol-16	4739	3556	4147	1183	4148	0.99	0.75	1.30
Waadan-2017	4457	2793	3625	1664	3625	0.73	0.63	1.02
NIFA-Aman	3595	2761	3178	834	3178	0.58	0.77	1.01
Shahkar-2013	4154	3595	3875	559	3875	0.87	0.87	1.31
Pakistan-13	4703	3506	4105	1197	4105	0.96	0.75	1.28
Anaaj-2017	4031	2675	3353	1356	3353	0.63	0.66	0.98
Kohat-2000	3601	1956	2778	1645	2779	0.41	0.54	0.71
NIFA Lalma-2013	4153	3033	3593	1120	3593	0.74	0.73	1.11
Pirsabak-2013	4161	3311	3736	850	3736	0.81	0.80	1.21
Pirsabak-2008	3665	2835	3250	830	3250	0.61	0.77	1.03
Pirsabak-15	4273	2565	3419	1708	3419	0.64	0.60	0.94
Khaista-2017	4600	3667	4133	933	4134	0.99	0.80	1.34
Atta Habib	3544	2371	2958	1173	2958	0.49	0.67	0.87
Ghaneemat	3810	1908	2859	1902	2859	1.99	0.87	0.70
Paseena-2017	4465	2562	3514	1903	3514	2.07	0.77	0.93
NARC-2011	3528	1891	2709	1637	2710	2.16	0.79	0.69
Means	4135	2740	-					
$LSD_{0.05}$ Genotypes	646.68	-	-					
$LSD_{0.05}$ Environments	31.28	-	-					
$LSD_{0.05}$ G × E	170.97	-	-					

Genotypes Zincol-16 (0.99 kg ha^{-1}) and Khaista-2017 (0.99 kg ha^{-1}) were found tolerant to heat stress by having maximum STI values, pursued by two other genotypes i.e., Pakistan-13 (0.96 kg ha^{-1}) and PR-123 (0.90 kg ha^{-1}) (Table 6). Though, the minimum STI value was observed in the least tolerant genotype NARC-2011 (0.39 kg ha^{-1}), accompanied by three other genotypes i.e., HPYT-48 (0.41 kg ha^{-1}), Kohat-2000 (0.41 kg ha^{-1}), and Ghaneemat (0.43 kg ha^{-1}). Regarding the TSI, the remarkable genotype with greater TSI value was Shahkar-2013 (0.87 kg ha^{-1}), followed by Pirsabak-2013, Khaista-2017, and NIFA-Aman ranged from 0.80 to 0.77 kg ha^{-1}. In contrast, the least TSI value was disclosed by genotype HPYT-48 (0.41 kg ha^{-1}), ensued by three other genotypes i.e., Ghaneemat (0.50 kg ha^{-1}), Kohat-2000 (0.54 kg ha^{-1}), and NARC-2011 (0.54 kg ha^{-1}). Genotype Khaista-2017 was identified as prominent and marked with the highest TI value (1.34 kg ha^{-1}), pursued by cultivars Shahkar-2013 (1.31 kg ha^{-1}) and Zincol-16 (1.30 kg ha^{-1}). Nonetheless, the reduced TI value was expressed by genotype NARC-2011 (0.69 kg ha^{-1}), followed by two other genotypes i.e., Ghaneemat (0.70 kg ha^{-1}) and Kohat-2000 (0.71 kg ha^{-1}).

Harvest index: For harvest index, the genotype means varied from 30 to 40% while genotype-environment interactions ranged from 27 to 46% (Table 7). The maximum harvest index was shown by genotypes with the late sowing environment (39%) as compared to the normal sowing (31%). Genotype Shahkar-2013 (40%) was recorded with the highest harvest index and it was found at par with eight other genotypes ranged from 36 to 39%. However, genotype Faislabad-2008 produced the minimum harvest index (30%) which was equalized with fourteen other genotypes ranged from 32 to 35%. For genotype by environment interaction, genotype Shahkar-2013 expressed maximum harvest index (46%) and it was found alike with two other genotypes i.e., Pirsabak-2013 (45%) and PR-123 (45%) with delayed planting. Though the genotype Faislabad-2008 produced the least harvest index (27%), and it was observed the same in performance with four other genotypes ranged from 28 to 29% with normal planting.

Table 7. Mean performance and stress selection indices in bread wheat genotypes for harvest index evaluated under optimum and late planting environments.

Genotypes	Harvest index (%)							
	Optimum	Late	Means	TOL	MP	STI	TSI	TI
Advanced lines								
PR-123	32	45	38	-13	39	1.51	1.41	1.14
PR-125	29	38	34	-9	34	1.15	1.31	0.96
PR-128	33	39	36	-6	36	1.35	1.18	0.99
PR-129	30	41	35	-11	36	1.29	1.37	1.04
HPYT-48	30	39	34	-9	35	1.22	1.30	0.99
HPYT-47	29	39	34	-10	34	1.18	1.34	0.99
Commercial cultivars								
Janbaz	34	35	35	-1	35	1.24	1.03	0.89
Faislabad-2008	27	34	30	-7	31	0.97	1.27	0.87
Zincol-16	30	38	34	-8	34	1.19	1.27	0.96
Waadan-2017	35	38	37	-3	37	1.39	1.09	0.96
NIFA-Aman	30	38	34	-8	34	1.19	1.27	0.96
Shahkar-2013	35	48	40	-13	42	1.76	1.37	1.21
Pakistan-13	34	43	39	-9	39	1.53	1.26	1.09
Anaaj-2017	28	40	34	-12	34	1.17	1.43	1.01
Kohat 2000	30	38	34	-8	34	1.19	1.27	0.96
NIFA Lalma-2013	29	41	35	-12	35	1.24	1.41	1.04
Pirsabak-2013	29	46	37	-17	38	1.40	1.59	1.16
Pirsabak-2008	28	38	33	-10	33	1.11	1.36	0.96
Pirsbak-15	34	39	36	-5	37	1.39	1.15	0.99
Khaista-2017	34	43	38	-9	39	1.53	1.26	1.09
Atta Habib	30	38	34	-8	34	1.19	1.27	0.96
Ghaneemat	28	37	32	-9	33	1.08	1.32	0.94
Paseena-2017	34	38	36	-4	36	1.35	1.12	0.96
NARC-2011	30	35	32	-5	33	1.10	1.17	0.89
Means	31	39	-					
$LSD_{0.05}$ Genotypes	-	-	-					
$LSD_{0.05}$ Environments	0.53	-	-					
$LSD_{0.05}$ G × E	2.42	-	-					

The least and zero value of TOL was shown by genotype Janbaz (0%), pursued by three other genotypes i.e., Waadan-2017 (-2%), Paseena-2017 (-4%), and Pirsabak-15 (-6%) (Table 7). However, the highest TOL value was unveiled by four genotypes i.e., Pirsabak-2013 (-16%), PR-123 (-13%), NIFA Lalma-2013 (-12%), and Shahkar-2013 (-11%). Genotype Shahkar-2013 was noted with an exceeding MP value (40%), pursued by genotypes Pakistan-13 (39%), PR-123 (38%), and Khaista-2017 (38%). However, the least MP value was denoted by genotype Faislabad-2008 (30%), followed by three other genotypes i.e., Pirsabak-2008 (33%), Ghaneemat (32%), and NARC-2011 (32%). For STI, genotype Shahkar-2013 (1.76%) outmatched other wheat genotypes, followed by Pakistan-13 (1.53%), Khaista-2017 (1.53%), and PR-123 (1.51%). However, the least and undesirable STI value was attained by genotype Faislabad-2008 (0.97%), succeeded by three other genotypes i.e., Ghaneemat (1.08%), NARC-2011 (1.10%), and Pirsabak-2008 (1.11%).

Promising genotype Pirsabak-2013 was having the highest value of TSI (1.55%), pursued by Anaaj-17 (1.44%), NIFA Lalma-2013 (1.41%), and PR-123 (1.39%) (Table 7). Nevertheless, the least TSI value was shown by genotype Janbaz (1.01%), followed by three other genotypes i.e., Waadan-2017 (1.06%), Paseena-2017 (1.16%), and Pirsabak-15 (1.17%). According to TI, genotype Shahkar-2013 (1.21%) excelled all the genotypes and it was followed by three other genotypes i.e., Pirsabak-2013 (1.16%), PR-123 (1.14%), and Pakistan-13 (1.09%). Genotype Faislabad-2008 showed the least value of TI (0.87%), ensued by three other genotypes Janbaz (0.89%), NARC-2011 (0.89%), and Ghaneemat (0.94%).

Correlation analysis: The correlation coefficient among grain yield and yield attributing parameters across optimum (non-stress) and delayed (stress) planting environments are discussed herein (Table 8). In optimum sowing environment, spike length showed significant ($p \leq 0.01$) positive association with spikelets per spike and grain yield, significant ($p \leq 0.05$) positive with harvest index and biological yield. In the case of late sowing environment, spike length had a significant ($p \leq 0.01$) positive relationship with spikelets per spike, while nonsignificant positive with biological yield, grain yield, and harvest index. In an early planting environment, spikelets per spike showed significant ($p \leq 0.05$) positive association with harvest index, nonsignificant positive with grain yield, and nonsignificant negative with biological yield. With delayed sowing, spikelets per spike showed a nonsignificant positive correlation with grain yield and harvest index, while the nonsignificant negative relationship with biological yield. Under optimum sowing, a significant ($p \leq 0.01$) positive correlation was revealed by biological yield with grain yield, and significant ($p \leq 0.01$) negative affiliation with harvest index. In a delayed sowing environment, a significant ($p \leq 0.01$) positive correlation of biological yield was noted with grain yield, significant ($p \leq 0.05$) positive with harvest index. In optimum and late planting environments, grain yield expressed a significant ($p \leq 0.01$) positive correlation with harvest index.

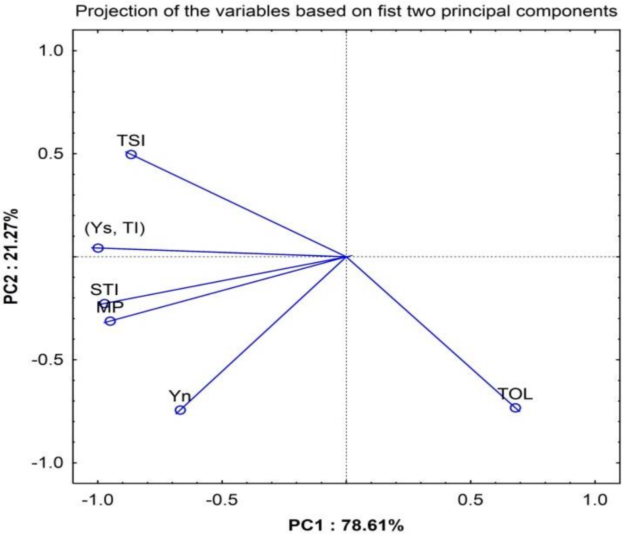

Fig. 2. Biplot diagram based on first two principal components (PC1 and PC2) of stress selection indices in 24 bread wheat genotypes evaluated under optimum and late planting environments.

Correlation among grain yield (Yn and Ys) and stress selection indices: Grain yield under normal (Yn - non-stress) and late (Ys - stress) planting environments were significantly and positively correlated (Table 9). Similarly, grain yield at non-stress condition (Yn) was significantly and positively associated with MP, STI, and TI, while negatively correlated with TOL. Grain yield with stress condition (Ys) had also a significant positive correlation with MP, STI, TI, and TSI whereas its relationship was negative with TOL. In association, the stress index TOL was found nonsignificant positive with MP while negative with STI, TI, and TSI. All other indices revealed a significant positive and positive correlation with each other.

To further examine and confirm the said relationship between the grain yield and stress selection indices, the principal component analysis (PCA) biplot was constructed (Fig. 2). The first two principal components cumulatively explained 99.88% of the total variation in stress selection indices. The small angle between the STI and MP implied a strong positive correlation. A similar strong correlation was also observed between Ys and TI. However, Yn, Ys, and TOL fell in separate quadrants implying their distinct type of nature. Dendrogram based on cluster analysis of the stress selection indices also confirmed the results of the principal component analysis that TOL and Yn were in distinct directions, whereas STI, TI, Ys, MP, and TSI had a strong positive correlation (Fig. 3).

Table 8. Correlation coefficient among various traits in bread wheat genotypes evaluated under optimum (above diagonal) and late planting (below diagonal) environment.

Traits	Spike length	Spikelets spike^{-1}	Biological yield	Grain yield	Harvest index
Spike length	-	-0.40**	0.26*	0.52**	0.27*
Spikelets spike^{-1}	0.44**	-	-0.14	0.08	0.23*
Biological yield	0.11	-0.06	-	0.51**	-0.46**
Grain yield	0.13	0.03	0.90**	-	0.53**
Harvest index	0.11	0.19	0.26*	0.65**	-

*,**: Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively, Correlation coefficient under non-stress environment: Above diagonal, Correlation coefficient under stress environment: Below diagonal

Table 9. Correlation matrix between grain yield (under non-stress and stress conditions) and various stress selection indices in bread wheat.

SSI	Yn	Ys	TOL	MP	STI	TI	TSI
Yn	-						
Ys	0.512*	-					
TOL	0.538**	-0.448*	-				
MP	0.878**	0.860**	0.070	-			
STI	0.814**	0.914**	-0.049	0.992**	-		
TI	0.516**	0.999**	-0.443*	0.862**	0.916**	-	
TSI	-0.278	0.682**	-0.957**	0.214	0.328	0.678**	-

*,**: Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively, SSI: Stress selection indices, Yn: Yield (non-stress), Ys: Yield (stress), TOL: Tolerance index, MP: Mean productivity, STI: Stress tolerance index, TI: Trait index, TSI: Trait stability index

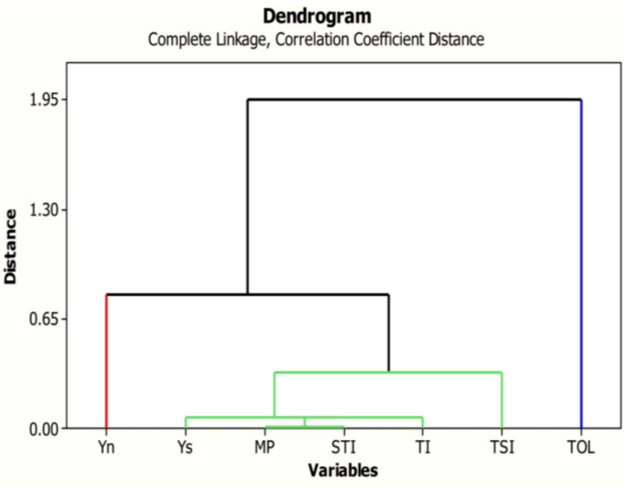

Fig. 3. Dendrogram tree based on various stress selection indices of 24 bread wheat genotypes evaluated under optimum and late planting environments.

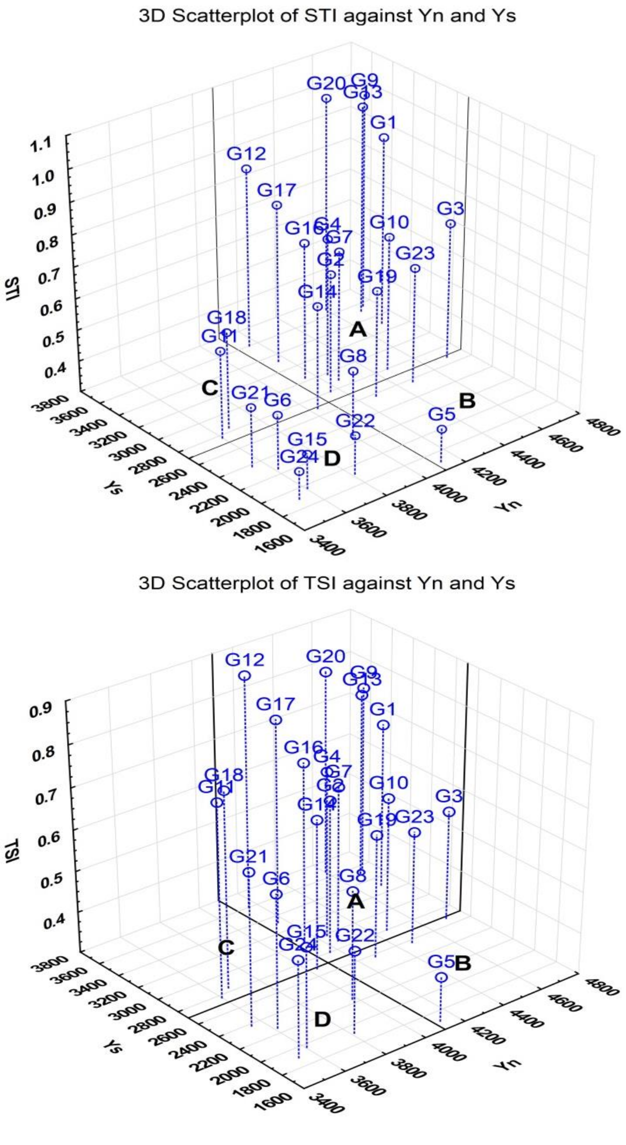

Fig. 4a, b. Three-dimensional scatter graphs showing relationship among a) Yn (Grain yield in non-stress), Ys (Grain yield in stress) and STI; b) Yn (Grain yield in non-stress), Ys (Grain yield in stress) and TSI of 24 bread wheat genotypes evaluated under optimum and late planting environments.

3D biplot analysis: Three-dimensional scatter graph was drawn to simultaneously visualize the best wheat genotypes with increased grain yield under non-stress (Yn) and stress (Ys) environmental conditions and stress tolerance indices STI and TSI (Fig. 4a, b, Table 1). The Yn, Ys, and STI were plotted on X, Y, and Z axes, respectively (Fig. 4a). The X and Y axes were partitioned into four quadrants (A, B, C, and D) based on their response to each environmental condition. Quadrant-A had high earning wheat genotypes under both non-stress and stress environmental conditions, Quadrant-B contained high yielding genotypes under stress planting environment, Quadrant-C comprised of poor yielding genotypes under stress planting environment, whereas Quadrant-D included the poor performing genotypes both under non-stress and stress environmental conditions.

Genotypes having a long projection on Z-axis have good STI, and hence were likely to perform best under stress conditions. In this regard, genotypes G-9 (Zincol-16), G-13 (Pakistan-13) and G-20 (Khaista-2017) with their long projection on Z-axis produced maximum grain yield both under non-stress and stress environmental conditions with good STI (Fig. 4a, Table 1). Conversely, genotypes G-15 (Kohat-2000) and G-24 (NARC-11) were poor yielders under non-stress and stress environmental conditions. The Yn, Ys, and TSI were plotted on X, Y, and Z axes, respectively (Fig. 4b). The superiority of G-9 (Zincol-16), G-13 (Pakistan-13), and G-20 (Khaista-2017) were also confirmed as indicated by their long projection on Z-axis. Similarly, G-12 (Shahkar-2013) had better TSI; however, it was a moderate yielder (Fig. 4b, Table 1). Based on Yn, Ys, and TSI, the genotypes G-15 (Kohat-2000) and G-24 (NARC-11) were poor performing genotypes under normal and late plantings conditions.

Discussion

For identification and selection of heat stress tolerant wheat genotypes with greater yield potential, the breeding material should be screened in different targeted environmental conditions. Multi-location trials of bread wheat genotypes assist in the characterization of the new emerging planting environments and ideal cultivars for specific and broad adaptability. With an intricate interaction between plant and existing environment, the appraisal of impressions is not inconsequential and requires the formulation and use of different crop production models (Semenov, 2009). Therefore, the germplasm identification with enhanced heat stress tolerance is a precondition phase of breeding for thermo-tolerance.

In present studies, genotypes and genotype by environment interactions were noted with significant differences for grain yield and its related traits. Larger genetic variability was observed in the wheat germplasm through its diverse response across the different planting environments. Planting times significantly affected the grain yield traits in the studied wheat genotypes. Past studies enunciated significant environmental effects on wheat genotypes for morphological and yield traits grown under diverse planting environments (Khan & Mohammad, 2018; Montesinos-López *et al.*, 2018). Former studies reported significant variations among the planting environments, cultivars, and cultivar by environment relationship for yield traits in wheat (Aktaş, 2016; Bacha *et al.*, 2017).

On average, wheat germplasm performed well with optimum planting as compared to delayed planting which adversely affects the growth and crop productivity. Reduction in growth period due to late sowing might be one of the causes of decline in wheat yield (Basir *et al.*, 2015). Likewise, spike traits were also significantly decreased in genotypes with delayed planting due to heat stress. Past studies revealed that a yield reduction of 0.7% per day was reported with delayed wheat sowing because of the exposure of growth and reproductive stages to high temperatures resulting in reduced grain yield (Kaur & Behl, 2010). Hence, early maturing wheat genotypes with optimum planting are advocated to avoid late planting heat stress which hastens grain filling (Khichar & Niwas, 2007).

With optimum planting, cultivar Zincol-16 excelled all other genotypes for grain yield, followed by advanced line PR-128 and cultivar Pakistan-13. Nevertheless, with delayed planting, cultivar Khaista-2017 surpassed all other genotypes in grain yield, succeeded by two other genotypes i.e., Shahkar-2013 and Zincol-16. Wheat genotypes with optimum planting expressed the utmost yield because of the long growing period and sufficient photosynthates. The decreased biological and grain yields might be due to a shorter growth period and lack of photosynthates due to late plantation. Late sowing heat stress was found to have a significant influence on germination and growth and significantly affected the grain yield and quality parameters in wheat (Prasad *et al.*, 2020). Therefore, in wheat, the appropriate planting time is one of the most vital agronomic practices for getting optimum plant growth and grain yield (Kajla *et al.*, 2015).

In the present study, five stress selection indices i.e., TOL, MP, STI, TSI, and TI were used to evaluate the recital of wheat genotypes under optimum (non-stress) and delayed (stress) planting environments (Bouslama & Schapaugh, 1984; Hossain *et al.*, 1990; Fernandez, 1992; Gavuzzi *et al.*, 1997). Genotypes mean comparison for grain yield and its component traits under various planting dates revealed that the highest grain yield was achieved by optimum planting. Based on stress selection indices like TOL, MP, STI, TSI, and TI, the early sowing was found suitable and recommended under prevailing planting environments. Past studies revealed that based on stress indices like GMP, MP, STI, and YI, the early sowing was found more appropriate by producing increased grain yield in wheat (Mohammadi *et al.*, 2012). During the grain-filling period, the grain formation and its filling competency are mostly affected by late planting heat stress in wheat (Rajalam *et al.*, 2009; Hossain *et al.*, 2019).

Selection indices revealed that for spike traits, genotypes PR-123, Zincol-16, HPYT-47, and Khaista-2017 outclassed all other genotypes. Based on selection indices for grain yield, the genotypes Zincol-16, Khaista-2017 and Pakistan-13 were outstanding in terms of stability. Using the stress indices i.e., STI, GMP, and MP, some of the wheat genotypes were found promising with comparatively the highest grain yield and their suitability to both planting environments (Jahan *et al.*, 2018). Genotypes revealed a significant decrease in spike traits due to the late sowing environment because of heat emphasis that caused a reduction in seed size due to seed shrinkage in wheat (Kajla *et al*., 2015; Kalwar *et al.*, 2018). A significant reduction was reported for yield-related traits because of the floret abortion due to delayed sowing heat stress (Rahman *et al*., 2018; Hossain *et al*., 2019) while accelerating the growth with reduced phenology in wheat (Zahedi & Jenner, 2003). Wheat genotypes interpreted the drop in spike and yield related traits due to late sowing heat stress (Elbashir *et al*., 2017; Khairnar *et al*., 2018).

In correlation studies, grain yield under non-stress and stress (Yn and Ys) conditions exhibited significant positive association which suggested that promising genotypes can be preferred based on their response to both planting environments. Substantial positive association among grain yield and stress tolerance indices could efficiently identify the superior genotypes in crop plants under stress planting environments (Mitra, 2001). In the current study, grain yield under Yn and Ys environmental conditions was significantly and positively correlated with stress selection indices i.e., MP, STI, TI, and TSI, whereas the yield relationship was negative with TOL. Grain yield under non-stress and stress conditions exhibited a significant positive correlation with stress tolerance indices i.e., MP, GMP, STI, and HM in bread wheat (Mardeh *et al*., 2006). The Yn and Ys were reported with a significant positive correlation with stress indices (MP, GMP, and STI) under different planting environments and hence were recommended as better predictors in wheat (Mohammadi *et al.*, 2011, 2012).

The above observations about correlation were also confirmed through principal component and cluster analyses. The present investigations suggested that stress tolerance indices could serve as efficient predictors for grain yield under non-stress and stress planting environments. Jahan *et al*., (2018) also reported that grain yield had a significant positive correlation with stress selection indices i.e., MP, STI, TI, and TSI in wheat. In the principal component analysis, the past findings demonstrated a significant positive correlation of grain yield (under stress-free and stress conditions) with stress indices i.e., MP, GM, STI, and TI, however, yield possessed a negative association with drought response index (DRI) in bread wheat (Mohammadi *et al.*, 2011, 2012; Farshadfar *et al*., 2012). Principal component analysis based on the correlation of Yn, Ys, with stress tolerance indices was used to recognize the stable genotypes in wheat (Dorostkar *et al.*, 2015; Aktaş, 2016). Past findings suggested that assortment based on the alignment of stress tolerance indices may provide a more useful measure for improving stress resistance in wheat (Khan & Kabir, 2015).

A three-dimensional graph was used to envisage the superior wheat genotypes under non-stress and stress planting environments. Two stress tolerance indices i.e., STI and TSI under non-stress and stress environmental conditions, respectively were used as predictors based on their strong positive association with grain yield. The X and Y axes partitioned the genotypes into four different groups based on their response to planting environments as suggested by Fernandez (1992). In the past studies, the same scatter graph was used to divide the wheat genotypes into different groups based on their mean performance under non-stress and stress planting environments (Mohammadi *et al*., 2012). In biplot analysis and based on stress tolerance indices (STI and TSI), the genotypes Zincol-16, Pakistan-13, and Khaista-2017 produced maximum grain yield under non-stress and stress environments indicating their potency to effectively tackle late planting heat stress. The principal component and biplot analyses were found useful in identifying the promising and heat stress tolerant wheat genotypes under different planting environments (Farshadfar *et al.*, 2012; Bacha *et al.*, 2017; Tulu & Wondimu, 2019).

Appropriate sowing time is one of the most crucial environmental factors in determining the optimum crop growth and grain yield. Delayed wheat sowing copes with abiotic stresses including heat stress, which shortens the period of spike emergence and maturity, ultimately affecting the grain yield and quality (Hakim *et al.*, 2012; Hossain & da-Silva, 2012; Babiker *et al*., 2017). To avoid the adverse effects of delayed sowing on wheat yield, the crop should be sown at the recommended time. In the future, the changing climate also suggested augmented summer aridity and winter humidity with more chances of concentrated rains and inundation due to the larger water storage capability of a warmer atmosphere (Rahman *et al*., 2018). Climate models have predicted the augmentation in temperature up to 1-4˚C by 2099, with more frequent heatwaves which is alarming for the crops like wheat which is already threatened by heat stress (Field, 2014). Therefore, to overcome future challenges and to secure sustainable wheat production, alternative breeding methods are required to acquire heat stress tolerant wheat cultivars (Hakim *et al.*, 2012).

Conclusion

Wheat genotypes performed well with normal planting as compared to late due to heat stress which adversely affects the growth and crop productivity. Cultivars Zincol-16, Pakistan-13, and Khaista-2017, followed by Shahkar-2013 for yield related traits were identified as promising genotypes under stress selection indices. However, the wheat lines PR-123 and HPYT-47 were worth mentioning in terms of stability. With optimum planting, cultivar Zincol-16 excelled all other genotypes, followed by line PR-128 and cultivar Pakistan-13 for grain yield. With delayed planting, cultivar Khaista-2017 produced the maximum grain yield, followed by Shahkar-2013 and Zincol-16. The aforementioned wheat genotypes should be taken into special consideration for approaching breeding strategies.

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References

Aktaş, H. 2016. Drought tolerance indices of selected landraces and bread wheat (*T. aestivum* L.) genotypes derived from synthetic wheat. *Appl. Ecol. Environ. Res.,* 14: 177-189.

Babiker, W.A., A.A. Abdelmula, H. Ibrahaim, S. Eldin and M. Gasim. 2017. The Effect of location, sowing date, and genotype on seed quality traits in bread wheat (*T. aestivum* L.). *Asian J. Plant Sci. Res.,* 7: 24-28.

Bacha, T., Z. Taddesse and M. Mehari. 2017. GGE-Biplot analysis of genotype × environment interaction and grain yield stability of bread wheat (*T. aestivum* L.) genotypes in Ethiopia. *J. Biol. Agri. Healthc.,* 7: 22-30.

Basir, A., R. Ali, M. Alam, A.S. Shah and K. Afridi. 2015. Potential of wheat (*T. aestivum* L.) advanced lines for yield and yield attributes under different planting dates in Peshawar valley. *Amer. J. Agri. Environ. Sci.,* 15: 2484-2488.

Bhanu, A.N., B. Arun and V.K. Mishra. 2018. Genetic variability, heritability and correlation study of physiological and yield traits in relation to heat tolerance in wheat (*T. aestivum* L.). *Biomed. J. Sci. Tech. Res.,* 2: 2112-2116.

Bouslama, M. and W.T. Schapaugh. 1984. Stress tolerance in soybeans. I. Evaluation of three screening techniques for heat and drought tolerance. *Crop Sci.,* 24: 933-937.

Dorostkar, S., A. Dadkhodaie and B. Heidari. 2015. Evaluation of grain yield indices in hexaploid wheat genotypes in response to drought stress. *Arch. Agron. Soil Sci.,* 61: 397-413.

Elbashir, A.A.E, Y.S.A. Gorafi, I.S.A. Tahir, J.S. Kim and H. Tsujimoto. 2017. Wheat multiple synthetic derivatives: a new source for heat stress tolerance adaptive traits. *Breed. Sci.,* 67: 248-256.

Farshadfar, E., B. Jamshidi and M. Aghaee. 2012. Biplot analysis of drought tolerance indicators in bread wheat landraces of Iran. *Int. J. Agric. Crop Sci.,* 4: 226-233.

Fernandez, G.C.J. 1992. Effective selection criteria for assessing plant stress tolerance. *Proceeding of the international symposium on adaptation of vegetables and other Food crops in temperature and water stress, Aug. 13-16, Shanhua, Taiwan, 1992*. pp. 257-270.

Field, C.B. 2014. *Climate change 2014–Impacts, adaptation and vulnerability: Regional aspects*. Cambridge University Press.

Gavuzzi, P., F. Rizza, M. Palumbo, R.G. Campanile, G.L. Ricciardi and B. Borghi. 1997. Evaluation of field and laboratory predictors of drought and heat tolerance in winter cereals. *Can. J. Plant Sci.,* 77: 523-531.

Hakim, M.A., A. Hossain, J.A.T. da-Silva, V.P. Zvolinsky and M.M. Khan. 2012. Protein and starch content of 20 wheat (*T. aestivum* L.) genotypes exposed to high temperature under late sowing conditions. *J. Scien. Res.,* 4(2): 477. https://doi.org/10.3329 /jsr.v4i2.8679.

Hossain, A. and J.A.T. da-Silva. 2012. Phenology, growth and yield of three wheat (*T. aestivum* L.) varieties as affected by high temperature stress. *Not. Sci. Biol.,* 4: 97-109.

Hossain, A.B.S., R.G. Sears, T.S. Cox and G.M. Paulsen. 1990. Desiccation tolerance and its relationship to assimilate partitioning in winter wheat. *Crop Sci.,* 30: 622-627.

Hossain, M.M., M.M. Rahman, R. Islam, M.N. Alam, A. Ahmed, R. Begum and M.Z. Islam. 2019. Evaluation of some wheat genotypes growing under heat stress conditions in two environments in Bangladesh. *J. Multidiscip. Sci.,* 1: 5993-6004.

Jahan, M., A. Hossain, J. Timsina and J.A.T. da-Silva. 2018. Evaluation of tolerance of six irrigated spring wheat (*T. aestivum* L.) genotypes to heat stress using stress tolerance indices and correlation analysis. *Agric. Res.,* 13: 39-52.

Kajla, M., V.K. Yadav, R.S. Chhokar and R.K. Sharma. 2015. Management practices to mitigate the impact of high temperature on wheat. *J. Wheat Res.,* 7: 1-12.

Kalwar, Z.A., A. Tunio, M.Y. Shaikh, K.J. Imran and Q. Jogi. 2018. Impact of sowing dates on the growth and yield of wheat variety Benazir-2013, Sindh Province, Pakistan. *Int. J. Agron. Agric. Res.,* 12: 65-71.

Kaur, V. and R.K. Behl. 2010. Grain yield in wheat as affected by short periods of high temperature, drought and their interaction during pre-and post-anthesis stages. *Cereal Res. Commun.,* 38: 514-520.

Khairnar, S.S., J.H. Bagwan, K.J. Kumar, V.S. Baviskar, B.K. Honrao, V.D. Surve, V.M. Khade, A.M. Chavan and B.N. Bankar. 2018. Studies on genetic variability parameters and character association in bread wheat (*T. aestivum* L.) under timely and late sown environments of irrigated condition. *Electr. J. Plant Breed.,* 9: 190-198.

Khan, A.A. and M.R. Kabir. 2015. Evaluation of spring wheat genotypes (*T. aestivum* L.) for heat stress tolerance using different stress tolerance indices. *Cercet. Agron. Mold.,* 47: 49-63.

Khan, M.A.U. and F. Mohammad. 2018. Effect of genotype × environment interaction on grain yield determinants in bread wheat. *Sarhad J. Agric.,* 34: 54-62.

Khazratkulova, S., R.C. Sharma, A. Amanov, Z. Ziyadullaev, O. Amanov, S. Alikulov, Z. Ziyaev and D. Muzafarova. 2015. Genotype × environment interaction and stability of grain yield and selected quality traits in winter wheat in Central Asia. *Turk. J. Agric. For.,* 39: 920-929.

Khichar, M.L. and R. Niwas. 2007. Thermal effect on growth and yield of wheat under different sowing environments and planting systems. *Indian J. Agric. Res.,* 41: 92-96.

Kwon, S.H. and J.H. Torrie. 1964. Heritability and interrelationship among traits of two soybean populations. *Crop Sci.,* 4: 196-198.

Lepekhov, S.B. and L.P. Khlebova. 2018. Assessment of drought resistance indices in spring bread wheat under various environmental conditions. *Ukr. J. Ecol.,* 8: 314-319.

Mardeh, A.S.S., A. Ahmadi, K. Poustini and V. Mohammadi. 2006. Evaluation of drought resistance indices under various environmental conditions. *Field Crop Res.,* 98: 222-229.

Mehari, M. and A. Workineh. 2018. Adaptation study and genotype by environment interaction of bread wheat genotypes in Tigray, North, Ethiopia. *Basic Res. J. Agric. Sci. Rev.,* 6: 9-14.

Mitra, J. 2001. Genetics and genetic improvement of drought resistance in crop plants. *Curr. Sci.,* 80(6): 758-763.

Mohammadi, M., R. Karimizadeh and M. Abdipour. 2011. Evaluation of drought tolerance in bread wheat genotypes under dryland and supplemental irrigation conditions. *Aust. J. Crop Sci.,* 5: 487-493.

Mohammadi, S., M. Janmohammadi, A. Javanmard, N. Sabaghnia, M. Rezaie and A. Yezdansepas. 2012. Assessment of drought tolerance indices in bread wheat genotypes under different sowing dates. *Cercet. Agron. Mold.,* 45: 25-39.

Montesinos-López, O.A., P.S. Baenziger, K.M. EskridgeK, R.S. Little, E. Martínez-Crúz and E. Franco-Perez. 2018. Analysis of genotype-by-environment interaction in winter wheat growth in organic production system. *Emirates J. Food Agric.,* 30: 212-223.

Pakistan Economic Survey. 2020-2021. Ministry of Economic Affairs Division, Govt. of Pakistan, Islamabad, Pakistan.

Prasad, R.B., M.A. Joshi, S. Basu and K.B. Gaikwad. 2020. Development of suitable mitigation strategy to counter the adverse effect of heat stress in wheat varieties (*T. aestivum* L.). *Int. J. Curr. Microbiol. Appl. Sci.,* 9: 646-653.

Rahman, M.M., M.A. Hasan, M.F. Chowdhury, M.R. Islam and M.S. Rana. 2018. Performance of wheat varieties under late planting-induced heat stress conditions. *Bangladesh Agron. J.,* 21: 9-24.

Raiyani, G.D., P. Komal, R.M. Javia, V.J. Bhatiya and V.V. Ramani. 2015. Selection indices for yield improvement in bread wheat under late sown condition. *Asian J. Biol. Sci.,* 10: 148-152.

Rajalam A., K. Hakala, P. Mäkelä, S. Muurinen and P. Peltonen-Sainio. 2009. Spring wheat response to timing of water deficit through sink and grain filling capacity. *Field Crop. Res.,* 114: 263-271.

Rosielle, A.A. and J. Hamblin. 1981. Theoretical aspects of selection for yield in stress and non-stress environment. *Crop Sci.,* 21: 943-946.

Sabit, Z., B. Yadav and P.K. Rai. 2017. Genetic variability, correlation and path analysis for yield and its components in F_5 generation of bread wheat (*T. aestivum* L.). *J. Pharmacogn. Phytochem.,* 6: 680-687.

Semenov, M.A. 2009. Impacts of climate change on wheat in England and Wales. *J. R. Soc. Interface.,* 6: 343-350.

Smith, H.F. 1936. A discriminant function for plant selection. *Ann. Eugen.,* 7: 240-250.

Tulu, L. and A. Wondimu. 2019. Adaptability and yield stability of bread wheat (*T. aestivum* L.) varieties studied using GGE-biplot analysis in the highland environments of South-Western Ethiopia. *Afr. J. Plant Sci.,* 13: 153-162.

Yan, W. 2001. GGE biplot- A windows application for graphical analysis of multi-environment trial data and other types of two-way data. *Agron. J.,* 93: 1111-1118.

Yan, W. and J.B. Holland. 2010. A heritability-adjusted GGE biplot for test environment evaluation. *Euphytica,* 171: 355-369.

Yan, W., M.S. Kang, B. Ma, S. Woods and P.L. Cornelius. 2007. GGE biplot vs. AMMI analysis of genotype-by-environment data. *Crop Sci.,* 47: 643-655.

Yang, R., D. Stanton, S.F. Blade, J. Helm, D. Spaner, S. Wright and D. Domitruk. 2006. Isoyield analysis of barley cultivar trials in the Canadian Prairies. *J. Agron. Crop Sci.,* 192: 284-294.

Yang, R.C. 2007. Mixed-model analysis of crossover genotype–environment interactions. *Crop Sci.,* 47: 1051-1062.

Zahedi, M. and C.F. Jenner. 2003. Analysis of effects in wheat of high temperature on grain filling attributes estimated from mathematical models of grain filling. *J. Agric. Sci.,* 141: 203-212.

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