Pak. J. Bot., 54(3): 823-834, 2022. DOI: http://dx.doi.org/10.30848/PJB2022-3(33)

WHEAT ASSESSMENT FOR HEAT STRESS TOLERANCE USING STRESS SELECTION INDICES UNDER DISTINCT PLANTING REGIMES

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Abstract

Heat stress is a widespread problem due to changing climatic conditions which influence wheat productivity and quality. To assess the heat stress tolerance, thirty-six wheat genotypes (including six advance lines and 30 cultivars) were sown under optimum and delayed planting conditions during 2017-18 at Cereal crops Research Institute (CCRI), Pirsabak - Nowshera. The experiment was constructed in a randomized complete block design replicated thrice. Analysis of variance exhibited significant ($p \leq 0.01$) variations among the wheat genotypes, environments, and their interactions for all the traits. Generally, a decline was observed in yield trait means under stressed environment than the optimum environment. Over both test environments, wheat genotype Pakistan-2013 (3746 kg ha^{-1}) produced the highest grain yield, followed by Zincol-2016 (3712 kg ha^{-1}) and PR-122 (3671 kg ha^{-1}). With optimum planting conditions, wheat genotype Israr-2017 (4767 kg ha^{-1}) was promising for the grain yield, followed by NIFA-Lalma (4733 kg ha^{-1}) and Paseena-2017 (4725 kg ha^{-1}). However, genotype PR-122 (3158 kg ha^{-1}) was prominent in terms of grain yield, followed by Zincol-2016 (3029 kg ha^{-1}) and Pakistan-2013 (2938 kg ha^{-1}) with late sowing and stress conditions. Stress selection indices tools i.e., tolerance index (TOL), mean productivity (MP), stress tolerance index (STI), trait stability index (TSI), and trait index (TI) were used and found more effective for identifying stress tolerant wheat genotypes. Based on the selection indices, wheat genotype Pirsabak-2013, followed by Zincol-2016 and PR-122 were found more tolerant and high yielding and that can be used in future breeding schemes for further improvement.

Key words: *Triticum aestivum* L. genetic diversity; Stress selection indices; Normal and late planting; genotype × environment interaction.

Introduction

Wheat (*Triticum aestivum* L.) is a self-pollinated cereal crop that belongs to the family Gramineae has grown worldwide for edible grains. Among cereals, wheat has a prominent position because of its staple food nature used by more than 36% of the world's population. Wheat has been grown in many countries because of its versatile nature in adaptation and utility in innumerable ways (Singh *et al*., 2020). To feed the increasing population, an increase in the per-unit yield of wheat is a necessity to meet the food requirements of the world population. A marginal increase has occurred in wheat productivity under favorable growth conditions. However, considerable scope for further improvement in wheat productivity under unfavorable environments is still vaguely characterized by abiotic constraints like high-temperature stresses (Bouslama & Schapaugh, 1984; Bhanu *et al*., 2018)

There are several factors like diseases, insect pests, drought, high temperature, salinity, waterlogging, and other biotic and abiotic stresses that are responsible for wheat low yield, however, terminal heat stress is most vital. The rise in temperature during the grain filling period is referred to as terminal heat stress. Heat stress due to late planting is the main reason for the lower yield per unit area in wheat (Hura, 2020; Tahir *et al*., 2022). In the present era, the breeding for heat tolerance in wheat is one of the big challenges for breeders. To resolve this problem, plant breeders work on the selection of heat-tolerant genotypes under targeted environments. Therefore, to fulfill the diversified goals of plant breeding, the development of heat-tolerant genotypes are essential for enhancement in grain yield, improvement in quality traits, and wider adaptation to varied environments, to meet the food demand of the population (Schmidt *et al*., 2020; Van, 2020).

Breeders are interested in the development of new wheat genotypes that perform better and maintain the production at the sustainable intensity on diversified agro-climatic environments especially stressed conditions. The development of new wheat cultivars for stress conditions requires information based on screening and identification of superior genotypes suited best to stress and non-stress environments. In such studies, several stress selection indices are used by wheat breeders to identify the superior wheat genotypes under diverse climatic conditions. These indices include, tolerance index (TOL), mean productivity (MP), stress tolerance index (STI), trait stability index (TSI), and trait index (TI) which have been extensively used in wheat breeding (Hossain *et al.*, 1990; Fernandez, 1992; Gavuzzi *et al.*, 1997; Lepekhov & Khlebova, 2018).

The expression of genetic material over a wide range of diverged environments is commonly known as genotype-by-environment interaction (GEI) which is very important for the estimation of genotypes performance because it reduces the genotypic firmness values under various environmental conditions. A wheat genotype is assessed by three factors i.e., genotypic effects, environments, and their interactions. Conventional wheat genotypes that accurately respond to diverse planting and environmental conditions become favorable for farmers by their consistency in production (Janni *et al*., 2020; Tahir *et al*., 2022). The information on genotype by environment interaction is crucial in determining the stability and competency of the selection in breeding. The conformation of genotype by environment interaction is a substantial feature for any breeding scheme and the identification of superior wheat genotypes for yield stability (Khalil *et al*., 2017). In this regard, the present study was carried with the aim out to identify the wheat genotypes with tolerance to late planting heat stress by using stress selection indices under genotype by environment interactions, and correlation coefficient among the morphological and yield traits under different planting regimes.

Materials and Methods

In the present study, wheat genotypes were assessed in a randomized complete block design with a factorial arrangement using three replications across two planting environments (non-stress and stressed) during crop season 2017-18 at Cereal Crops Research Institute (CCRI), Pirsabak - Nowshera, Pakistan. The genetic material comprising 36 wheat genotypes (including six advance lines and thirty wheat cultivars) was procured from various Agricultural Research Institutes all over Pakistan (Table 1). Each sub-plot consisted of four rows having five meters length with rows spacing of 30 cm. Normal planting (non-stress) was made on November 09, 2017; whereas the late planting (stressed) was done on December 18, 2017. All the recommended cultural practices (other than planting dates) were kept the same for all the entries of wheat.

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 days to heading were recorded as days from sowing till the day when half of the plants showed spike emergence. Plant height was deliberated by meter rod after the crop maturity. The tillers per square meter were counted in each sub-plot and replication. Flag leaf area of ten randomly selected plants in each genotype per replication was determined by following the formula of Francis *et al*., (1969). Biological and grain yields 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: Various stress selection indices i.e., tolerance index (TOL), mean productivity (MP) (Lepekhov & Khlebova, 2018), stress tolerance index (STI), trait stability index (TSI), and trait index (TI) were used for assessing the mean performance of wheat genotypes under non-stressed (optimum planting) and stressed (late planting) environments (Hossain *et al.*, 1990; Fernandez, 1992; Gavuzzi *et al*., 1997). Tolerance index (TOL) is defined as the difference in yield between non-stressed and stressed planting environments. The term mean productivity (MP) is the average yield under non-stressed and stressed planting environments. The stress tolerance index (STI) is used for the identification of wheat genotypes that produce higher yields under non-stressed and stressed environments. Trait stability index (TSI) grouped the wheat genotypes based on the yield of wheat under stressed planting environments relative to yield under optimum planting environment. Trait index (TI) is based on the yield of wheat genotype to mean yield of all the genotypes under stressed conditions and it ranks the wheat genotypes based on mean performance under stressed planting environment. Apart from that, the optimum and late planting environments were assumed as non-stressed (Yn) and stressed (Ys) environments to work out the following stress selection indices.

Table 1. Detail of wheat advance lines of CCRI and cultivars used in the study.

S. No.	Cultivar	Institution	S. No.	Cultivar	Institution
1.	PR-114	CCRI, Pirsabak	19.	Borlaug-2016	NARC, Islamabad
2.	PR-118	-do-	20.	Zincol-2016	-do-
3.	PR-119	-do-	21.	Pakistan-2013	-do-
4.	PR-122	-do-	22.	Ujala	AARI, Faisalabad
5.	PR-123	-do-	23.	Faisalabad-2008	-do-
6.	PR-124	-do-	24.	Fateh Jhang	BARI, Chakwal
7.	Paseena-2017	-do-	25.	Ehsan	AARI, Faisalabad
8.	Khaista-2017	-do-	26.	Johar-2016	-do-
9.	Wadan-2017	-do-	27.	Gold-2016	-do-
10.	Pakhtunkhwa-2015	-do-	28.	Ghaneemat-e-IBGE	AUP, Peshawar
11.	Pirsabak-2015	-do-	29.	KT-2000	BARS, Kohat
12.	Pirsabak-2013	-do-	30.	KT-2017	-do-
13.	Shahkar-2013	-do-	31.	Israr-2017	ARI, D.I.Khan
14.	Pisabak-2008	-do-	32.	Shahid-2017	-do-
15.	Pirsabak-2005	-do-	33.	NARC-2011	NARC, Islamabad
16.	Insaf	NIFA, Peshawar	34.	Amin-2010	ARS, Naurang
17.	NIFA-Aman	-do-	35.	Dharabi-2011	BARI Chakwal
18.	NIFA-Lalma	-do-	36.	Benazir	ARI, Tandojam

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

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

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

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

$$\text{Trait Stability Index (TSI)} = \frac{Y_s}{Y_n}$$

Where;

$Y_{n.}$ = Genotype means for that trait within the optimum planting

Y_s = Genotype means for that trait within late planting

$\bar{Y}_n$ = Grand mean of a specific trait within the optimum planting

$\bar{Y}_s$ = Grand mean of a specific trait within late planting

Statistical analysis

All the data were analyzed according to the analysis of variance (ANOVA) using the proper paradigm for genotype-environment interaction (GEI) (Gomez & Gomez, 1984; Yang *et al.*, 2006; Yang, 2007; Tahir *et al.*, 2022). After analysis, the means for each category and parameter were further compared and separated by using $LSD_{0.05}$.

Correlation analysis

The analysis of correlation coefficient for earliness, morphological, and yield associated traits was carried out under non-stressed and stressed planting environments (Kwon & Torrie, 1964).

Results

Combined analysis of variance over both planting environments revealed significant ($p \leq 0.01$) variations among the genotypes, environments, and genotype by environment interactions for all the studied traits (Table 2). These findings exhibited that there is a considerable magnitude of genetic variability among the genotypes with diversified planting environments under which the study has been carried out. The trait-wise results are discussed as follows.

Days to 50% heading: Early heading and maturity are of utmost importance in cereal crops due to changing climatic conditions. Therefore, stress-tolerant cultivars can escape the biotic and abiotic stresses to enhance productivity. Among wheat genotypes, the mean days to heading varied from 103 to 112 days while the interactions ranged from 91 to 125 days (Table 3). By comparing both environments, late-planted wheat genotypes took lesser days to heading (95 days) and dominated over normal plating environment (121 days) and showed a decline of 19.4% in days to heading. Across both test environments, minimum days to heading were consumed by wheat genotype Shahid-2017 (103 days), while maximum days to heading were taken by wheat genotype Fateh Jhang (112 days). Based on interactions due to genotypes and environments, minimum days to heading were exhibited by wheat genotype Shahid-2017 with late planting (91 days) whereas the maximum were accounted for wheat genotype Ehsan with early planting (125 days). According to test environments and genotype by environment interactions, wheat genotype Shahid-2017 took minimum days to heading as compared to all other genotypes and interactions.

For days to heading, the genotypes mean values and stress selection indices are illustrated in Table 3. Based on the tolerance index (TOL), the least and favorable value was determined by wheat genotypes i.e., Faisalabad-2008, Johar-2016, and Gold-2016. Likewise, the maximum favorable figure in terms of mean productivity (MP) and stress tolerance index (STI) were shown by wheat genotypes Fateh Jhang, Ehsan, and KT-2000. In concern with trait stability index (TSI), the most tolerant genotypes with increased values were Faisalabad-2008, Johar-2016, and Gold-2016. Similarly, in the case of trait index (TI), the wheat genotype Borlaug-2016 was appeared to be the top ranking, followed by two other genotypes i.e., Fateh Jhang and KT-2000.

Plant height: Plant stature is of crucial importance in wheat crop and up to some extent it contributes also to final yield if lodging has not occurred. However, medium stature genotypes are preferred because of their well responsive nature to fertilizers, resistance to lodging, and other unforeseen environmental conditions. Among genotypes, the plant height varied from 80 to 105 cm over both planting conditions, while genotype × environment interaction means ranged from 67 to 119 cm (Table 4). Across both planting conditions, minimum plant height was measured for wheat genotype Pirsabak-2008 (80 cm) while the maximum for wheat genotype Insaf (105 cm). Overall, the late-planted wheat genotypes produced shorter plants (81 cm) than normal planting (105 cm) indicating a 30% decrease in plant height due to stressed conditions. In terms of genotype-environment interactions, wheat genotype Pirsabak-2008 with late planting showed minimum plant height (67 cm), whereas maximum plant stature was determined by wheat genotype Insaf with normal sowing (118 cm). Wheat genotype Pirsabak-2008 performed well under both test environments and genotype × environment interactions for plant height.

For plant height, genotype means and stress selection indices across both planting environments are presented in Table 4. Regarding TOL, the superlative wheat genotypes with reduced and desirable TOL values were Pirsabak-2013, PR-123, and PR-124. About mean MP and ST, the most tolerant and better performing genotypes were Insaf, PR-122, and KT-2017. Concerning TSI, the upper limits were exhibited by most tolerant wheat genotypes i.e., Wadan-2017, PR-123, and PR-124. With TI, the maximum desirable values were shown by wheat genotypes Wadan 2017, Pirsabak-2015, and KT-2017.

Table 2. Mean squares for yield and yield contributing traits in wheat genotypes evaluated under normal (non-stressed) and late (stressed) sown conditions.

Variables	Mean squares				CV%
	Environments	Genotypes	G × E Interactions	Error	
Degree of freedom (d.f.)	1	35	35	140	-
Days to heading	35805.38**	26.29**	8.03*	5.29	2.13
Plant height	32144.56**	168.27**	34.44**	16.80	4.40
Flag leaf area	1666.67**	45.64**	22.50**	11.48	13.02
Tillers meter^2	1233671.19**	4887.09**	4719.24**	541.62	7.23
Biological yield	6848410949**	12028803**	8483705**	2650917	12.27
Grain yield	125795906**	780914.9**	359782.5**	123716.2	11.25
Harvest index	6900.91**	82.88**	52.58**	13.66	13.85

*, ** = Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively

Table 3. Mean performance and stress selection indices of wheat genotypes for days to heading evaluated under normal (non-stressed) and late (stressed) sown environments.

Genotypes	Days to heading (days)						
	Normal	Late	TOL	MP	STI	TSI	TI
PR-114	123	97	26.00	110.00	1.32	0.79	1.02
PR-118	123	97	26.00	110.00	1.32	0.79	1.02
PR-119	124	95	29.00	109.50	1.30	0.77	1.00
PR-122	121	94	27.00	107.50	1.26	0.78	0.99
PR-123	119	95	24.00	106.50	1.24	0.80	0.99
PR-124	116	93	23.33	104.67	1.20	0.80	0.98
Paseena-2017	123	96	27.00	109.00	1.29	0.78	1.00
Khaista-2017	121	93	27.17	106.92	1.24	0.77	0.98
Wadan-2017	123	95	28.00	109.00	1.29	0.77	1.00
Pakhtunkhwa-2015	121	94	27.33	107.67	1.26	0.77	0.99
Pirsabak-2015	121	93	27.50	106.75	1.24	0.77	0.98
Pirsabak-2013	121	94	27.50	107.25	1.25	0.77	0.98
Shahkar-2013	121	95	26.50	107.75	1.26	0.78	0.99
Pirsabak-2008	122	92	29.50	106.75	1.24	0.76	0.97
Pirsabak-2005	122	97	25.00	109.50	1.31	0.80	1.02
Insaf	123	97	26.00	110.00	1.32	0.79	1.02
NIFA-Aman	119	93	26.00	106.00	1.22	0.78	0.98
NIFA-Lalma	122	94	28.00	107.50	1.26	0.77	0.98
Borlaug-2016	124	99	25.00	111.00	1.35	0.80	1.04
Zincol-2016	122	93	28.50	107.25	1.25	0.77	0.98
Pakistan-2013	120	96	24.00	107.50	1.26	0.80	1.00
Ujala	122	97	25.00	109.50	1.31	0.80	1.02
Faisalabad-2008	118	97	21.00	107.00	1.25	0.82	1.01
Fateh Jhang	124	99	24.83	111.58	1.36	0.80	1.04
Ehsan	125	98	27.00	111.50	1.35	0.78	1.03
Johar-2016	117	96	21.00	106.00	1.23	0.82	1.00
Gold-2016	117	96	21.50	106.25	1.24	0.82	1.00
Ghaneemat-e-IBGE	115	94	21.83	104.42	1.19	0.81	0.98
KT-2000	124	99	25.00	111.00	1.35	0.80	1.04
KT-2017	124	98	26.33	110.83	1.34	0.79	1.03
Israr-2017	124	93	30.17	108.42	1.27	0.76	0.98
Shahid-2017	116	91	24.50	103.25	1.16	0.79	0.96
NARC-2011	117	93	24.00	105.00	1.20	0.79	0.98
Amin-2010	120	95	25.00	107.50	1.26	0.79	1.00
Dharabi-2011	124	97	27.17	110.08	1.32	0.78	1.01
Benazir	119	95	24.50	106.75	1.24	0.79	0.99
Means	121	95	25.75	107.97	1.27	0.78	1.00

TOL = Tolerance index, MP = Mean productivity, STI = Stress tolerance index, TSI = Trait stability index, TI = Trait index

Table 4. Mean performance and stress selection indices of wheat genotypes for plant height evaluated under normal (non-stressed) and late (stressed) sown environments.

Genotypes	Plant height (cm)						
	Normal	Late	TOL	MP	STI	TSI	TI
PR-114	104	78	25.94	90.87	1.23	0.75	0.96
PR-118	104	81	23.42	92.71	1.29	0.78	1.00
PR-119	103	81	22.60	91.87	1.27	0.78	0.99
PR-122	118	92	25.47	105.03	1.66	0.78	1.14
PR-123	101	85	16.17	93.28	1.32	0.84	1.05
PR-124	103	86	16.20	94.40	1.35	0.84	1.06
Paseena-2017	107	80	27.40	93.50	1.30	0.74	0.98
Khaista-2017	104	79	25.00	91.90	1.26	0.76	0.98
Wadan-2017	108	92	16.60	100.00	1.51	0.85	1.13
Pakhtunkhwa-2015	107	88	19.20	97.40	1.43	0.82	1.08
Pirsabak-2015	96	78	18.70	86.95	1.14	0.81	0.96
Pirsabak-2013	90	74	16.00	81.90	1.01	0.82	0.91
Shahkar-2013	101	73	28.20	86.60	1.11	0.72	0.89
Pirsabak-2008	94	67	26.80	80.30	0.95	0.71	0.83
Pirsabak-2005	105	88	17.07	96.47	1.41	0.84	1.09
Insaf	118	93	25.70	105.45	1.67	0.78	1.14
NIFA-Aman	107	87	19.40	97.00	1.42	0.82	1.08
NIFA-Lalma	108	83	24.70	95.35	1.36	0.77	1.02
Borlaug-2016	111	82	28.50	96.45	1.39	0.74	1.01
Zincol-2016	107	82	25.07	94.57	1.34	0.77	1.01
Pakistan-2013	107	82	25.10	94.85	1.35	0.77	1.02
Ujala	100	77	23.20	88.50	1.17	0.77	0.95
Faisalabad-2008	103	71	32.30	87.15	1.12	0.69	0.88
Fateh Jhang	102	82	19.90	91.55	1.26	0.80	1.01
Ehsan	107	77	30.10	92.25	1.26	0.72	0.95
Johar-2016	105	75	30.30	90.25	1.21	0.71	0.93
Gold-2016	100	78	22.00	89.30	1.20	0.78	0.97
Ghaneemat-e-IBGE	112	81	31.23	96.22	1.37	0.72	0.99
KT-2000	101	81	20.90	90.95	1.24	0.79	0.99
KT-2017	113	88	25.20	100.30	1.51	0.78	1.08
Israr-2017	108	75	33.10	91.35	1.23	0.69	0.92
Shahid-2017	110	84	26.10	96.85	1.40	0.76	1.03
NARC-2011	103	77	25.70	89.65	1.20	0.75	0.95
Amin-2010	109	80	29.70	94.35	1.32	0.73	0.98
Dharabi-2011	113	83	29.30	97.95	1.43	0.74	1.03
Benazir	107	80	27.10	93.65	1.31	0.75	0.99
Means	105	81	24.43	93.25	1.31	0.77	1.00

TOL = Tolerance index. MP = Mean productivity, STI = Stress tolerance index, TSI = Trait stability index, TI = Trait index

Flag leaf area: In wheat genotypes, the flag leaf area varied from 21 to 33 cm^2 while the interactions ranged from 17 to 35 cm^2 over early and late sowing conditions (Table 5). On average, wheat genotype Pirsabak-2015 showed maximum flag leaf area (33 cm^2) whereas the minimum value for said trait was recorded in wheat genotype Benazir (21 cm). For planting environment means, optimum sowing produced more flag leaf area (29 cm^2) as compared to stressed planting condition (23 cm^2) which indicated a 25% decline in leaf area with stressed conditions. In genotype by environment interaction means, maximum flag leaf area was recorded for wheat genotype PR-123 with early sowing (35 cm^2), while the minimum value for the said trait was recorded in wheat genotype Dharbi-2011 with late planting (17 cm^2). Over genotypes and genotype by environment interactions, the maximum flag leaf area was expressed by genotypes Pirsabak-2015, and PR-123, respectively.

Genotypes mean values and their stress selection indices for flag leaf area are provided in Table 5. In terms of TOL, the minimum and desirable values were observed for wheat genotypes i.e., Ghaneemat-e-IBGE, Pirsabak-2005, and Benazir. Similarly, the maximum favorable figures in terms of MP and STI were attained by wheat genotypes Pirsabak-2015, PR-123, and Pirsbak-2005. According to TSI, the most tolerant genotypes with increased values were Ghaneemat-e-IBGE, Pirsabak-2005, and Fateh Jhang. Likewise, in the case of TI, Pirsabak-2015 was appeared to be the top ranking genotype, followed by two other genotypes i.e., Pirsabak-2005, and Ghaneemat-e-IBGE.

Table 5. Mean performance and stress selection indices of wheat genotypes for flag leaf area evaluated under normal (non-stressed) and late (stressed) sown environments.

Genotypes	Flag leaf area (cm^2)						
	Normal	Late	TOL	MP	STI	TSI	TI
PR-114	29	21	8.35	24.73	1.10	0.71	0.88
PR-118	34	21	12.39	27.43	1.32	0.63	0.91
PR-119	28	22	5.81	25.00	1.14	0.79	0.95
PR-122	34	27	6.99	30.53	1.71	0.79	1.16
PR-123	35	29	6.42	31.81	1.86	0.82	1.23
PR-124	31	23	8.18	26.74	1.29	0.73	0.98
Paseena-2017	28	20	8.32	24.06	1.04	0.71	0.86
Khaista-2017	30	21	9.49	25.59	1.17	0.69	0.90
Wadan-2017	28	24	4.58	25.92	1.24	0.84	1.02
Pakhtunkhwa-2015	33	22	11.08	27.17	1.31	0.66	0.93
Pirsabak-2015	35	31	4.03	32.56	1.96	0.88	1.32
Pirsabak-2013	32	24	8.38	27.69	1.39	0.74	1.01
Shahkar-2013	27	21	5.19	24.08	1.06	0.81	0.93
Pirsabak-2008	27	23	3.92	25.04	1.16	0.85	0.99
Pirsabak-2005	28	29	-0.84	28.78	1.54	1.03	1.26
Insaf	27	23	3.57	24.72	1.13	0.87	0.99
NIFA-Aman	32	27	5.16	29.13	1.56	0.84	1.14
NIFA-Lalma	25	18	7.17	21.54	0.84	0.71	0.77
Borlaug-2016	28	26	1.33	26.94	1.34	0.95	1.13
Zincol-2016	25	21	3.99	22.72	0.95	0.84	0.89
Pakistan-2013	34	23	11.03	28.23	1.42	0.67	0.98
Ujala	23	20	3.45	21.53	0.85	0.85	0.85
Faisalabad-2008	28	26	2.07	26.76	1.33	0.93	1.11
Fateh Jhang	27	25	1.22	26.03	1.26	0.95	1.09
Ehsan	32	26	6.28	28.72	1.51	0.80	1.10
Johar-2016	28	21	6.90	24.40	1.08	0.75	0.90
Gold-2016	29	23	5.48	25.97	1.24	0.81	1.00
Ghaneemat-e-IBGE	23	29	-6.43	25.73	1.21	1.29	1.25
KT-2000	29	24	4.30	26.55	1.30	0.85	1.05
KT-2017	31	25	5.80	28.39	1.48	0.81	1.10
Israr-2017	26	21	5.66	23.51	1.01	0.79	0.89
Shahid-2017	31	23	7.79	26.83	1.31	0.75	0.99
NARC-2011	26	24	2.36	24.72	1.13	0.91	1.01
Amin-2010	25	19	5.60	21.84	0.87	0.77	0.82
Dharabi-2011	31	17	14.23	24.24	1.00	0.55	0.74
Benazir	21	20	1.08	20.61	0.79	0.95	0.86
Means	29	23	5.57	26.00	1.25	0.81	1.00

TOL = Tolerance index. MP = Mean productivity, STI = Stress tolerance index, TSI = Trait stability index, TI = Trait index

Tillers per square meter: For tillers per square meter, wheat genotypes varied from 259 to 374, while the interactions due to genotypes and planting environments ranged from 172 to 468 (Table 6). Across both test environments, the maximum tillers m^2 were shown by wheat genotype Ujala (374 tillers m^2) while minimum tillers were observed in wheat genotype Fateh Jhan (259 tillers m^2). Generally relating to both environments, wheat genotypes with normal planting produced more tillers (397 tillers m^2) and dominated the late plating environment (246 tillers m^2) by showing a decline of 19.4% in tillers m^2 under stressed conditions. Based on interactions due to genotypes and environments, the maximum tillers per square meter were exhibited by wheat genotype Ujala with early planting (468 tillers m^2), whereas the minimum number of tillers was accounted for wheat genotype Khaista-2017 with late planting (172 tillers m^2). As per genotype means and genotype by environment interactions, wheat genotype Ujala produced more tillers per square meter as compared to other genotypes and their interaction with both planting environments.

In the case of TOL, wheat genotype Pirsbak-2015 was prominent and marked with the lowest value, followed by two other genotypes i.e., Pakhtunkhwa-2015, and Pakistan-2013 (Table 6). Keeping in view the MP and STI, the most noteworthy wheat genotypes in terms of the highest values were Ujala, NIFA-Aman, and PR-124. In correspondence with TSI and TI, the highest and desirable values were recorded in wheat genotypes i.e., Pirsabak-2015, Pirsabak-2005, and Dharbi-2011.

Table 6. Mean performance and stress selection indices of wheat genotypes for tiller meter^{-2} evaluated under normal (non-stressed) and late (stressed) sown environments.

Genotypes	Tillers meter^{-2}						
	Normal	Late	TOL	MP	STI	TSI	TI
PR-114	398	193	205.00	295.83	1.27	0.49	0.79
PR-118	360	254	106.33	306.83	1.51	0.70	1.03
PR-119	405	217	187.67	310.83	1.45	0.54	0.88
PR-122	415	257	158.00	336.00	1.76	0.62	1.04
PR-123	408	290	118.00	349.00	1.95	0.71	1.18
PR-124	413	313	100.00	363.33	2.14	0.76	1.27
Paseena-2017	383	172	211.67	277.50	1.09	0.45	0.70
Khaista-2017	407	218	188.33	312.50	1.46	0.54	0.89
Wadan-2017	449	250	199.33	349.67	1.85	0.56	1.02
Pakhtunkhwa-2015	342	288	53.33	315.00	1.63	0.84	1.17
Pirsabak-2015	353	320	33.33	336.67	1.87	0.91	1.30
Pirsabak-2013	338	258	79.33	298.00	1.44	0.77	1.05
Shahkar-2013	392	183	208.33	287.50	1.18	0.47	0.74
Pirsabak-2008	387	275	111.67	330.83	1.75	0.71	1.12
Pirsabak-2005	397	315	81.67	355.83	2.06	0.79	1.28
Insaf	438	227	211.33	332.33	1.64	0.52	0.92
NIFA-Aman	457	290	166.67	373.33	2.18	0.64	1.18
NIFA-Lalma	412	272	140.67	342.00	1.85	0.66	1.10
Borlaug-2016	423	192	231.67	307.50	1.34	0.45	0.78
Zincol-2016	421	270	151.33	345.67	1.88	0.64	1.10
Pakistan-2013	348	273	75.00	310.83	1.57	0.78	1.11
Ujala	468	280	188.33	374.17	2.16	0.60	1.14
Faisalabad-2008	393	217	176.33	305.17	1.41	0.55	0.88
Fateh Jhang	310	207	102.67	258.67	1.06	0.67	0.84
Ehsan	439	242	196.67	340.67	1.76	0.55	0.98
Johar-2016	380	195	185.00	287.50	1.22	0.51	0.79
Gold-2016	410	247	163.00	328.50	1.67	0.60	1.00
Ghaneemat-e-IBGE	323	207	116.67	265.00	1.10	0.64	0.84
KT-2000	382	278	103.33	330.00	1.75	0.73	1.13
KT-2017	388	244	144.00	315.67	1.56	0.63	0.99
Israr-2017	418	285	133.33	351.67	1.97	0.68	1.16
Shahid-2017	465	217	248.33	340.83	1.66	0.47	0.88
NARC-2011	422	183	239.00	302.83	1.28	0.43	0.74
Amin-2010	428	213	215.00	320.83	1.51	0.50	0.87
Dharabi-2011	375	295	80.33	335.17	1.83	0.79	1.20
Benazir	357	225	131.67	290.83	1.32	0.63	0.91
Means	397	246	151.18	321.79	1.61	0.63	1.00

TOL = Tolerance index. MP = Mean productivity, STI = Stress tolerance index, TSI = Trait stability index, TI = Trait index

Biological yield: For biological yield, the genotype means varied from 11073 to 16229 kg ha^{-1}, while in genotype × environment interactions the values ranged from 4583 to 23500 kg ha^{-1} (Table 7). Across planting conditions, the maximum biological yield was measured for wheat genotype Israr-2017 (16229 kg ha^{-1}), while the minimum value for the said trait was obtained by wheat genotype NARC-2011 (11073 kg ha^{-1}). Overall, wheat genotypes with optimum planting time accounted for more biological yield (18902 kg ha^{-1}) as compared to late sowing (7640 kg ha^{-1}) and indicated a 30% decrease in biological yield due to a stressed environment. In terms of genotype-environment interactions, wheat genotype Pakistan-2013 with normal sowing showed the highest biological yield (23500 kg ha^{-1}), whereas minimum biological yield was determined by wheat genotype NARC-2011 with late sowing (4583 kg ha^{-1}). Regarding biological yield, the superior performance was shown by wheat genotype Pakistan-2013 and Israr-2017 across the genotypes and genotype × environment interactions under both planting environments.

For biological yield, genotype means and their stress selection indices across both environments are presented in Table 7. As per TOL, the superior wheat genotypes with minimum and favorable TOL values were Pirsabak-2015, PR-123, and PR-124. Based on MP and STI, the most tolerant and better performing genotypes were Israr-2017, Pakistan-2013, and NIFA-Lalma. According to TSI, the higher values were obtained by tolerant wheat genotypes i.e., PR-124, Pirsabak-2015, and PR-123. For TI, the maximum and desirable values were exhibited by wheat genotypes i.e., PR-124, Israr-2017, and NIFA-Aman.

Table 7. Mean performance and stress selection indices of wheat genotypes for biological yield evaluated under normal (non-stressed) and late (stressed) sown environments.

Genotypes	Biological Yield (kg ha^{-1})						
	Normal	Late	TOL	MP	STI	TSI	TI
PR-114	17917	5792	12125.00	11854.17	1.78	0.32	0.76
PR-118	23125	7958	15166.67	15541.67	3.15	0.34	1.04
PR-119	22292	7125	15166.67	14708.33	2.72	0.32	0.93
PR-122	18500	7917	10583.33	13208.33	2.51	0.43	1.04
PR-123	15445	9250	6195.00	12347.50	2.45	0.60	1.21
PR-124	17388	10938	6450.00	14162.50	3.26	0.63	1.43
Paseena-2017	18542	5313	13229.17	11927.08	1.69	0.29	0.70
Khaista-2017	18542	7583	10958.33	13062.50	2.41	0.41	0.99
Wadan-2017	20042	7667	12375.00	13854.17	2.63	0.38	1.00
Pakhtunkhwa-2015	17396	8542	8854.17	12968.75	2.55	0.49	1.12
Pirsabak-2015	15521	9417	6104.17	12468.75	2.50	0.61	1.23
Pirsabak-2013	16042	8667	7375.00	12354.17	2.38	0.54	1.13
Shahkar-2013	17813	5792	12020.83	11802.08	1.77	0.33	0.76
Pirsabak-2008	19688	8104	11583.33	13895.83	2.73	0.41	1.06
Pirsabak-2005	21625	9208	12416.67	15416.67	3.41	0.43	1.21
Insaf	19271	7646	11625.00	13458.33	2.52	0.40	1.00
NIFA-Aman	18708	9521	9187.50	14114.58	3.05	0.51	1.25
NIFA-Lalma	22479	8854	13625.00	15666.67	3.41	0.39	1.16
Borlaug-2016	18750	6271	12479.17	12510.42	2.01	0.33	0.82
Zincol-2016	20458	9063	11395.83	14760.42	3.18	0.44	1.19
Pakistan-2013	23500	7854	15645.83	15677.08	3.16	0.33	1.03
Ujala	20354	7354	13000.00	13854.17	2.56	0.36	0.96
Faisalabad-2008	19000	6854	12145.83	12927.08	2.23	0.36	0.90
Fateh Jhang	17083	6000	11083.33	11541.67	1.76	0.35	0.79
Ehsan	19333	6042	13291.67	12687.50	2.00	0.31	0.79
Johar-2016	16667	5688	10979.17	11177.08	1.62	0.34	0.74
Gold-2016	17083	5313	11770.83	11197.92	1.55	0.31	0.70
Ghaneemat-e-IBGE	16875	5958	10916.67	11416.67	1.72	0.35	0.78
KT-2000	16771	9333	7437.50	13052.08	2.68	0.56	1.22
KT-2017	20000	8542	11458.33	14270.83	2.93	0.43	1.12
Israr-2017	22083	10375	11708.33	16229.17	3.93	0.47	1.36
Shahid-2017	20646	8042	12604.17	14343.75	2.84	0.39	1.05
NARC-2011	17563	4583	12979.17	11072.92	1.38	0.26	0.60
Amin-2010	18646	8125	10520.83	13385.42	2.60	0.44	1.06
Dharabi-2011	16875	7438	9437.50	12156.25	2.15	0.44	0.97
Benazir	18438	6917	11520.83	12677.08	2.18	0.38	0.91
Means	18902	7640	11261.55	13270.82	2.48	0.41	1.00

TOL = Tolerance index. MP = Mean productivity, STI = Stress tolerance index, TSI = Trait stability index, TI = Trait index

Grain yield: Grain yield is a complex quantitative parameter managed by numerous yield contributing traits and also influenced by environmental conditions. Yield enhancement remains the main aim of every breeding program. In wheat genotypes, grain yield varied from 2469 to 3746 kg ha^{-1} over two planting environments, while genotype by environment interactions ranged from 1596 to 4767 kg ha^{-1} (Table 8). On average, wheat genotype Pakistan-2013 produced maximum grain yield (3746 kg ha^{-1}), whereas minimum grain yield was recorded in wheat genotype NARC-2011 (2469 kg ha^{-1}). For environment means, on average the genotypes with optimum sowing produced more grain yield (3888 kg ha^{-1}) than genotypes grown in a stressed environment (2362 kg ha^{-1}) with a net reduction of 1526 kg ha^{-1} with delayed sowing. In genotype by environment interaction, the highest grain yield was recorded in wheat genotype Israr-2017 with early sowing (4767 kg ha^{-1}), while minimum grain yield was obtained in wheat genotype Ghaneemat-e-IBGE with late sowing (1596 kg ha^{-1}). Overall, across the genotypes and genotype by environment interactions, the maximum grain yield was expressed by two genotypes Israr-2017, and Pakistan-2013.

Average grain yield and stress selection indices for various wheat genotypes are illustrated in Table 8. For TOL, the least and exceptional values were determined by wheat genotypes i.e., Pirsabak-2013, Pirsabak-2015, and Pakhtunkhwa-2015. Likewise, the highest and desirable values in terms of MP and STI were revealed by wheat genotypes Pakistan-2013, Zincol-2016, and PR-122. In the case of TSI, the most tolerant with an increased value of TSI was genotype Pirsabak-2013, followed by PR-122, and Pirsabak-2015. Similarly, in the case of TI, wheat genotype PR-122 was appeared to be a top ranking, followed by two other cultivars Zincol-2016, and Pakistan-2013.

Table 8. Mean performance and stress selection indices of wheat genotypes for grain yield evaluated under normal (non-stressed) and late (stressed) sown environments.

Genotypes	Grain yield (kg ha^{-1})						
	Normal	Late	TOL	MP	STI	TSI	TI
PR-114	4396	2064	2332.33	3229.67	1.63	0.47	0.87
PR-118	4329	2696	1633.33	3512.50	2.09	0.62	1.14
PR-119	4121	2179	1941.67	3150.00	1.61	0.53	0.92
PR-122	4183	3158	1025.00	3670.83	2.37	0.75	1.34
PR-123	4154	2525	1629.17	3339.58	1.88	0.61	1.07
PR-124	3604	2608	995.83	3106.25	1.68	0.72	1.10
Paseena-2017	4725	2213	2512.50	3468.75	1.87	0.47	0.94
Khaista-2017	3938	2700	1237.50	3318.75	1.91	0.69	1.14
Wadan-2017	3879	2450	1429.17	3164.58	1.70	0.63	1.04
Pakhtunkhwa-2015	3288	2333	954.17	2810.42	1.37	0.71	0.99
Pirsabak-2015	3417	2529	887.50	2972.92	1.55	0.74	1.07
Pirsabak-2013	3333	2825	508.33	3079.17	1.69	0.85	1.20
Shahkar-2013	3358	2419	939.50	2888.58	1.46	0.72	1.02
Pirsabak-2008	4650	2638	2012.50	3643.75	2.20	0.57	1.12
Pirsabak-2005	3708	2563	1145.83	3135.42	1.70	0.69	1.08
Insaf	3238	2142	1095.83	2689.58	1.24	0.66	0.91
NIFA-Aman	3563	2317	1245.83	2939.58	1.48	0.65	0.98
NIFA-Lalma	4733	2563	2170.83	3647.92	2.17	0.54	1.08
Borlaug-2016	4138	1967	2170.83	3052.08	1.46	0.48	0.83
Zincol-2016	4454	3029	1425.00	3741.67	2.42	0.68	1.28
Pakistan-2013	4554	2938	1616.67	3745.83	2.40	0.65	1.24
Ujala	3513	2504	1008.33	3008.33	1.58	0.71	1.06
Faisalabad-2008	3696	2154	1541.67	2925.00	1.43	0.58	0.91
Fateh Jhang	3763	1783	1979.17	2772.92	1.20	0.47	0.76
Ehsan	4217	2671	1545.83	3443.75	2.02	0.63	1.13
Johar-2016	3079	1988	1091.67	2533.33	1.10	0.65	0.84
Gold-2016	4263	2348	1914.17	3305.42	1.79	0.55	0.99
Ghaneemat-e-IBGE	3758	1596	2162.50	2677.08	1.08	0.42	0.68
KT-2000	3446	2178	1268.33	2811.67	1.34	0.63	0.92
KT-2017	4163	2717	1445.83	3439.58	2.03	0.65	1.15
Israr-2017	4767	2358	2409.00	3562.17	2.01	0.49	1.00
Shahid-2017	3283	2117	1166.67	2700.00	1.25	0.64	0.90
NARC-2011	3167	1771	1395.83	2468.75	1.01	0.56	0.75
Amin-2010	3863	2034	1828.83	2948.08	1.41	0.53	0.86
Dharabi-2011	3400	1825	1575.00	2612.50	1.11	0.54	0.77
Benazir	3842	2138	1704.17	2989.58	1.47	0.56	0.90
Means	3888	2362	1526.29	3125.17	1.66	0.61	1.00

TOL = Tolerance index. MP = Mean productivity, STI = Stress tolerance index, TSI = Trait stability index, TI = Trait index

Harvest index: Among wheat genotypes, the harvest index varied from 21.26 to 34.58% while for genotype × environment interactions the mean values ranged from 16.40 to 46.24 % (Table 9). Across both planting conditions, the maximum harvest index was calculated for wheat genotype Gold-2016 (34.58%) while the minimum for genotype NIFA-Aman (21.26%). Overall, the late-planted wheat genotypes indicated more harvest index (32.32%) as compared to normal planting conditions (21.02%). In terms of genotype-environment interactions, wheat genotype Shahkar-2013 showed maximum harvest index (46.24%) whereas minimum harvest index was observed for genotype Shahid-2017 (16.40%). Superior performance in terms of harvest index was shown by two wheat genotypes i.e., Shahkar-2013 and Gold-2016 over genotypes and genotype × environment interactions.

Following TOL, wheat genotype Shahkar-2013 was prominent and marked with the lowest and enviable value followed by two other genotypes Ehsan, and NARC-2011 (Table 9). Keeping in view MP and STI, the most noteworthy in terms of the highest values were unveiled by three wheat genotypes i.e., Gold-2016, Paseena-2017, and Ehsan. In the case of TSI and TI, the highest and desirable values were recorded for wheat genotypes i.e., Shahkar-2013, NARC-2011, and Gold-2016.

Correlation among morphological and yield traits: Days to heading revealed significant ($p \leq 0.05$) positive correlation with grain yield under normal planting, while non-significant positive under delayed planting condition (Table 10). Tillers per plant showed a significant negative correlation with harvest index under both planting conditions. Grain yield showed a significant ($p \leq 0.01$) positive association with tillers per square meter and biological yield under both planting conditions. Harvest index displayed a significant ($p \leq 0.01$) positive association with grain yield while simply positive with the said traits under late planting.

Table 9. Mean performance and stress selection indices of wheat genotypes for harvest index evaluated under normal (non-stressed) and late (stressed) sown environments.

Genotypes	Harvest index (%)						
	Normal	Late	TOL	MP	STI	TSI	TI
PR-114	24.39	35.80	-11.41	30.09	0.84	1.47	1.11
PR-118	22.43	35.04	-12.61	28.74	0.75	1.56	1.08
PR-119	23.51	31.78	-8.28	27.65	0.72	1.35	0.98
PR-122	24.51	40.35	-15.85	32.43	0.95	1.65	1.25
PR-123	21.67	27.97	-6.29	24.82	0.58	1.29	0.87
PR-124	20.70	23.93	-3.23	22.32	0.47	1.16	0.74
Paseena-2017	25.72	41.37	-15.65	33.55	1.02	1.61	1.28
Khaista-2017	20.17	36.54	-16.36	28.36	0.71	1.81	1.13
Wadan-2017	17.94	31.83	-13.88	24.88	0.55	1.77	0.98
Pakhtunkhwa-2015	18.77	28.70	-9.93	23.73	0.52	1.53	0.89
Pirsabak-2015	21.88	27.35	-5.47	24.62	0.57	1.25	0.85
Pirsabak-2013	20.78	32.53	-11.75	26.65	0.65	1.57	1.01
Shahkar-2013	18.75	46.24	-27.49	32.49	0.83	2.47	1.43
Pirsabak-2008	23.42	32.72	-9.30	28.07	0.73	1.40	1.01
Pirsabak-2005	17.07	27.88	-10.81	22.48	0.46	1.63	0.86
Insaf	16.70	28.28	-11.58	22.49	0.45	1.69	0.88
NIFA-Aman	18.22	24.29	-6.07	21.26	0.42	1.33	0.75
NIFA-Lalma	19.75	29.30	-9.55	24.53	0.55	1.48	0.91
Borlaug-2016	22.22	32.07	-9.86	27.14	0.68	1.44	0.99
Zincol-2016	25.28	33.56	-8.28	29.42	0.81	1.33	1.04
Pakistan-2013	23.65	38.64	-14.99	31.14	0.87	1.63	1.20
Ujala	17.99	34.15	-16.16	26.07	0.59	1.90	1.06
Faisalabad-2008	19.93	32.87	-12.94	26.40	0.63	1.65	1.02
Fateh Jhang	21.87	33.13	-11.26	27.50	0.69	1.51	1.03
Ehsan	21.97	44.00	-22.03	32.98	0.93	2.00	1.36
Johar-2016	18.31	36.50	-18.19	27.41	0.64	1.99	1.13
Gold-2016	24.93	44.22	-19.29	34.58	1.06	1.77	1.37
Ghaneemat-e-IBGE	22.51	27.77	-5.26	25.14	0.60	1.23	0.86
KT-2000	20.34	23.39	-3.05	21.86	0.46	1.15	0.72
KT-2017	20.49	33.88	-13.38	27.19	0.66	1.65	1.05
Israr-2017	22.04	22.63	-0.59	22.34	0.48	1.03	0.70
Shahid-2017	16.40	26.37	-9.97	21.39	0.41	1.61	0.82
NARC-2011	17.93	39.05	-21.13	28.49	0.67	2.18	1.21
Amin-2010	21.18	24.67	-3.49	22.92	0.50	1.16	0.76
Dharabi-2011	20.01	24.41	-4.40	22.21	0.47	1.22	0.76
Benazir	23.35	30.20	-6.86	26.77	0.68	1.29	0.93
Means	21.02	32.32	-11.30	26.67	0.66	1.55	1.00

TOL = Tolerance index. MP = Mean productivity, STI = Stress tolerance index, TSI = Trait stability index, TI = Trait index

Table 10. Correlation coefficient among yield components and grain yield in wheat genotypes evaluated under optimum - non-stressed (above diagonal) and late - stressed (below diagonal) sowing environments.

Traits	Days to heading	Plant height	Flag leaf area	Tillers meter^{-2}	Biological yield	Grain yield	Harvest index
Days to heading	-	0.085	0.060	0.008	0.3-33	0.357*	0.164
Plant height	0.089	-	-0.081	0.256	0.257	0-074	-0.089
Flag leaf area	0.017	0.190	-	-0.110	-0.129	-0.034	0.035
Tillers meter^{-2}	-0.192	0.252	0.217	-	0.279	0.024	-0.334*
Biological yield	-0.329	0.310	0.137	0.816**	-	0.515**	0.011
Grain yield	-0.217	0.121	0.080	0.492**	0.491**	-	0.713**
Harvest index	0.187	-0.284	-0.071	-0.499**	-0.692**	0.252	-

Discussion

Breeders are trying to develop the wheat genotypes adapted to a wide range of environments and such type of selection should be made based on stress selection indices for yield under test environments. The present studies were conducted on 36 bread wheat genotypes to exploit their genetic potential and heat tolerance under non-stress and stressed environments. Highly significant differences were recorded among wheat genotypes, environments, and genotype-by-environment interactions for all of the traits. Former investigations also revealed significant genetic diversity among the different wheat genotypes and genotype by environment interactions for various morphological and yield traits across different planting conditions (Ishaq *et al.*, 2018; Nofouzi, 2018; Habti *et al.*, 2020). The environmental effects were devastating as compared to genotypic possessions which enlighten that these variations resulted due to heat stress and moisture deficient conditions.

Formerly, highly significant variations were observed among the wheat genotypes, environments, and their interactions for yield traits (Poudel *et al.*, 2020; Tahir *et al.*, 2022). Apart from this, comparing the performance of early and late planting environments, the significant influence of wheat genotypes unveiled a substantial amount of divergence in the wheat genotypes which could be prevailed by using different breeding schemes. Conversely, some preceding findings showed a non-significant influence of wheat genotypes for yield related traits across normal and late planting environments (Schittenhelm *et al.*, 2020). Such ambiguity between findings might be due to the varied performance of wheat genotypes under diverse climatic conditions and disruption of plant mechanisms by heat stress under harsh environmental conditions.

In the current scenario, the normally planted wheat genotypes outclassed the delayed planted genotypes in all aspects which linked with the former studies in wheat under heat stress environments (Dwivedi *et al*., 2017; Poudel & Poudel 2020). Current studies suggested that late sown wheat genotypes reflected a considerable amount of decrease in mean values for yield attributing parameters and grain yield. Under stress conditions, due to high temperature and least growth period at the initial stage of the crop, force the crop plants to complete their life cycle soon by converting from vegetative to the reproductive phase which consequently results in less growth and shriveled grains (Jaiswal *et al*., 2018). With time the stability and heat tolerance of wheat genotypes adversely affected and changed under stressed environments due to insufficient availability of required inputs.

In present findings, the plant stature is greatly affected by heat stress due to reduced cell division and elongation processes. Severe environmental conditions decelerate the plant growth and development mechanisms and alter them accordingly to the stressed conditions (Singh *et al*., 2020). Under stressed conditions, the scarcity of moisture and plant competition for limited resources compels the wheat genotypes to produce smaller leaves, alternately reducing the tillers per plant and biological yield which indirectly and eventually affect the final grain yield (Ali *et al*., 2017). Besides this, the fluctuating day and night temperatures remarkably disturb wheat plant growth and yield that helps wheat plant in escaping heat stress and mature early by producing poor and shriveled grains (Mehraban *et al.*, 2018).

By studying the stress selection indices under both planting environments, it was concluded that early maturing wheat genotypes were best suited to heat stress under late planting conditions, while late maturing genotypes will be more appropriate under optimum planting conditions. Based on stress tolerance indices, the best and superior genotypes can be detected by using different groups and patterns of selection indices with the least moisture requirement and to suffer less grain yield (Amarshettiwar & Berad, 2018). Water deficient environments articulated that heat tolerance and stress tolerance indices could result in better conclusions than the trait stability index in spring wheat (Poudel *et al*., 2020). In present proceedings, wheat genotypes Pirsabak-2013 and Pakistan-2013 were found more stable and performed better across both stress and non-stress environments and could lead to utilizing as best genetic resources in heat tolerance breeding programs.

Existing outcomes were also in connotation with earlier verdicts that presented that practically using a different pattern and combination of stress selection indices are preferred for identifying superior wheat genotypes in terms of water limiting and heat stress environments (Habti *et al*., 2020). Past investigations exposed that grain yield being a complex character was found very sensitive to heat stress and considerably affected by abiotic stressed conditions and varying planting dates (Khairnar *et al*., 2018). The effectiveness of stress selection indices depends on the severity of stress and the most tolerant genotypes with the highest grain yield can be achieved in such severe environmental conditions (Khalil *et al*., 2017). The different stress indices like mean productivity (MP) and stress tolerance index (STI) were found to be more fruitful in discriminating drought-sensitive and heat stress tolerant wheat genotypes under stress conditions (Bhardwaj *et al*., 2018; Tahir *et al*., 2022).

Wheat grain yield exhibited a significant positive relationship with days to heading and yield contributing components. Previously, studies on wheat genotypes under different planting environments revealed that grain yield had a significant positive association with days to heading and yield-related traits (Hura, 2020). Present findings are also in close conformity with former investigations that revealed a significant positive association of grain yield with morphological traits (Khan & Hassan, 2017; Khan *et al*., 2018). Although, some previous studies also suggested that days to heading and tillers had a non-significant positive association with maturity, biological yield, and yield related traits (Van, 2020).

Conclusion

Significant variation among wheat genotypes confirmed that existing germplasm is of broader genetic background. A remarkable decline was noted in grain yield and its related traits with delayed planting as compared to normal planting. Wheat genotypes Pakistan-2013, Zincol-2016, and PR-122 performed best under non-stress and stressed planting environments. Stress selection indices were recognized as ample tools for the identification and selection of wheat genotypes with desirable yield performance under non-stress and stressed conditions. Based on stress tolerance indices like mean productivity, stress tolerance index, trait stability index, and yield index, the above promising wheat genotypes were found as heat stress-tolerant and can be used in future heat stress wheat breeding programs.

Acknowledgments

This work was supported by the Wheat Breeding Section, Cereal Crops Research Institute (CCRI), Pirsabak, Nowshera, Khyber Pakhtunkhwa, Pakistan. Authors also pay thanks to the Department of Plant Breeding and Genetics, University of Agriculture, Peshawar, Khyber Pakhtunkhwa, Pakistan for their support.

References

Ali, A., Z. Ullah, N. Ali and M.M. Anjum. 2017. Evaluation of wheat advanced lines for agronomic traits under vary sowing dates. *J. Agric. Res. Technol.*, 7(1): 1-12.

Amarshettiwar, S.B. and P.B. Berad. 2018. Biochemical and yield responses of wheat genotypes to normal and heat stress conditions. *J. Pharm. Phytochem.*, 7(1): 2663-2666.

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. Technol. Res*., 2(1): 1-5.

Bhardwaj, R.K., S.S. Gautam and R.R. Saxena. 2018. Adaptation of G x E interaction of wheat genotypes in Chhattisgarh State through regression analysis. *Int. J. Curr. Microbiol. Appl. Sci.*, 7: 4598-4604.

Bouslama, M. and W.T. Schapaugh. 1984. Stress tolerance in soybean. Part 1: Evaluation of three screening techniques for heat and drought tolerance. *Crop Sci*., 24: 933-937.

Dwivedi, R., S. Prasad, B. Jaiswal, A. Kumar, A. Tiwari, S. Patel, S. Pandey and G. Pandey. 2017. Evaluation of wheat genotypes (*T. aestivum* L.) at grain filling stage for heat tolerance. *Int. J. Pure Appl. Biosci*., 5(2): 971-97.

Fernandez, G.C.J. 1992. Effective selection criteria for assessing plant stress tolerance. In Proceedings of the international symposium on the adaptation of vegetable and other food crops in temperature and water stress. AVRDC Publication, Taiwan. 257-270.

Francis, C.A., J.N. Rutger and A.F.E. Palmer. 1969. A rapid method for plant leaf area estimation in maize. *Crop Sci*., 9: 537-539.

Gavuzzi, P., F. Rizza, M. Palumbo, R.G. Campaline, 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.

Gomez, K.A. and A.A. Gomez. 1984. Statistical procedures for Agricultural Research (pp: 20-30). John Wiley and Sons Inc. Canada.

Habti, A.E., D. Fleury, N. Jewell, T. Garnett and P.J. Tricker. 2020. Tolerance of combined drought and heat stress is associated with transpiration and water soluble carbohydrates in wheat grains. *Front. Plant Sci*., 11: 568-693.

Hossain, A.B.S., A.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.

Hura, T. 2020. Wheat and Barley: Acclimatization to abiotic and biotic stress. *Int. J. Mol. Sci*., 21(7423): doi:10.3390/ ijms21197423.

Ishaq, M., G. Ahmad, K. Afridi, M. Ali, T.U. Khan, I.A. Shah, M. Khalid, N. Ahmad, B. Iqbal, B. Ahmad, M.A. Qureshi, A. Saleem, M. Miraj and K. Din. 2018. Assessment of genetic potential and stress selection indices for important yield related traits in bread wheat (*T. aestivum* L.). *Pure Appl. Biol*., 35(5): 22-38.

Jaiswal, B., S. Prasad, R. Rani, S. Singh, A. Kumar, A. Kumar and R.K. Yadav. 2018. Evaluation of wheat (*T. aestivum* L.) lines at reproductive stage for heat stress tolerance. *Int. J. Curr. Microbiol. Appl. Sci*., 7: 1350-1357.

Janni, M., M. Gullì, E. Maestri, M. Marmiroli, B. Valliyodan, H.T. Nguyen and N. Marmiroli. 2020. Molecular and genetic bases of heat stress responses in crop plants and breeding for increased resilience and productivity. *J. Exp. Bot*., 71(13): 3780-3802.

Khairnar, S.S., J.H. Bagwan, K.J.Y. 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(1): 190-198.

Khalil, I.H., A. Wahab, D. Nayab, S.S. Ghani, M. Alam, H. Ullah and W.U. Khan. 2017. Heritability and selection response for morphological and yield traits in normal and late planted wheat. *Int. J. Agric. Environ. Res*., (2): 202-211.

Khan, A., I. Khaliq, M. Ahmad, H.G.M. Ahmed, A.G. Khan and M.S. Farooq. 2018. Comparative performance of spring wheat (*T. aestivum* L.) through heat stress indices. *Pak. J. Bot*., 50(2): 481-488.

Khan, S.A. and G. Hassan. 2017. Heritability and correlation studies of yield and yield related traits in bread wheat. *Sarhad J. Agric*., 33(1): 103-107.

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.

Mehraban, A., A. Tobe, A. Gholipouri, E. Amiri, A. Ghafari and M. Rostaii. 2018. Evaluation of drought tolerance indices and yield stability of wheat cultivars to drought stress in different growth stages. *World J. Environ. Biosci*., 7(1): 8-14.

Nofouzi, F. 2018. Evaluation of seed yield of durum wheat (*T. durum* L.) under drought stress and determining correlation among some yield components using path coefficient analysis. *UNED Res. J*., 10(1): 179-183.

Poudel M.R., S. Ghimire1, M.P. Pandey, K.H. Dhakal, D.B. Thapa and H.K. Poudel. 2020. Evaluation of wheat genotypes under irrigated, heat stress and drought conditions. *J. Biol. Today's World*, 9(1): 212: 1-12.

Poudel, P.B. and M.R. Poudel. 2020. Heat stress effects and tolerance in wheat: A Review. *J. Biol. Today's World*, 9(4): 217: 1-6.

Schittenhelm, S., T.L. Wedde, M. Kraft, L. Kottmann and K. Matschiner. 2020. Effect of two-week heat stress during grain filling on stem reserves, senescence, and grain yield of European winter wheat cultivars. *J. Agron. Crop Sci*., 206: 722-733.

Schmidt, J., J. Claussen, N. Wörlein, A. Eggert, D. Fleury, T. Garnett and S. Gerth. 2020. Drought and heat stress tolerance screening in wheat using computed tomography. *Plant Methods*, 16(15). https://doi.org/10.1186/s13007-020-00565-w.

Singh, P.K., S. Prasad, A.K. Verma, B. Lal, R. Singh, S.P. Singh and D.K. Dwivedi. 2020. Screening for heat tolerant traits in wheat (*T. aestivum* L.) genotypes by physio-biochemical markers. *Int. J. Curr. Microbiol. Appl. Sci*., 9(2): 2335-2343.

Tahir, I., N.U. Khan, S. Gul, S. Ahmed, Y. Andleeb, A. Habib, S. Ali, S.A. Khan, N. Ali and I. Hussain. 2022. Late planting induced heat stress tolerance in wheat. *Pak. J. Bot*., 54(3): DOI: http://dx.doi.org/10.30848/PJB2022-3(17):

Van, S.W.E. 2020. Too hot to handle, the adverse effect of heat stress on crop yield. *Int. J. Plant Biol*., 169(4): 499-500.

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.

(Received for publication 22 November 2020)