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WHEAT STABILITY ASSESSMENT FOR LATE-PLANTING HEAT STRESS USING STRESS SELECTION INDICES, PRINCIPAL COMPONENT, AND BIPLOT ANALYSES

Z. Ahmad[1], N.U. Khan[1,*], S. Gul[2], S.U. Khan[3], S. Ahmed[1], S. Ali[4], N. Ali[4], S.A. Khan[4], M. Amin[4], A. Iqbal[5], W. Ali[6], K. Din[1] and A. Khan[1]

[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]Institute of Biotechnology and Genetic Engineering, University of Agriculture, Peshawar, Pakistan
[4]Department of Plant Breeding and Genetics, University of Haripur, Haripur, Pakistan
[5]Department of Plant Breeding and Genetics, Lasbela University of Agriculture, Water and Marine Sciences (LUAWMS), Uthal, Balochistan, Pakistan
[6]Department of Soil and Environmental Science, University of Agriculture, Peshawar, Pakistan
*Corresponding author's email: nukmarwat@yahoo.com; nukmarwat@aup.edu.pk

ABSTRACT

Wheat grain yield decreases by 1.50% per day with a subsequent delay in optimum sowing and the crop becomes vulnerable to numerous abiotic and biotic stresses. However, climate change had apparent effects on the environment and created an alarming scenario for wheat breeders to tackle the problem in different ways. The present research is aimed to identify the stable wheat genotypes through stress selection indices, principal component, and biplot analyses under genotype by environment interaction with non-stress and stress environments. Thirty-six wheat genotypes were appraised through genotype by environment interactions under optimum (non-stressed) and late (stressed) planting environments during 2017-18 at the Cereal Crops Research Institute (CCRI), Pirsabak - Nowshera, Pakistan. The experiment was laid out in a randomized complete block design with three replications. In addition to stress selection indices, the principal component and biplot analyses were also used to assess the performance and stability of the wheat genotypes under non-stress and stress environments. Genotypes, planting environments, and genotype-by-environment interactions (GEI) revealed significant differences for the majority of the traits. Across both planting environments, cultivar Pakistan-13 produced the highest grain yield, followed by genotypes Zincol-16 and PR-122. Under optimum planting environment, the best performing cultivar was Israr-17, followed by two other genotypes NIFA-Lalma-13 and Paseena-17. However, genotypes PR-122, Zincol-16, and Pakistan-13 produced higher grain yields under the stressed environment. According to stress selection indices, principal component, and biplot analyses, wheat cultivars Pirsabak-13, Zincol-16, and PR-122 were found as the most tolerant and high-yielding genotypes and could be used as source material for the development of stress-tolerant genotypes.

Keywords: *Triticum aestivum* L.; genetic diversity; optimum and late planting environments; genotype by environment interaction; stress selection indices; principal component and biplot analyses

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INTRODUCTION

Wheat (*Triticum aestivum* L.) is the principal cereal crop of the world and the most commonly cultivated crop species of the family *Poaceae* (*Gramineae*). It is also known as the 'King of Cereals' because of the acreage it occupies, its high productivity, and the prominent position it holds globally in the grain trade (Bhanu *et al*., 2018; Ahmad *et al*., 2022). Among edible crop species, wheat is a staple food to over 36% of the global community and ranks second after rice, but still, the demand is increasing day by day due to the ever-increasing human population and its significant use in a variety of food products (Khalil *et al*., 2016; Afridi *et al*., 2017, 2018). In wheat production, the biotic and abiotic stresses, planting time and methods, varietal potential, and poor agronomic management practices are important limiting factors that greatly affect the yield (Hossain *et al*., 2021; Tahir *et al*., 2022). However, among abiotic stresses, the heat stress created due to late planting causes serious threats to wheat production globally (Khan and Kabir, 2015; Khazratkulova *et al*., 2015).

Wheat planting becomes delayed due to insufficient moisture and drought at sowing time, late harvesting of basmati rice, and varied time of precipitation. Late planting heat stress is a particular problem owing to its pronounced spatial and temporal variations leading to a decline in plant growth and productivity in wheat (Ishaq *et al*., 2018). Late planting heat stress that occurred during the flowering period is known to affect the grain formation and its filling proficiency in wheat (Rajala *et al*., 2009). For wheat anthesis and grain filling, the optimum temperature ranges from 12 to 22°C. However, during floret formation, the high temperatures (>30°C) may cause complete sterility which can significantly reduce grain yield in wheat (Tewolde *et al*., 2006; Rehman *et al*., 2021). Even though high temperatures hasten the growth, but also reduce the phenology, which cannot be remunerated by the increased growth rate in wheat (Poudel and Poudel, 2020).

Global warming may further intensify the heat stress problem in the future. Therefore, efforts should be made to lessen the reduction in grain yield that occurred due to late planting by screening and developing high-temperature stress tolerant wheat genotypes and also by remodeling agronomic approaches (soil, water, and crop management practices) to minimize the heat stress effects (Bhanu *et al*., 2018; Rahman *et al*., 2018). To overcome this challenge, the plant breeders use a common technique of selecting heat-tolerant wheat genotypes by planting the breeding material in a hot targeted environment (Poudel *et al*., 2020). Therefore, for successful wheat production, the wheat breeders must identify and develop high-yielding and climatic resilient cultivars under variable environmental conditions to meet the increasing demand for food (Khan *et al*., 2018). Some studies reported that bold seed size can provide better stand establishment and vigorous germination to significantly improve wheat production under late sown conditions (Muhsin *et al*., 2021). Hence, it is necessary for promising advanced lines of wheat to be tested under both optimum and late planting (heat stressed) environments. In Pakistan, an area of 9.178 million hectares was engaged by wheat crop which produced 27.293 million tons of wheat with an average grain yield of 2974 kg ha^{-1} (Pakistan Eco. Survey, 2020-2021).

Despite the availability of numerous selection methods, index selection is one of the fundamental methods for the genetic improvement of quantitative traits in crop plants. The theory of selection indices to improve genetic values of the traits was introduced as the Smith-Hazel index (SHI) in crop plants (Smith, 1936; Hazel, 1943), and has been demonstrated to be a more reliable tool in terms of maximizing genetic gain in crop populations (Ghaed-Rahimi *et al*., 2017). With some modifications, various stress selection indices have been used for assessing the mean performance of wheat genotypes and to identify the stress-tolerant cultivars under non-stressed (optimum planting) and stressed (late planting) environments (Fernandez, 1992; Gavuzzi *et al*., 1997; Lepekhov and Khlebova, 2018). The stress selection indices i.e., tolerance index (TOL), mean productivity (MP), stress tolerance index (STI), trait stability index (TSI), and trait index (TI) have been employed in bread wheat under various environmental conditions (Raiyani *et al*., 2015).

The basic factor in determining the final grain yield is the interaction of the genotype with prevailing environmental conditions. The genotype by environment interaction plays an important role in the expression of quantitative characters in bread wheat that are controlled by a polygenic system (Rehman *et al*., 2021). These quantitative traits are also greatly modified by environmental influences. Thus, it is necessary to have impartial estimates of various genetic components, and the wheat breeding material should be evaluated over different environmental conditions (Siddhi *et al*., 2018). Most of the time the plant breeder is interested in the yield of the crop which is the end product of the genotypes, environments, and their interaction resulting in stability and adaptability of the bread wheat genotypes (Khan and Mohammad, 2018). If a significant genotype by environment interaction exists, the preference will be changed for different planting environments. Thus, the stability of the yield over various planting environments is a key factor.

The main task of the breeder is the exploration and identification of the promising wheat genotypes that perform well under diverse climatic conditions, especially late planting in a stressed environment and the genotypes subjected to other abiotic stresses (Mohammadi *et al*., 2012; Iqbal *et al*., 2017; Kaur *et al*., 2017). In this context, the objectives of the present study were to; a) determine the performance of wheat genotypes under genotype by environment interaction, and b) identify the superior wheat genotypes through stress selection indices, principal component, and biplot analyses under non-stressed and stress environments.

MATERIALS AND METHODS

Plant Material, Experimental Design, and Procedure: The experimental material comprised 36 wheat genotypes (including six advanced wheat lines procured from Cereal Crops Research Institute (CCRI), Pirsabak - Nowshera, Pakistan, and 30 cultivars collected from different provinces of Pakistan (Table 1). The experiment was designed according to randomized complete block design (RCBD) with three replications, having six rows per genotype. The row length of each experimental unit was kept at six meters with a row spacing of 30 cm. Optimum planting was done on November 09, 2017; whereas the late planting was made on December 18, 2017, with an interval of 40 days. The seed rate of 110 kg ha^{-1} was used in both early and late seedings.

Crop Husbandry: Before planting, the field was well irrigated to create conditions conducive for seedbed preparation. The field was ploughed with a deep plough and then harrowed with planking each time to make the soil loose, fine, leveled, and pulverized. The fertilizers were applied at the rate of 120:90:60 NPK kg ha^{-1}, respectively. All the fertilizers i.e., P_2O_5, K_2O, and half N were applied at planting time while the remaining half N was applied in two split doses with first and second irrigations. Overall, four irrigations were applied to the crop till maturity. The broad and narrow-leaved weeds were controlled with herbicides i.e., Buctril Super (Bromoxynil) (750 mL ha^{-1}) and Puma Super (Fenoxaprop-P-ethyl 69 g) (1250 mL ha^{-1}), respectively. Both herbicides were applied after the first irrigation at the three-leaf stage of the weeds, however, broad-leaf sprayed earlier than narrow-leaf herbicides. For early sown crop, the herbicides were used earlier compared to late sowing. However, the leftover weed plants were removed manually in the early and late sown crops.

Table 1. Wheat advance lines and cultivars used in the study.

S.No.	Advanced lines	Year of release	Institution	S.No.	Cultivars	Year of release	Institution
1	PR-114	Adv. line	CCRI, Pak.	19	Borlaug-16	2016	NARC, Islamabad, Pak.
2	PR-118	-do-	-do-	20	Zincol-16	2016	-do-
3	PR-119	-do-	-do-	21	Pakistan-13	2013	-do-
4	PR-122	-do-	-do-	22	Ujala-16	2016	AARI, Faisalabad, Pak.
5	PR-123	-do-	-do-	23	Faisalabad-08	2008	-do-
6	PR-124	-do-	-do-	24	Fateh Jhang-16	2016	BARI, Chakwal, Pak.
	Cultivars			25	Ehsan-16	2016	AARI, Faisalabad, Pak.
7	Paseena-17	2017	-do-	26	Johar-16	2016	-do-
8	Khaista-17	2017	-do-	27	Gold-16	2016	-do-
9	Wadan-17	2017	-do-	28	Ghanimat-e-IBGE	2015	AUP, Peshawar, Pak.
10	Pakhtunkhwa-15	2015	-do-	29	Kohat-2000	2000	BARS, Kohat, Pakistan
11	Pirsabak-15	2015	-do-	30	Kohat-17	2017	-do-
12	Pirsabak-13	2013	-do-	31	Israr-17	2017	ARI, D.I.Khan, Pak.
13	Shahkar-13	2013	-do-	32	Shahid-17	2017	-do-
14	Pisabak-08	2008	-do-	33	NARC-11	2011	NARC, Islamabad, Pak.
15	Pirsabak-05	2005	-do-	34	Amin-10	2010	ARS, Serai Naurang, Pak.
16	NIFA-Insaf-15	2015	NIFA, Pak.	35	Dharabi-11	2011	BARI, Chakwal, Pak.
17	NIFA-Aman-17	2017	-do-	36	Benazir-13	2013	ARI, Tandojam, Pak.
18	NIFA-Lalma-13	2013	-do-	-	-	-	-

Data Recorded: For recording the data on traits i.e., days to physiological maturity, spike length, spikelets per spike, grains per spike, and 1000-grain weight, 20 randomly selected plants were used and harvested on a single plant basis and threshed separately for each genotype in all the replications. All the individual plants were threshed with a single plant thresher. For grain yield, the whole plot of each genotype in each replication was harvested, threshed, weighed, and then converted to grain yield per hectare.

Biometrical Analyses: All the collected data were subjected to analysis of variance (ANOVA) appropriate for genotype by environment interaction (Gomez and Gomez, 1984; Yang *et al*., 2006; Yang, 2007). After getting the significant variation among the genotypes, planting environments, and genotype by environment interactions (GEI) for various parameters, the means for each category and parameter were further separated and compared by using the least significant difference (LSD) test at a 5% level of probability (Fisher, 1935).

Stress Selection Indices: Various stress selection indices i.e., tolerance index (TOL), mean productivity (MP) (Lepekhov and 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 (Fernandez, 1992; Gavuzzi *et al*., 1997). The 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. The 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. The trait index (TI) is based on the yield of wheat genotype to the mean yield of all the genotypes under stressed conditions and it ranks the wheat genotypes based on mean performance under a stressed planting environment. According to Fernandez (1992), crop genotypes can be divided into four groups based on their yield response to stressed conditions i.e., a) genotypes producing high yield under both non-stressed and water-stressed conditions, b) genotypes with high yield under non-stressed conditions, c) genotypes with high yield under a stressed condition, d) genotypes with poor performance under both non-stressed and stressed conditions. Apart from that, the optimum and late planting environments were assumed as non-stressed and stressed environments to work out the following stress selection indices.

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

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

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

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

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

Where;

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

Y_s = Genotype means for that trait within late planting

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

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

Correlation Analysis: The analysis of the correlation coefficient for yield and its associated traits was carried out separately under optimum/non-stressed and late/stressed planting environments (Kwon and Torrie, 1964).

Principal Component and Biplot Analyses: Data obtained for various selection indices were standardized before subjecting to principal component and biplot analyses to reduce wide ranges and better visualization of the genotypes. All the statistical procedures including correlation analysis among grain yield and stress selection indices, dendrogram tree, principal component analysis, and 2D and 3D biplot analyses were performed using MINITAB ver. 16, STATISTICA ver. 10 and GEN STAT ver. 12.

RESULTS

A combined analysis of variance across planting environments (Non-stressed and Stressed) revealed significant (p≤0.01) variations among the wheat genotypes for all the traits except spike length (Table 2). However, the planting environments showed significant (p≤0.01) differences for almost all the traits except days to physiological maturity. The differences due to genotype by environment interactions were significant (p≤0.01) for grains per spike, 1000-grain weight, and grain yield, while nonsignificant for other traits. Genotype by environment interaction is of prime importance for plant breeders in developing cultivars that are adaptable to a wide range of planting environments. However, the G × E interaction with non-significant values for some traits showed stability of the wheat genotypes across both planting environments. Therefore, for the analysis of impartial estimates of various genetic components under diverse planting environments, the breeding material should be evaluated over different planting environments.

Genetic Diversity and Stability among Genotypes

Days to Physiological Maturity: In wheat genotypes, mean days to physiological maturity varied from 143 to 150 while in genotype × environment interactions the range was 130 to 164 days across two planting environments (Table 3).

Table 2. Mean squares of yield and yield contributing traits in wheat genotypes evaluated under optimum (non-stress) and late (stressed) planting environments.

Variables	Mean Squares				CV%
	Genotypes	Environments	G × E Interactions	Error	
d.f.	35	1	35	140	-
Days to maturity	36712.30**	15.13^{NS}	4.81^{NS}	5.27	1.56
Spike length	02.61^{NS}	195.87**	0.61^{NS}	2.08	13.74
Spikelets spike^{-1}	04.58**	506.00**	2.52^{NS}	2.69	9.13
Grains spike^{-1}	81.41**	4257.78**	47.10**	23.77	11.80
1000-grain weight	3382.48**	70.67**	22.15**	11.96	10.03
Grain yield	780914.9**	125795906**	359782.5**	123716.2	11.25

*, ** = Significant at p≤0.05 and p≤0.01, respectively, NS = Non-Significant

Overall, the genotypes with optimum planting took more days to physiological maturity (160 days) than late planting (134 days), and showed a net difference of 26 days. On average across both environments, minimum days to physiological maturity were observed for wheat genotype NARC-11 (143 days), followed by Johar-16 (144 days), and Ghanimat-e-IBGE-15, Shahid-17, NIFA-Aman-17, and PR-123 with same days to physiological maturity (145 days). However, the maximum days to maturity were recorded for wheat genotype Gold-16 (150 days) followed by Khaista-17, NIFA-Insaf-15, Borlaug-16, NIFA-Lalma-13, and Pakistan-13 ranging from 149 to 148 days. In genotype × environment interaction effects, the minimum days to maturity were taken by wheat genotype NARC-11 (130 days), followed by Pirsabak-08 (131 days), and Johar-16, PR-123, Shahid-17, and Ghanimat-e-IBGE-15 with same days to physiological maturity (132 days) under late planting condition. However, the maximum days to maturity were taken by wheat genotype Gold-16 (164 days), followed by genotypes PR-122, Khaista-17, Israr-17, PR-118, NIFA-Lalma-13, and Borlaug-16 ranging from 163 to 162 days with optimum planting conditions. Based on genotype means, and G × E interactions, the genotype NARC-11 took minimum days to physiological maturity in both environments.

Table 3. Mean performance and stress selection indices of wheat genotypes for days to physiological maturity evaluated under optimum (non-stress) and late (stressed) planting environments.

Genotypes	Days to physiological maturity (days)							
	Optimum	Late	Means	TOL	MP	STI	TSI	TI
Advanced lines								
PR-114	160	135	148	25.00	147.50	1.20	0.84	1.01
PR-118	163	134	148	29.00	148.00	1.21	0.82	1.00
PR-119	161	136	148	25.17	148.08	1.21	0.84	1.01
PR-122	163	134	148	28.83	148.42	1.22	0.82	1.00
PR-123	159	132	145	27.33	145.17	1.16	0.83	0.98
PR-124	160	134	147	26.83	146.92	1.19	0.83	1.00
Cultivars								
Paseena-17	159	134	146	25.17	146.08	1.18	0.84	1.00
Khaista-17	163	136	149	27.33	149.17	1.23	0.83	1.01
Wadan-17	160	135	147	25.50	147.25	1.20	0.84	1.00
Pakhtunkhwa-15	159	133	146	26.83	145.92	1.18	0.83	0.99
Pirsabak-15	159	132	146	27.00	145.50	1.17	0.83	0.99
Pirsabak-13	161	133	147	27.50	146.75	1.19	0.83	0.99
Shahkar-13	158	135	146	23.50	146.25	1.19	0.85	1.00
Pirsabak-08	160	131	145	28.17	145.42	1.17	0.82	0.98
Pirsabak-05	159	134	146	24.50	146.25	1.18	0.85	1.00
NIFA-Insaf-15	161	138	149	23.50	149.25	1.23	0.85	1.03
NIFA-Aman-17	158	132	145	25.83	144.92	1.16	0.84	0.99
NIFA-Lalma-13	163	135	149	28.17	148.58	1.22	0.83	1.00
Borlaug-16	162	136	149	25.50	148.75	1.22	0.84	1.02
Zincol-16	160	134	147	26.83	146.92	1.19	0.83	1.00
Pakistan-13	161	136	148	25.67	148.33	1.22	0.84	1.01
Ujala-16	161	135	148	25.83	147.92	1.21	0.84	1.01
Faisalabad-08	157	135	146	22.00	146.00	1.18	0.86	1.01
Fateh Jhang-16	160	137	148	23.50	148.25	1.22	0.85	1.02
Ehsan-16	161	135	148	26.00	147.50	1.20	0.84	1.00
Johar-16	157	132	144	25.17	144.08	1.15	0.84	0.98
Gold-16	164	136	150	27.67	149.83	1.24	0.83	1.02
Ghanimat-e-IBGE-15	157	132	145	25.00	144.50	1.16	0.84	0.99
Kohat-2000	161	135	148	25.17	147.92	1.21	0.84	1.01
Kohat-17	162	134	148	27.83	147.75	1.21	0.83	1.00
Israr-17	163	133	148	29.83	147.92	1.21	0.82	0.99
Shahid-17	158	132	145	25.50	144.75	1.16	0.84	0.99
NARC-11	157	130	143	26.33	143.33	1.14	0.83	0.97
Amin-10	159	136	147	23.50	147.25	1.20	0.85	1.01
Dharabi-11	162	135	148	27.33	148.17	1.21	0.83	1.00
Benazir-13	158	133	146	25.33	145.67	1.17	0.84	0.99
Means	160	134	-	26.09	146.95	1.20	0.84	1.00

$LSD_{0.05}$ Environments: 0.62

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

Data on genotypes means and stress selection indices for days to physiological maturity revealed that according to the tolerance index the most tolerant cultivars with minimum and desirable TI values were Faisalabad-08, NIFA-Insaf-15, and Shahkar-13 (Table 3). Similarly, the top-ranking genotypes in terms of mean productivity and stress tolerance index were reported as Gold-16, NIFA-Insaf-15, and Khaista-17. Likewise, genotypes with greater estimates of trait stability index were cultivar Faisalabad-08 followed by two other genotypes i.e., NIFA-Insaf-15 and Shahkar-13. Trait index grouped most tolerant genotypes likewise cultivar NIFA-Insaf-15 followed by Borlaug-16 and Faisalabad-08.

Spike Length: Averaged over both planting environments, the genotype means varied from 8.98 to 11.63 cm while in genotype × environment interactions the said range was 8.24 to 12.49 cm for spike length (Table 4). Overall, the genotypes produced more spike length with optimum planting (11.45 cm) than late planting (9.54 cm) and showed a net difference of 1.91 cm between both environments. Average across both environments, the spikes with maximum length were observed in wheat genotype Gold-16 (11.63 cm), followed by PR-122 (11.60 cm), Pakhtunkhwa-15 (11.55 cm), Ghanimat-e-IBGE-15 (11.47 cm), Kohat (11.31 cm), and Ehsan-16 (11.18 cm). However, minimum spike length was indicated by wheat genotype Ujala-16 (8.98 cm), followed by Pirsabak-08, PR-114, Faisalabad-08, Israr-17, and Fateh Jhang-16 ranging from 9.35 to 9.86 cm. In terms of genotype × environment interactions, the maximum spike length was also observed in wheat genotype Gold-16 (12.49 cm), followed by Dharbi-2011 (12.47 cm), Pirsabak-05 (12.39 cm), Kohat-17 (12.30 cm), NIFA-Lalma-13 (12.21 cm), and Ghanimat-e-IBGE-15 (12.18 cm) with optimum planting environment. However, the minimum value for spike length was displayed by wheat genotype Pirsabak-08 (8.24 cm), followed by five other genotypes i.e., Ujala-16, PR-114, Zincol-16, Pirsabak-05, and PR-118 ranging from 8.30 to 8.87 cm with stressed planting conditions. Based on genotype and G × E interaction means, the wheat genotype Gold-16 showed maximum spike length across both environments.

Based on stress selection indices, for spike length, the superior wheat genotypes for mean productivity (MP) and stress tolerance index (STI) were Gold-16, PR-122, and Pakhtunkhwa-15 (Table 4). The negative values (as most desirable) of TOL were displayed by wheat genotypes Pakistan-13, PR-122, and Ehsan-16. The top-ranking and most tolerant genotypes based on the trait stability index were Pakhtunkhwa-15, PR-122, and NIFA-Insaf-15.

Spikelets per Spike: Across two planting environments, the genotype means ranged from 16.05 to 19.30 while for genotype × environment interactions the means were ranging from 13.30 to 22.10 for spikelets per spike (Table 5). On average, the genotypes produced more spikelets spike^{-1} with optimum planting (19.51) than late planting (16.44) and showed a net difference of 3.07 spikelets per spike. In genotypes across both planting environments, the maximum spikelets per spike were exhibited by wheat genotype NIFA-Lalma-13 (19.30), followed by Kohat-17 (19.30), PR-118 (19.10), Ehsan-16 (19.05), Pakhtunkhwa-15 (18.80), and NIFA-Insaf-15 (18.75). However, the minimum spikelets per spike were determined by wheat genotype NARC-11 (16.05), closely followed by four other genotypes i.e., Faisalabad-08, Pirsabak-05, Ujala-16, PR-119, and Pakistan-13 ranging from 16.10 to 17.00 spikelets per spike. For G × E interactions, the maximum spikelets per spike were indicated by genotype NIFA-Lalma-13 (22.10), followed by PR-118 (21.00), NIFA-Insaf-15 (21.00), Borlaug-16 (29.90), Dharbi-2011 (20.70), and Pirsabak-08 (20.70) with optimum planting. However, minimum spikelets per spike were owned by wheat genotype Pirsabak-05 (13.30), followed by NARC-11, Faisalabad-08, Ujala-16, Pakistan-13, and Pirsabak-08 ranging from 14.60 to 15.30 with late planting. Overall, the genotype NIFA-Lalma-13 displayed maximum spikelets under both environments.

The most favorable genotypes with negative and minimum tolerance index and high desirable trait stability index were PR-123, Pirsabak-15, and PR-122 (Table 5). Likewise, maximum mean productivity and stress tolerance index were observed for wheat genotypes NIFA-Lalma-13, Kohat-17, and PR-118 which were found as most tolerant. Similarly, high desirable values of trait index were also recorded for the said genotypes.

Grains per Spike: Averaged over two planting environments, the genotype means varied from 32 to 48 while the genotype × environment interactions were ranging from 28 to 53 grains per spike (Table 6). On average, wheat genotypes revealed the maximum number of grains per spike (46) with optimum planting than stressed planting (37) with a net difference of nine grains per spike.

Table 4. Mean performance and stress selection indices of wheat genotypes for spike length evaluated under optimum (non-stress) and late (stressed) planting environments.

Genotypes	Spike length (cm)							
	Optimum	Late	Means	TOL	MP	STI	TSI	TI
Advanced lines								
PR-114	10.60	8.42	9.51	2.18	9.51	0.98	0.79	0.88
PR-118	11.85	8.87	10.36	2.98	10.36	1.15	0.75	0.93
PR-119	11.20	8.88	10.04	2.32	10.04	1.09	0.79	0.93
PR-122	12.08	11.12	11.60	0.96	11.60	1.47	0.92	1.16
PR-123	12.03	10.19	11.11	1.84	11.11	1.35	0.85	1.07
PR-124	11.17	8.96	10.07	2.21	10.07	1.10	0.80	0.94
Cultivars								
Paseena-17	11.15	9.05	10.10	2.10	10.10	1.11	0.81	0.95
Khaista-17	11.14	9.59	10.37	1.55	10.37	1.17	0.86	1.00
Wadan-17	11.55	9.30	10.43	2.25	10.43	1.18	0.81	0.97
Pakhtunkhwa-15	12.00	11.10	11.55	0.90	11.55	1.46	0.93	1.16
Pirsabak-15	11.15	9.52	10.33	1.63	10.33	1.17	0.85	1.00
Pirsabak-13	10.85	9.39	10.12	1.46	10.12	1.12	0.87	0.98
Shahkar-13	10.61	9.29	9.95	1.32	9.95	1.08	0.88	0.97
Pirsabak-08	10.45	8.24	9.35	2.21	9.35	0.95	0.79	0.86
Pirsabak-05	12.39	8.59	10.49	3.80	10.49	1.17	0.69	0.90
NIFA-Insaf-15	11.45	10.15	10.80	1.30	10.80	1.28	0.89	1.06
NIFA-Aman-17	11.85	9.79	10.82	2.06	10.82	1.27	0.83	1.03
NIFA-Lalma-13	12.21	9.31	10.76	2.90	10.76	1.25	0.76	0.98
Borlaug-16	12.01	9.99	11.00	2.02	11.00	1.32	0.83	1.05
Zincol-16	11.57	8.47	10.02	3.09	10.02	1.08	0.73	0.89
Pakistan-13	10.83	9.94	10.39	0.90	10.39	1.18	0.92	1.04
Ujala-16	9.65	8.30	8.98	1.35	8.98	0.88	0.86	0.87
Faisalabad-08	10.68	8.98	9.83	1.70	9.83	1.05	0.84	0.94
Fateh Jhang-16	10.47	9.24	9.86	1.23	9.86	1.06	0.88	0.97
Ehsan-16	11.79	10.56	11.18	1.23	11.18	1.37	0.90	1.11
Johar-16	12.10	9.89	11.00	2.21	11.00	1.31	0.82	1.04
Gold-16	12.49	10.77	11.63	1.72	11.63	1.48	0.86	1.13
Ghanimat-e-IBGE-15	12.18	10.75	11.47	1.43	11.47	1.44	0.88	1.13
Kohat-2000	11.43	9.55	10.49	1.88	10.49	1.20	0.84	1.00
Kohat-17	12.30	10.31	11.31	1.99	11.31	1.39	0.84	1.08
Israr-17	10.71	8.96	9.84	1.75	9.84	1.05	0.84	0.94
Shahid-17	11.96	10.00	10.98	1.96	10.98	1.31	0.84	1.05
NARC-11	10.97	9.27	10.12	1.70	10.12	1.12	0.85	0.97
Amin-10	10.78	9.17	9.98	1.61	9.98	1.09	0.85	0.96
Dharabi-11	12.47	9.70	11.09	2.77	11.09	1.33	0.78	1.02
Benazir-13	12.00	9.94	10.97	2.06	10.97	1.31	0.83	1.04
Means	11.49	9.54	-	1.91	10.50	1.20	0.83	1.00

$LSD_{0.05}$ Environments: 0.39

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

Table 5. Mean performance and stress selection indices of wheat genotypes for spikelets per spike evaluated under optimum (non-stress) and late (stressed) planting environments.

Genotypes	Spikelets per spike							
	Optimum	Late	Means	TOL	MP	STI	TSI	TI
Advanced lines								
PR-114	18.80	15.50	17.15	3.30	17.15	1.08	0.82	0.94
PR-118	21.00	17.20	19.10	3.80	19.10	1.34	0.82	1.05
PR-119	18.40	15.30	16.85	3.10	16.85	1.04	0.83	0.93
PR-122	19.00	17.80	18.40	1.20	18.40	1.25	0.94	1.08
PR-123	18.10	17.90	18.00	0.20	18.00	1.20	0.99	1.09
PR-124	19.20	16.90	18.05	2.30	18.05	1.20	0.88	1.03
Cultivars								
Paseena-17	20.50	15.90	18.20	4.60	18.20	1.21	0.78	0.97
Khaista-17	19.90	16.70	18.30	3.20	18.30	1.23	0.84	1.02
Wadan-17	20.00	16.80	18.40	3.20	18.40	1.24	0.84	1.02
Pakhtunkhwa-15	19.90	17.70	18.80	2.20	18.80	1.30	0.89	1.08
Pirsabak-15	18.00	17.50	17.75	0.50	17.75	1.16	0.97	1.06
Pirsabak-13	18.70	16.60	17.65	2.10	17.65	1.15	0.89	1.01
Shahkar-13	18.40	16.60	17.50	1.80	17.50	1.13	0.90	1.01
Pirsabak-08	20.70	15.30	18.00	5.40	18.00	1.17	0.74	0.93
Pirsabak-05	19.00	13.30	16.15	5.70	16.15	0.93	0.70	0.81
NIFA-Insaf-15	21.00	16.50	18.75	4.50	18.75	1.28	0.79	1.00
NIFA-Aman-17	20.10	16.30	18.20	3.80	18.20	1.21	0.81	0.99
NIFA-Lalma-13	22.10	16.50	19.30	5.60	19.30	1.35	0.75	1.00
Borlaug-16	20.90	16.20	18.55	4.70	18.55	1.25	0.78	0.99
Zincol-16	19.20	15.40	17.30	3.80	17.30	1.09	0.80	0.94
Pakistan-13	18.70	15.30	17.00	3.40	17.00	1.06	0.82	0.93
Ujala-16	18.00	15.00	16.50	3.00	16.50	1.00	0.83	0.91
Faisalabad-08	17.50	14.70	16.10	2.80	16.10	0.95	0.84	0.89
Fateh Jhang-16	18.90	16.00	17.45	2.90	17.45	1.12	0.85	0.97
Ehsan-16	20.10	18.00	19.05	2.10	19.05	1.34	0.90	1.09
Johar-16	19.50	16.80	18.15	2.70	18.15	1.21	0.86	1.02
Gold-16	19.80	17.60	18.70	2.20	18.70	1.29	0.89	1.07
Ghanimat-e-IBGE-15	19.10	17.30	18.20	1.80	18.20	1.22	0.91	1.05
Kohat-2000	19.80	17.50	18.65	2.30	18.65	1.28	0.88	1.06
Kohat-17	20.40	18.20	19.30	2.20	19.30	1.37	0.89	1.11
Israr-17	20.20	16.40	18.30	3.80	18.30	1.23	0.81	1.00
Shahid-17	19.90	17.00	18.45	2.90	18.45	1.25	0.85	1.03
NARC-11	17.50	14.60	16.05	2.90	16.05	0.94	0.83	0.89
Amin-10	20.10	17.00	18.55	3.10	18.55	1.26	0.85	1.03
Dharabi-11	20.70	15.90	18.30	4.80	18.30	1.22	0.77	0.97
Benazir-13	19.10	16.80	17.95	2.30	17.95	1.19	0.88	1.02
Means	19.51	16.45	-	3.06	17.98	1.19	0.85	1.00

$LSD_{0.05}$ Genotypes: 1.87, $LSD_{0.05}$ Environments: 0.44

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

Table 6. Mean performance and stress selection indices of wheat genotypes for grains per spike evaluated under optimum (non-stress) and late (stressed) planting environments.

Genotypes	Grains per spike							
	Optimum	Late	Means	TOL	MP	STI	TSI	TI
Advanced lines								
PR-114	42	33	37	9.10	37.45	1.02	0.78	0.89
PR-118	50	41	46	8.50	45.65	1.52	0.83	1.12
PR-119	47	37	42	10.27	41.73	1.26	0.78	0.99
PR-122	43	43	43	-0.03	42.98	1.36	1.00	1.17
PR-123	43	40	41	3.60	41.30	1.25	0.92	1.07
PR-124	49	38	44	10.60	43.50	1.37	0.78	1.04
Cultivars								
Paseena-17	40	32	36	7.43	36.02	0.94	0.81	0.88
Khaista-17	52	41	46	11.20	46.40	1.56	0.78	1.11
Wadan-17	47	33	40	14.10	40.05	1.14	0.70	0.90
Pakhtunkhwa-15	53	43	48	10.80	48.00	1.67	0.80	1.16
Pirsabak-15	42	42	42	0.30	41.95	1.30	0.99	1.13
Pirsabak-13	52	36	44	16.30	43.75	1.36	0.69	0.97
Shahkar-13	41	31	36	10.10	36.05	0.94	0.75	0.84
Pirsabak-08	49	36	43	13.10	42.75	1.31	0.73	0.98
Pirsabak-05	47	28	37	18.90	37.45	0.97	0.60	0.76
NIFA-Insaf-15	36	34	35	1.90	34.75	0.89	0.95	0.92
NIFA-Aman-17	45	36	41	9.50	40.65	1.20	0.79	0.97
NIFA-Lalma-13	48	39	44	9.37	43.78	1.40	0.81	1.06
Borlaug-16	53	33	43	19.93	42.57	1.26	0.62	0.88
Zincol-16	53	38	45	14.73	45.47	1.48	0.72	1.03
Pakistan-13	52	39	46	12.20	45.50	1.50	0.76	1.07
Ujala-16	42	31	36	11.23	36.42	0.95	0.73	0.84
Faisalabad-08	46	37	41	9.03	41.32	1.24	0.80	1.00
Fateh Jhang-16	36	34	35	2.00	34.60	0.88	0.94	0.91
Ehsan-16	50	37	44	13.40	43.70	1.37	0.73	1.00
Johar-16	51	38	45	13.23	44.72	1.44	0.74	1.03
Gold-16	40	38	39	2.90	38.95	1.12	0.93	1.02
Ghanimat-e-IBGE-15	44	39	42	4.70	41.55	1.27	0.89	1.06
Kohat-2000	43	38	40	5.40	40.30	1.19	0.87	1.02
Kohat-17	44	43	44	0.83	43.62	1.40	0.98	1.17
Israr-17	39	39	39	-0.23	39.18	1.13	1.01	1.07
Shahid-17	48	42	45	6.00	44.50	1.45	0.87	1.13
NARC-11	33	32	32	0.63	32.42	0.77	0.98	0.87
Amin-10	50	34	42	16.70	41.95	1.24	0.67	0.91
Dharabi-11	50	35	43	14.30	42.55	1.30	0.71	0.96
Benazir-13	48	39	44	8.43	43.52	1.38	0.82	1.07
Means	46	37	-	8.90	41.31	1.25	0.81	1.00

$LSD_{0.05}$ Genotypes: 5.57, $LSD_{0.05}$ Environments: 1.31, $LSD_{0.05}$ G × E: 7.87

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

In genotypes, the maximum grains per spike were achieved for wheat genotype Pakhtunkhwa-15 (48), followed by genotypes Khaista-17 (46), PR-118 (46), Zincol-16 (46), Pakistan-13 (45), and Johar-16 with 45 grains per spike across both planting environments. However, the minimum grains per spike were counted for wheat genotype NARC-11 (32), followed by cultivars i.e., NIFA-Insaf-15, Fateh Jhang-16, Paseena-17, Shahkar-13, and Ujala-16 ranging from 35 to 36. Based on genotype × environment interactions, the maximum grains per spike were observed in wheat genotype Pakhtunkhwa-15 (53), followed by Zincol-16 (53), Borlaug-16 (53), Khaista-17 (52), Pirsabak-13 (52), and Pakistan-13 (52) with optimum planting condition. However, the least number of grains per spike were exhibited by wheat genotype Pirsabak-05 (28), followed by Ujala-16, Shahkar-13, NARC-11, Paseena-17, and Borlaug-16 ranged from 31 to 33 with late planting environment. Overall, the wheat genotype Pakhtunkhwa-15 showed maximum grains per spike across both planting environments.

Data about means and stress selection indices, and according to tolerance index, the best performing and most tolerant wheat genotypes with minimum desirable values of tolerance index were Israr-17, PR-122, and Pirsabak-05 (Table 6). Similarly, the top-ranking genotypes in terms of mean productivity and stress tolerance index were reported as Khaista-17, PR-118, and Pakistan-13. Likewise, genotypes with greater estimates of trait stability index were Israr-17, followed by PR-119 and Pirsabak-15. Trait index also grouped most of the tolerant wheat genotypes likewise Kohat-17, followed by PR-122 and Pakhtunkhwa-15.

1000-Grain Weight: For the 1000-grain weight, the genotype's means ranged from 28.23 to 40.50 g while in genotype × environment interactions the range of the means was 22.35 to 45.73 across both planting environments (Table 7). With an optimum time of planting, on average the wheat genotypes produced bolder grains and more 1000-grains weight (38.43 g) than late planting condition (30.52 g) with a net difference of 7.91 g. In genotypes, the maximum 1000-grain weight was recorded for wheat genotype NIFA-Insaf-15 (40.50 g), followed by cultivars i.e., Pirsabak-05 (39.84 g), Pakistan-13 (39.65 g), Khaista-17 (38.48 g), Pirsabak-13 (38.15 g), and Borlaug-16 (38.15 g). However, the least 1000-grain weight was recorded in wheat genotype NARC-11 (28.23 g), followed by cultivars i.e., Amin-2011, Ujala-16, Wadan-17, Faisalabad-08, and Gold-16 ranged from 28.54 to 29.60 g. According to genotype × environment interaction effects, the maximum 1000-grain weight was determined for wheat genotype Borlaug-16 (45.73 g), followed by Pakistan-13 (45.36 g), Pirsabak-05 (43.87 g), Kohat-17 (43.49 g), Pirsabak-15 (43.07 g), and NIFA-Insaf-15 (42.75 g) with optimum planting environment. However, the minimum 1000-grain weight was indicated by wheat genotype NARC-11 (22.35 g), followed by Gold-16, Ujala-16, Pirsabak-15, Faisalabad-08, and Benazir-13 ranging from 24.43 to 26.75 g with a late planting environment. Overall, the wheat genotype NIFA-Insaf-15, followed by Borlaug-16 showed a maximum 1000-grain weight across genotypes and genotype × environment interactions, respectively.

The most favorable genotypes with negative and minimum tolerance index and desirable trait stability index were Wadan-17, Amin-10, and Ehsan-16 (Table 7). Likewise, maximum mean productivity and stress tolerance index were reported in the genotypes NIFA-Insaf-15, Pirsabak-05, and Pakistan-13 which were found as most tolerant genotypes. Similarly, the desirable values of the trait index were also recorded for the said genotypes.

Grain Yield: Grain yield is a complex quantitative character greatly affected by various yield contributing parameters. For grain yield, the genotype means ranged from 2469 to 3746 kg ha^{-1} while for genotype × environment interactions the range of the means was 1596 to 4767 kg ha^{-1} (Table 8). On average, the genotypes with an optimum time of planting produced more grain yield (3888 kg ha^{-1}) as compared to the late planting environment (2362 kg ha^{-1}) and the net difference was 1526 kg ha^{-1}. The genotype means across two planting environments revealed that the maximum grain yield was produced by wheat genotype Pakistan-13 (3746 kg ha^{-1}), followed by Zincol-16 (3712 kg ha^{-1}), PR-122 (3671 kg ha^{-1}), NIFA-Lalma-13 (3648 kg ha^{-1}), Pirsabak-08 (3644 kg ha^{-1}) and Israr-17 (3562 kg ha^{-1}).

However, the minimum grain yield was achieved in wheat genotype NARC-11 (2469 kg ha^{-1}), followed by Johar-16, Dharbi-2011, Ghanimat-e-IBGE-15, NIFA-Insaf-15, and Shahid-17 ranged from 2533 to 2700 kg ha^{-1}. According to genotype × environment interactions, the maximum grain yield was achieved in wheat genotype Israr-17 (4767 kg ha^{-1}), followed by NIFA-Lalma-13 (4733 kg ha^{-1}), Paseena-17 (4725 kg ha^{-1}), Pirsabak-08 (4650 kg ha^{-1}), Pakistan-13 (4554 kg ha^{-1}), and Zincol-16 (4454 kg ha^{-1}) with optimum planting environment. However, the minimum grain yield was recorded for wheat genotype Ghanimat-e-IBGE-15 (1596 kg ha^{-1}), followed by NARC-11, Fateh Jhang-16, Dharbi-2011, Borlaug-16, and Johar-16 ranging from 1771 to 1987 kg ha^{-1} with late and stressed planting. Overall, the maximum grain yield was recorded for wheat genotype Pakistan-13 and Israr-17 across genotypes and genotype × environment interactions, respectively.

Means and stress selection indices for grain yield enunciated that because of tolerance index and trait stability index, the top-ranking and most tolerant wheat genotypes with minimum desirable values was Pirsabak-13, followed by two other cultivars Pirsabak-15 and Pakhtunkhwa-15 (Table 8). Similarly, according to the mean productivity and trait stability index, the greater desirable values were recorded for wheat genotypes Pakistan-13, followed by Zincol-16, PR-122, and NIFA-Lalma-13. Likewise, the trait index grouped most of the tolerant genotypes as PR-122, followed by Zincol-16, Pakistan-13, and Pirsabak-15.

Table 7. Mean performance and stress selection indices of wheat genotypes for 1000-grain weight evaluated under optimum (non-stress) and late (stressed) planting environments.

Genotypes	1000-grain weight (g)							
	Optimum	Late	Means	TOL	MP	STI	TSI	TI
Advanced lines								
PR-114	37.83	34.78	36.30	3.05	36.30	1.41	0.92	1.14
PR-118	38.78	33.38	36.08	5.40	36.08	1.39	0.86	1.09
PR-119	38.61	30.76	34.68	7.86	34.68	1.27	0.80	1.01
PR-122	39.52	34.43	36.97	5.09	36.97	1.46	0.87	1.13
PR-123	35.38	31.32	33.35	4.06	33.35	1.19	0.89	1.03
PR-124	37.61	32.62	35.11	4.99	35.11	1.32	0.87	1.07
Cultivars								
Paseena-17	38.98	30.29	34.63	8.68	34.63	1.27	0.78	0.99
Khaista-17	42.10	34.87	38.48	7.23	38.48	1.58	0.83	1.14
Wadan-17	29.44	28.85	29.15	0.59	29.15	0.91	0.98	0.95
Pakhtunkhwa-15	33.58	26.88	30.23	6.71	30.23	0.97	0.80	0.88
Pirsabak-15	43.07	25.28	34.17	17.79	34.17	1.17	0.59	0.83
Pirsabak-13	40.28	36.03	38.15	4.26	38.15	1.56	0.89	1.18
Shahkar-13	39.68	35.28	37.48	4.40	37.48	1.50	0.89	1.16
Pirsabak-08	37.02	27.00	32.01	10.02	32.01	1.07	0.73	0.88
Pirsabak-05	43.87	35.82	39.84	8.05	39.84	1.69	0.82	1.17
NIFA-NIFA-Insaf-15	42.75	38.25	40.50	4.50	40.50	1.76	0.89	1.25
NIFA-Aman-17	35.20	29.45	32.33	5.75	32.33	1.11	0.84	0.96
NIFA-Lalma-13	39.48	34.73	37.10	4.75	37.10	1.47	0.88	1.14
Borlaug-16	45.73	30.57	38.15	15.17	38.15	1.50	0.67	1.00
Zincol-16	41.95	31.61	36.78	10.34	36.78	1.42	0.75	1.04
Pakistan-13	45.36	33.94	39.65	11.43	39.65	1.65	0.75	1.11
Ujala-16	33.23	24.81	29.02	8.42	29.02	0.88	0.75	0.81
Faisalabad-08	33.07	25.61	29.34	7.46	29.34	0.91	0.77	0.84
Fateh Jhang-16	40.04	33.22	36.63	6.82	36.63	1.43	0.83	1.09
Ehsan-16	35.87	32.21	34.04	3.67	34.04	1.24	0.90	1.06
Johar-16	38.14	27.02	32.58	11.12	32.58	1.11	0.71	0.89
Gold-16	34.78	24.43	29.60	10.35	29.60	0.91	0.70	0.80
Ghanimat-e-IBGE-15	40.93	28.55	34.74	12.38	34.74	1.25	0.70	0.94
Kohat-2000	36.86	27.80	32.33	9.06	32.33	1.10	0.75	0.91
Kohat-17	43.49	32.78	38.13	10.72	38.13	1.53	0.75	1.07
Israr-17	35.58	29.64	32.61	5.94	32.61	1.13	0.83	0.97
Shahid-17	38.97	31.50	35.24	7.47	35.24	1.32	0.81	1.03
NARC-11	34.12	22.35	28.23	11.78	28.23	0.82	0.65	0.73
Amin-10	29.95	27.14	28.54	2.81	28.54	0.87	0.91	0.89
Dharabi-11	40.94	28.83	34.88	12.12	34.88	1.27	0.70	0.94
Benazir-13	41.51	26.75	34.13	14.76	34.13	1.19	0.64	0.88
Means	38.43	30.52	-	7.92	34.48	1.27	0.80	1.00

$LSD_{0.05}$ Genotypes: 3.95, $LSD_{0.05}$ Environments: 0.93, $LSD_{0.05}$ G × E: 5.58

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

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

Genotypes	Grain yield (kg ha^{-1})							
	Optimum	Late	Means	TOL	MP	STI	TSI	TI
Advanced lines								
PR-114	4396	2064	3230	2332.33	3229.67	1.63	0.47	0.87
PR-118	4329	2696	3513	1633.33	3512.50	2.09	0.62	1.14
PR-119	4121	2179	3150	1941.67	3150.00	1.61	0.53	0.92
PR-122	4183	3158	3671	1025.00	3670.83	2.37	0.75	1.34
PR-123	4154	2525	3340	1629.17	3339.58	1.88	0.61	1.07
PR-124	3604	2608	3106	995.83	3106.25	1.68	0.72	1.10
Cultivars								
Paseena-17	4725	2213	3469	2512.50	3468.75	1.87	0.47	0.94
Khaista-17	3938	2700	3319	1237.50	3318.75	1.91	0.69	1.14
Wadan-17	3879	2450	3165	1429.17	3164.58	1.70	0.63	1.04
Pakhtunkhwa-15	3288	2333	2810	954.17	2810.42	1.37	0.71	0.99
Pirsabak-15	3417	2529	2973	887.50	2972.92	1.55	0.74	1.07
Pirsabak-13	3333	2825	3079	508.33	3079.17	1.69	0.85	1.20
Shahkar-13	3358	2419	2889	939.50	2888.58	1.46	0.72	1.02
Pirsabak-08	4650	2638	3644	2012.50	3643.75	2.20	0.57	1.12
Pirsabak-05	3708	2563	3135	1145.83	3135.42	1.70	0.69	1.08
NIFA-Insaf-15	3238	2142	2690	1095.83	2689.58	1.24	0.66	0.91
NIFA-Aman-17	3563	2317	2940	1245.83	2939.58	1.48	0.65	0.98
NIFA-Lalma-13	4733	2563	3648	2170.83	3647.92	2.17	0.54	1.08
Borlaug-16	4138	1967	3052	2170.83	3052.08	1.46	0.48	0.83
Zincol-16	4454	3029	3742	1425.00	3741.67	2.42	0.68	1.28
Pakistan-13	4554	2938	3746	1616.67	3745.83	2.40	0.65	1.24
Ujala-16	3513	2504	3008	1008.33	3008.33	1.58	0.71	1.06
Faisalabad-08	3696	2154	2925	1541.67	2925.00	1.43	0.58	0.91
Fateh Jhang-16	3763	1783	2773	1979.17	2772.92	1.20	0.47	0.76
Ehsan-16	4217	2671	3444	1545.83	3443.75	2.02	0.63	1.13
Johar-16	3079	1988	2533	1091.67	2533.33	1.10	0.65	0.84
Gold-16	4263	2348	3305	1914.17	3305.42	1.79	0.55	0.99
Ghanimat-e-IBGE-15	3758	1596	2677	2162.50	2677.08	1.08	0.42	0.68
Kohat-2000	3446	2178	2812	1268.33	2811.67	1.34	0.63	0.92
Kohat-17	4163	2717	3440	1445.83	3439.58	2.03	0.65	1.15
Israr-17	4767	2358	3562	2409.00	3562.17	2.01	0.49	1.00
Shahid-17	3283	2117	2700	1166.67	2700.00	1.25	0.64	0.90
NARC-11	3167	1771	2469	1395.83	2468.75	1.01	0.56	0.75
Amin-10	3863	2034	2948	1828.83	2948.08	1.41	0.53	0.86
Dharabi-11	3400	1825	2613	1575.00	2612.50	1.11	0.54	0.77
Benazir-13	3842	2138	2990	1704.17	2989.58	1.47	0.56	0.90
Means	3888	2362	-	1526.29	3125.17	1.66	0.61	1.00

$LSD_{0.05}$ Genotypes: 401.49, $LSD_{0.05}$ Environments: 94.63, $LSD_{0.05}$ G × E: 567.79
TOL: Tolerance index, MP: Mean productivity, STI: Stress tolerance index, TSI: Trait stability index, TI: Trait index

Correlation among various Traits: Days to physiological maturity showed a significant ($p \leq 0.01$) positive association with spikelets per spike and grain yield in optimum planting, significant ($p \leq 0.05$) with 1000-grain weight under late planting, however, physiological maturity was non-significant positively correlated with grain yield under late planting (Table 9). Spike length displayed a significant ($p \leq 0.01$) positive correlation with spikelets per spike under late planting and significant ($p \leq 0.05$) with optimum planting, significant ($p \leq 0.01$) positive association with grains per spike (late planting), while the positive correlation with grains per spike and 1000-grain weight under optimum planting. Spikelets per spike had a non-significant positive correlation with grain yield under both planting conditions, however, had a significant ($p \leq 0.01$) positive association with grains per spike under late planting. Grains per spike and 1000-grain weight revealed a non-significant positive correlation with grain yield under both planting conditions.

Table 9. Correlation coefficients among various traits in wheat genotypes evaluated under optimum (above diagonal) and late (below diagonal) planting environments.

Traits	Days to maturity	Spike length	Spikelets spike^{-1}	Grains spike^{-1}	1000-grain weight	Grain yield
Days to maturity	-	0.121	0.485**	0.100	0.195	0.497**
Spike length	-0.016	-	0.416*	0.257	0.256	-0.020
Spikelets spike^{-1}	-0.043	0.689**	-	0.270	0.123	0.342
Grains spike^{-1}	-0.235	0.525**	0.666**	-	0.155	0.095
1000-grain weight	0.418*	-0.010	0.022	-0.022	-	0.095
Grain yield	0.021	-0.040	0.134	0.333	0.394	-

Correlation among Grain Yield (Yn, Ys) and Stress Selection Indices: Correlation analysis revealed a significant ($p \leq 0.05$) positive association between grain yield under non-stressed (Yn) and stressed (Ys) environmental conditions (Table 10). Similarly, grain yield under normal planting (Yn) was significantly ($p \leq 0.01$) positively correlated with TOL, MP, STI, and TI. However, the relationship was significantly ($p \leq 0.01$) negative with TSI. On the contrary, grain yield under stressed planting (Ys) was significantly ($p \leq 0.01$) and positively correlated with MP, STI, TSI and whereas the relationship was significantly negative with TOL. The majority of the selection indices were significantly positively correlated with one another however, TOL had a significant negative association with TSI and TI (Table 10). The STI revealed no association with TOL and TSI.

Table 10. Correlation matrix between grain yield under non-stress (Yn) and stress (Ys) conditions and various stress tolerance indices in bread wheat.

Stress selection indices	Yn	Ys	TOL	MP	STI	TSI
Ys	0.386*	-				
TOL	0.722**	-0.360**	-			
MP	0.883**	0.774**	0.312	-		
STI	0.79**	0.866**	0.149	0.983**	-	
TSI	-0.419**	0.669**	-0.925**	0.053	0.211	-
TI	0.387*	1.000**	-0.359*	0.775**	0.867**	0.668**

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

To visualize and confirm the mentioned associations of selection indices, a biplot based on principal component analysis was constructed (Figure 1). The first two principal components explained 99.80% of the total variation in the genotypes. Genotypes lying near the origin were generally stable across normal and late planting environments. The angle between the two vectors of selection indices indicated their relationship, and the smaller the angle, the higher the association. For instance, TI and Ys had a perfect correlation as indicated by their very small angle. Similarly, a smaller angle between STI and MP suggested their strong relationship. A close association was also found between Yn and MP. However, MP, TSI, and TOL emerged as unique selection indices and were found dispersed in separate quadrants. Similarly, genotypes having high PC1 and low PC2 (right lower quadrant) were found suitable for both normal and late planting environments. Therefore, genotypes G-4 (PR-122), G-12 (Pirsabak-13), G-20 (Zincol-16), and G-21 (Pakistan-13) were identified as favorable genotypes for both normal and late planting conditions. Similarly, the lower PC1 and higher PC2 indicated susceptibility of the different genotypes. In this regard, genotypes 24 (Fateh Jhang-16), 28 (Ghanimat-e-IBGE-15), 33 (NARC-11), and 35 (Dharabi-11) were found as poor yielders across normal and late planting environments.

Dendrogram based on cluster analysis further confirmed the results obtained through principal component analysis that Yn, STI, and MP were found strongly correlated (Figure 2). Similarly, Ys, TI, and TSI were grouped into a single cluster suggesting that these selection indices were positively linked. However, TOL formed a separate cluster which established its uniqueness in the studied selection indices.

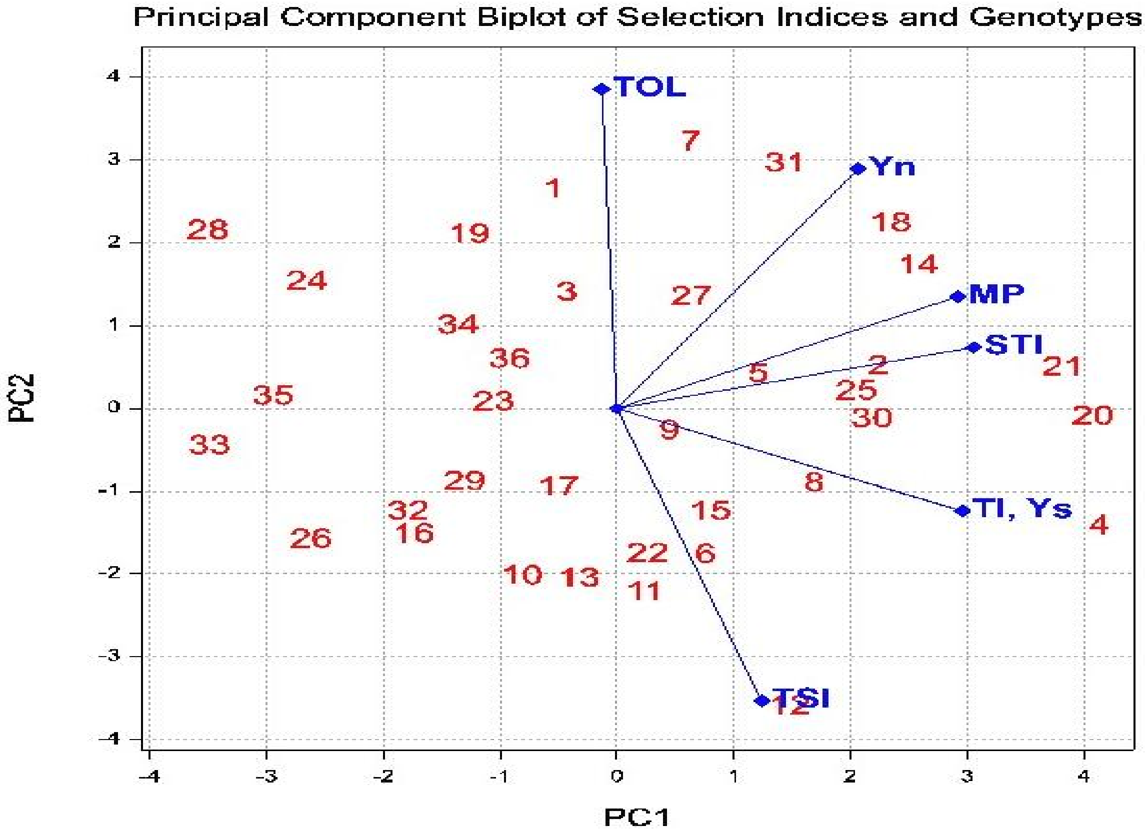

Figure 1. Biplot diagram based on first two principal components (PC1 and PC2) of stress selection indices and 36 bread wheat genotypes evaluated under optimum and late planting environments. The numbers in the figure are genotypes (see Table 1).

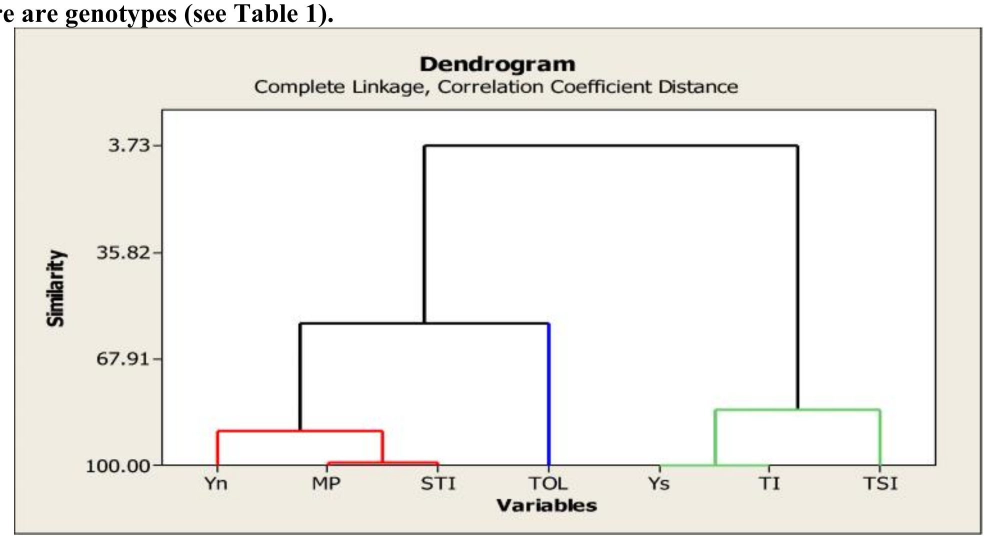

Figure 2. Dendrogram tree based on various stress selection indices of 36 bread wheat genotypes evaluated under optimum and late planting environments.

3D Biplot Analysis: A three-dimensional scatter graph was constructed for a concurrent view of grain yield under normal (Yn) and stressed (Ys) planting environments and stress tolerance indices (Figure 3a, b). In Figure 3a, Yn was plotted against Ys and STI on X, Y, and Z-axis, respectively. Genotypes were partitioned into four quadrants (A, B, C, and D) based on how genotypes performed under normal and late planting environments. High-yielding wheat genotypes under non-stressed and stressed environments are grouped into quadrant A. The quadrant B received genotypes having superior performance under stressed conditions. Similarly, quadrant C comprised the genotypes which performed better under a stressed environment. However, quadrant D had poor yielding genotypes under both non-stressed and stressed environments. Moreover, longer projection on Z-axis indicated good STI values for the genotypes. Therefore, such genotypes are expected to perform better under stressed environments. In this regard, genotypes 20 (Zincol-16) and 21 (Pakistan-13) appeared to be high yielding under both non-stressed and stressed environments as indicated by their longer projection on Z-axis (Figure 3a). On the contrary, genotypes G-26 (Johar-16) and G-33 (NARC-11) were identified as poor yielding genotypes having a smaller projection on Z-axis. However, genotype 12 (Pirsabak-13)

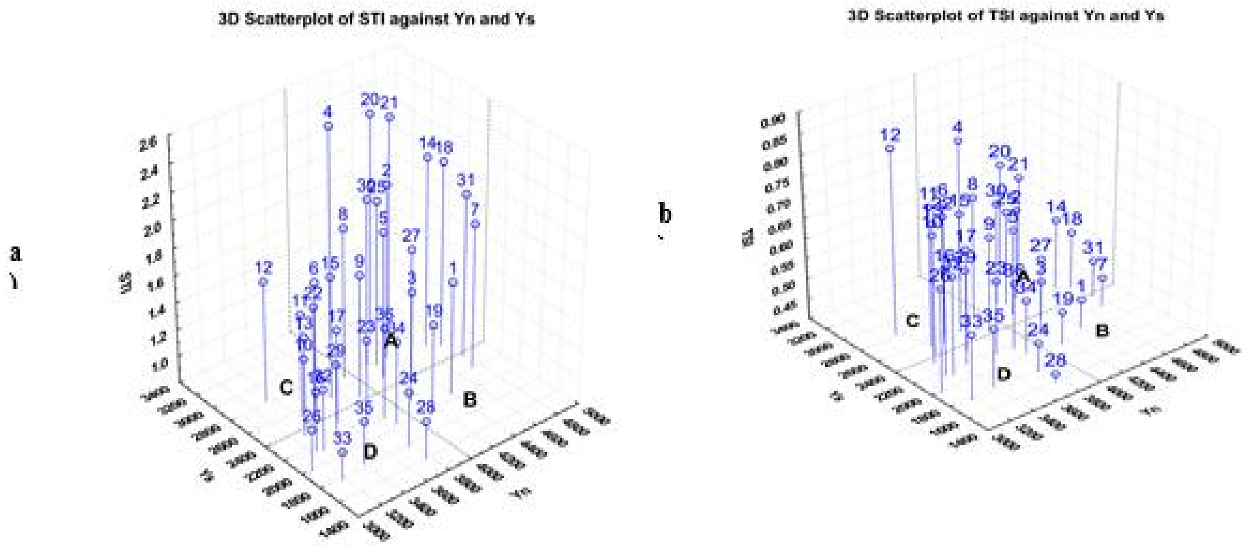

Figure 3a, b. Three-dimensional scatter graphs showing the relationship among a) Yn (grain yield under non-stress), Ys (grain yield under stress), and STI; (b) Yn (grain yield under non-stress), Ys (grain yield under stress), and TSI of 36 bread wheat genotypes evaluated under optimum and late planting environments.

performed better only under a stressed environment (Figure 3a). In Figure 3b, Yn is plotted against Ys and TSI. Genotypes G-20 (Zincol-16) and G-21 (Pakistan-13) were confirmed as high yielding under both non-stressed and stressed environments. Similarly, genotype 12 (Pirsabak-13) also performed better under stressed conditions (Figure 3b).

DISCUSSION

In the present study, 36 bread wheat genotypes were studied across non-stress and stressed planting environments to assess their genetic potential and heat stress tolerance indices. Highly significant variation was observed among the wheat genotypes, planting environments, and their G × E interaction for the majority of the traits. Past studies also revealed significant differences among the wheat genotypes, planting environments, and cultivar by environment interaction under no-stressed and stressed environments (Khan *et al*., 2018; Siddhi *et al*., 2018; Tahir *et al*., 2022). Past findings also revealed significant differences among different sets of wheat genotypes for earliness, yield, and yield-related traits over two planting environments and supported the present findings (Sood *et al*., 2017; Ishaq *et al*., 2018).

Planting environments' effect was much greater as compared to genotypes and their interaction with the studied traits revealed that these variations might be solely due to wheat sowing conditions. In earlier studies, highly significant differences were observed among the wheat genotypes, planting environments, and genotype-by-environment interactions for yield-related traits (Moshatati *et al*., 2017). Besides this, the significant effect of genotypes on grain yield and yield-related traits revealed a high degree of genetic divergence in the wheat genotypes which could be exploited in future breeding programs. However, some studies reported non-significant differences among the wheat genotypes for some yield-related traits over two planting environments (Aabdolah *et al*., 2014). The contradiction between present and past findings might be due to wheat genotypes used in diverse environments.

Overall, the wheat genotypes performed far better with optimum (non-stressed) than late planting (stressed) which got support from certain previous studies on wheat under heat-stressed environments (Dwivedi *et al*., 2017; Elbashir *et al*., 2017; Ahmad *et al*., 2022). In present studies, the genotypes with a late planting environment revealed a significant decrease in the mean values for earliness, and grain yield which was mainly due to a stressed planting environment affecting the growth, morphological, and yield traits. A significant reduction among yield-related traits was reported with the delayed sown environment in wheat. Past investigations also showed the nonsignificant negative association of plant height with the majority of physiological and yield contributing parameters in wheat (Rahman *et al*., 2018).

In previous studies, in response to higher temperature stress, a significant reduction was noted in days to heading, physiological maturity, and yield-related traits in wheat (Bhanu *et al*., 2018). High temperature and less availability of moisture at the initial growth stage due to a stressed planting environment, compel the crop plants to complete their life cycle and mature in a shorter period by converting the vegetative phase to the reproductive stage with reduced spike length, grain per spike, and grain size in wheat (Jaiswal *et al*., 2018).

Similar investigations related to the present study were also formulated by past researchers that yield and yield attributes were significantly affected by different stressed environments in wheat genotypes (Ullah *et al*., 2014). A noteworthy decline in spikelets per spike and grain yield was also reported in wheat genotypes under diverse environmental conditions (Moshatati *et al*., 2017). Stability and heat tolerance of genotypes under a stressed environment vary from season to season and year to year in wheat (Khalil *et al*., 2016). An increase in the day and night temperatures affects the growth of the wheat crop in terms of yield because wheat plants are willing to escape heat stress and mature early by producing poor and shriveled grains (Narayanan, 2018).

Stress selection indices showed that early maturing wheat genotypes were found best suited to stressed planting environments, while late maturing genotypes will be appropriate for heat favorable environments. In the identification and selection of the most tolerant wheat genotypes, the use of different groups and patterns of indices could be more fruitful criteria under a stressed planting environment (Farshadfar *et al*., 2012). The findings of Narayanan (2018) revealed that the evaluation of spring wheat cultivars under a stressed planting environment expressed that tolerance (TOL) and stress tolerance index (STI) could be better applied than trait index (TI) and trait stability index (TSI). From the current scenario, it was revealed that genotypes Pirsabak-13 and Pakistan-13 had high stability across both heat favorable and heat-stressed environments and these genotypes could be the best genetic source for heat tolerance breeding schemes.

Grain yield revealed a positive association with days to physiological maturity and yield components. Past studies revealed a significant positive correlation between heading and maturity traits with grain yield in wheat under an optimum planting environment (Bhanu *et al*., 2018). Similar findings of the considerable positive correlation of grain yield with the bulk of the yield traits were also reported in the past studies on wheat (Jahan *et al*., 2018). Previous investigations were also in line with the current findings which determined a highly significant positive correlation of days to spike emergence and maturity with yield contributing traits in wheat (Azimi *et al*., 2017). However, some studies revealed that days to earliness had a nonsignificant negative correlation with days to anthesis, spike length, and yield contributing traits in wheat (Khamssi and Najaphy, 2012).

Present results were also in association with past findings that the use of several stress indices is preferred for practical use in selecting tolerant wheat genotypes under stressed planting environments (Moshatati *et al*., 2017). Apart from that, some studies revealed that the grain yield of various wheat genotypes was found very sensitive and greatly affected by heat stress and different planting environments (Khalil *et al*., 2016). Selection based on tolerance proved to be very efficient in producing stress tolerant wheat genotypes with high grain yield (Laghari *et al*., 2016). The mean productivity (MP), and stress tolerance index (STI) pattern indicated that these indices were found suitable to differentiate the wheat genotypes for drought sensitivity and tolerance in a stressed environment (Mohammadi *et al*., 2011). For instance, 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 spring wheat.

The principal component analysis is effective in comparing genotypes along with stress tolerance indices (Bahrami *et al*., 2014). The same approach of principal component analysis (PC1 and PC2) based on the correlation of Yn, Ys, with stress tolerance indices was used to recognize the stable genotypes in wheat (Dorostkar *et al*., 2015; Khan and Kabir, 2015). In the principal component analysis, past findings demonstrated a significant positive correlation of grain yield (under stress-free and stressed conditions) with heat stress indices i.e., mean productivity (MP), harmonic mean (HARM), geometric mean (GM), and stress tolerance index (STI), however, yield possessed a negative association with drought response index (DRI) in bread wheat (Mohammadi *et al*., 2012; Farshadfar *et al*., 2012). Past studies revealed that principal component and biplot analyses were found useful in identifying the promising and heat stress tolerant wheat genotypes under different planting environments (Bacha *et al*., 2017; Tulu and Wondimu, 2019).

A three-dimensional graph was constructed to scrutinize the wheat genotypes for non-stressed and stressed environments. For this purpose, two important predictors STI and TSI for stress tolerance were used based on their strong association with grain yield. The biplot was partitioned into four quadrants to categorize the genotypes based on their response to non-stressed and stressed environments (Fernandez, 1992). Based on STI and TSI, genotypes G-12 (PR-122), G-20 (Zincol-16), and G-21 (Pakistan-13) surpassed other genotypes in grain yield under both normal and late planting environments. These genotypes efficiently managed the late planting stress and hence, could serve as a baseline population for breeding strategies under a stressed environment.

Conclusion: Wheat yield was significantly influenced by optimum and late planting environments. Highly significant variations among the genotypes suggested a broader genetic base of the wheat germplasm. Due to late planting, the wheat genotypes revealed a decline in the mean values for heading and maturity, yield-related traits, and grain yield. Overall, the highest grain yield was observed for genotypes viz., Pakistan-13, Zincol-16, and PR-122 under non-stressed and stressed planting environments. Application of stress selection indices indicated adequate tools for the identification and selection of high-yielding and tolerant wheat genotypes under non-stressed and stressed environments. Based on stress selection indices, the most tolerant wheat genotypes were Pirsabak-13, Zincol-16, and PR-122, and could also be used for the development of stress-tolerant genotypes in future breeding programs.

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