IDENTIFICATION OF HEAT STRESS TOLERANT SPRING WHEAT GENOTYPES VIA YIELD-INFLUENCING CHARACTERISTICS

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Abstract

The present investigation utilized heat stress indicators to evaluate 50 wheat varieties cultivated in both normal and heat stress conditions. It was observed that heat stress significantly hinders the performance of all varieties when planted late, leading to reduced yields. Correlation coefficient analysis, PCA, and biplot assessments revealed a strong positive link between indices such as STI, MP, GMP, HM, and MRP with potential and stress yields (Yp and Ys), whereas TOL and SSPI demonstrated a negative correlation with Ys. Cluster analysis employed the same heat stress tolerance indices (STI, MP, GMP, HM, and MRP) to categorize the varieties as either heat tolerant or sensitive. Consequently, these indices proved to be superior in predicting which high-yield varieties are desirable under both conditions. Hence, these stress indicators may offer more effective methods for selecting genotypes that can withstand high temperatures from both environments. Through the contribution of these various indices, certain genotypes specifically 9452, 9521, 9707, and 9522 were pinpointed as tolerant and high performing in both settings. Therefore, these heat resilient varieties could serve as valuable genetic assets in programs aimed at agricultural advancement.

Introduction

Wheat (*Triticum aestivum* L.), the predominant crop across global agricultural landscapes, supports approximately one-third of humanity through direct consumption and as livestock feed. In Pakistan, wheat's role is pivotal, anchoring the nation's food security and undergirding its agrarian economy. As the principal crop by cultivated area, it furnishes vital nutrients to a substantial segment of the populace. Nonetheless, the confluence of climate change and population growth looms as a formidable threat to food stability. Climate-induced alterations manifest in intensified extreme temperatures, irregular rainfall patterns, and distribution shifts, thereby intensifying droughts and heat stress—factors that curtail wheat's yield potential and compromise food quality. The prevalence of high temperature stress, a notable constraint on agricultural productivity including wheat, is anticipated to escalate in tandem with climatic evolution. Forecasts intimate that by the terminus of the twenty-first century, average temperatures may ascend by 1–4 °C, which could precipitate a decline in wheat yields ranging from 4.1–6.4%. Such elevated temperatures hinder plant development, physiological operations, grain development, and ultimately, crop yield. Heat stress perturbs metabolic functions—protein synthesis, enzymatic actions—and cellular processes including membrane integrity and cellular division.

In the cultivation of wheat, temperature fluctuations beyond the ideal 22–25 °C range during key growth phases from anthesis to grain maturity can inflict irreversible damage. Wheat crops sown later in the season are particularly vulnerable to high temperatures between 25–32 °C, which can disrupt the anthesis and grain filling processes, leading to premature maturation and considerable reductions in yield. With the global population expected to reach 9.1 billion by 2050, the urgency to develop adaptive agricultural methods is heightened. Developing heat-tolerant wheat varieties is crucial for boosting production to satisfy the escalating food requirements of a burgeoning global populace. The impact of climate change on agriculture is evident in the extreme temperature stresses that affect wheat yields. It is therefore critical for agricultural scientists to identify and develop genotypes that exhibit resilience to heat stress.

The pursuit of heat stress tolerant wheat genotypes is a meticulous process that involves the cultivation of advanced lines in both optimal and challenging environments. Leveraging the inherent genetic diversity within wheat populations, plant breeders strive to forge varieties that exhibit robust stress resilience. This endeavour presents a formidable task for breeders, as they must adeptly identify heat tolerant cultivars amidst a plethora of candidates. A multitude of stress tolerance indices have been posited by researchers to aid in this selection, yet only a handful prove efficacious in isolating heat resistant genotypes. The Tolerance Index (TOL) quantifies the yield gap under normal versus stressed conditions. Mean productivity index (MP) encapsulates a genotype's yield performance across both favourable and unfavourable conditions, denoted as Yp and Ys respectively. The stress tolerance index (STI), conceived by Fernandez, and evaluates genotype vigour in both standard and heat-stressed milieus based on the geometric mean production index. Additionally, the stress susceptibility percentage index (SSPI) serves as an instrumental metric for assessing trait stability and variation under divergent environmental pressures. Fisher and Wood's Relative Stress Index (RSI) has become a critical measure during periods of drought-induced stress in wheat cultivars. In the evaluation of wheat–rye disomic addition lines. Harmonic Mean (HM), has been utilized which is calculated by doubling the product of genotype yields and dividing by their sum under both stressed and normal conditions. The Mean Relative Performance (MRP) is another significant index that assesses stress resilience. Yield Stability Index (YSI) compares yields under stressed conditions to those under normal conditions. Gavuzzi et al.'s Yield Index (YI) contrasts a genotype's performance under normal conditions with the average yield under stress. Indices such as MP, STI, GMP, HM, YSI, and YI are associated with higher values, while TOL, SSI, RSI, and PYR indicate lower values; these are crucial for selecting genotypes that are stable and tolerant. This study examined 50 wheat genotypes in two distinct environmental settings: normal and late sowing. Eleven stress indices were employed to pinpoint heat-tolerant genotypes: Stress Tolerance Index (STI), Mean Relative Performance (MRP), Harmonic Mean (HM), Geometric Mean Productivity (GMP), Mean Productivity (MP), Yield Index (YI), Yield Stability Index (YSI), Percent Yield Reduction (PYR), Relative Stress Index (RSI), Tolerance Index (TOL), and Stress Susceptibility Percentage Index (SSPI). Selection of heat-tolerant genotypes was based on the stress indices evaluations, with correlations between grain yield and indices determined through correlation coefficient principal component analysis, biplot, and cluster analysis.

Material and methods

The experimental materials were consisted of 50 genotypes of bread wheat (*Triticum aestivum* L). The experiment was conducted in Government Seed Farm Dhakkar which is situated at latitude of 29°10′N, longitude of 75°46′E and altitude of 215.2 m (705 ft) above sea level in subtropical region of North Western Plain Zone of Pakistan. The genotypes were sown in October (October, 26, 2021 and October 28, 2022) for normal sown conditions and in December (December 10, 2021 and December 10, 2022) for late sown conditions during Rabi season of years 2021–22 and 2022–23. The experiment was laid out in two replications in Randomized Block Design (RBD). When adequate moisture was available, genotypes were seeded in the field. In each replication, each genotypes were grown in 7.5 m^2 plot with 6 rows, each of 5 m in length and 1.5m width. Depending on the rainfall, the field was irrigated at regular intervals and recommended standard cultural and agronomic practices were followed to raise a healthy crop.

At crop maturity, harvested the genotypes from each plot separately and measured their grain yield (g). This grain yield (Yp and Ys) of genotype and mean yield (Xp and Xs) of all genotypes under normal and late sown respectively, was used to calculate all stress indices. Weekly minimum and maximum temperature (°C), relative humidity (morning and evening), bright sun shine hours and rainfall (mm) during wheat growing season at research farm are demonstrated in Fig. 1 and Table S1(Supplementry). The temperature higher than 25 °C during March adversely affects the anthesis and post anthesis stages of late sown genotypes.

The following calculations were used to compute heat tolerance indices:

Stress tolerance (TOL) = $Yp - Ys$ Rosielle and Hamblin13

Stress tolerance index (STI) = $(Yp \times Ys)/Xp2$ Fernandez14

Stress susceptibility percentage index (SSPI) = $Yp - Ys/ 2(Xp) \times 100$ Moosavi et al.15

Yield index (YI) = Ys/Xs Gavuzzi et al.19

Yield stability index (YSI) = Ys/Yp Bouslama and Schapaugh18

Relative stress index (RSI) = $(Yp/Ys)/(Xs/Xp)$ Fischer and Wood16

Mean productivity (MP) = $(Yp + Ys)/2$ Rosielle and Hamblin13

Geometric mean productivity (GMP) = $\sqrt{(Ys \times Yp)}$ Fernandez14

Harmonic mean (HM) = $2(Yp \times Ys)/(Yp + Ys)$ Bidinger et al.25

Mean relative performance (MRP) = $(Ys/Xs) + (Yp/Xp)$ Ramirez and Kelly26

Percent yield Reduction (PYR) = $(Yp - Ys)/Yp \times 100$ Farshadfar and Javadinia27

where Yp and Ys are the yield performance of varieties while, Xp and Xs are the mean yield of all varieties under normal and heat stress conditions, respectively. Microsoft Excel was used for calculation of stress indices. Variability package of R software with edition number R4.1.2 was used for analysis of variance and correlation coefficient whereas, IBM SPSS Statistics version 26 was used to exploit Principal component analysis (PCA) and the biplot diagrams for identification of tolerant and susceptible genotypes. Hierarchical cluster analysis (between-group linkage) to observe heat tolerant and susceptible genotypes was done using IBM SPSS Statistics version 26.

Results and Discussion

The comprehensive ANOVA delineated significant differences ($P < 0.001$) in grain yield among wheat genotypes under normal conditions, heat stress, and stress indicators (refer to Table 3). Data on weather parameters were obtained from the Department of Agricultural Meteorology in Pakpatan, Punjab, spanning two crop seasons from October to April (see Fig. 1). The highest temperature recorded was 26.0 °C for genotypes sown normally during the anthesis stage, whereas late-sown genotypes experienced temperatures of 29.2 °C during the 2021–2022 season. A temperature increase of 3 °C was observed under stressed conditions, leading to premature maturation and decreased grain yield due to elevated temperatures at the grain filling stage. In the anthesis stage of the same year, the highest relative humidity was 95%, with bright sunshine lasting for 6.7 hours and rainfall measuring 0.2 mm. Conversely, in the 2022–23 season, normal sown genotypes at anthesis faced a maximum temperature of 20.9 °C, relative humidity of 93%, bright sunshine for 5.8 hours, and rainfall of 14.8 mm. However, genotypes under stress conditions encountered a maximum temperature of 32.6 °C, relative humidity of 81%, bright sunshine for 7.3 hours, and no rainfall during the anthesis stage.

During the 2021–2022 anthesis stage, high relative humidity (RH) was observed due to rainfall, contrasting with the low RH experienced in the same period of 2022–2023. Consequently, late sown wheat genotypes underwent heat stress from anthesis to grain filling stage. High temperatures exceeding 28–30 °C during these stages can significantly reduce mature grain weight in wheat, thereby decreasing yields. This study employed various stress indices—STI, TOL, SSPI, YSI, YI, RSI, MP, HM, MRP, PYR, and GMP—to evaluate yield performance under normal and heat stress conditions. Data for selected genotypes are displayed in Table 4. Genotype 9705 exhibited the highest values for TOL, SSPI, YSI, RSI, and PYR, categorizing it as heat susceptible due to its high yield under normal conditions but low yield under heat stress; thus, it is recommended for normal sowing conditions. Conversely, Millat 2011 showed low values for these indices, indicating greater heat tolerance but lower overall performance under both conditions. The reduced index values reflect the minimal yield difference between the two conditions; hence, lower values do not necessarily equate to higher performance and should be considered alongside genotype grain yield. Genotype 9452 recorded the highest values for STI, MP, GMP, HM, and MRP, marking it as the most stable and productive genotype across both conditions. Genotypes with high values for STI, MP, GMP, HM, and MRP are deemed heat tolerant; however, Sariab 92 with the lowest values for these indices is classified as heat susceptible.

Over the years, the correlation coefficient between grain yield under both normal and late sown conditions, alongside heat tolerance indicators, was computed to identify the most suitable stress tolerance criterion as shown in Table 5. Notably, a positive significant correlation was observed between Yp and Ys (0.431), suggesting their potential utility in pinpointing high-yielding genotypes across varying conditions. Conversely, grain yield exhibited a negative correlation with TOL, SSPI, RSI, and PYR under stress conditions (−0.227, −0.227, −0.478, and −0.464, respectively), yet displayed a positive correlation under normal conditions (0.781, 0.781, and 0.582, respectively). This implies that selection based on these indices would boost grain production in non-stressed environments but may lead to a decline under stress conditions. YSI demonstrated a positive significant correlation with Ys (0.464), but a negative one with Yp (−0.586), establishing it as a more effective index for differentiating between heat tolerant and susceptible genotypes. YSI also serves as an indicator of genotypic stability under stress conditions [28]. Indices such as STI, YI, MP, GMP, HM, and MRP showed a high positive significant correlation with grain yield (Yp and Ys), marking them as preferable for identifying genotypes that maintain high yield in both conditions. Utilizing these indices, genotype 9452 followed by 9521, 9707, and 9522 were recognized as high yielding under both scenarios. Additionally, MP was found to have a positive significant association with all indices barring YSI.

TOL and SSPI exhibited positive correlations with all indices barring YI and YSI. The significant positive relationship of YI and YSI with Ys, contrasted by their negative correlation with TOL and SSPI, suggests that these indices are effective in differentiating genotypes that are stable and heat resistant. Selecting genotypes with the lowest TOL and SSPI values is advantageous for identifying those with high yields under heat stress, qualifying them as heat tolerant. Principal component analysis (PCA), utilizing grain yield (Yp and Ys) along with heat stress tolerance indicators, was instrumental in pinpointing stress-tolerant genotypes (refer to Table 6). Among the thirteen principal components (PCs) identified, the first two—each with an eigenvalue exceeding 1.0—accounted for the majority of the variation, precisely 97.7%. PC1 alone contributed 54.7% to the total variance, while PC2 accounted for 43% (details in Table 6). PC1 was strongly positively correlated with STI, MRP, HM, and GMP (0.99), which displayed the highest variation among all stress indices. Conversely, PC2 showed a strong positive correlation with PYR, SSPI, PYR again, and RSI. A biplot incorporating PC1 and PC2 facilitated a comparative analysis of genotypes and their correlations with heat tolerance indices (illustrated in Fig. 2). Genotypes numbered 11, 21, 28, 41, and 50 emerged as stable under both normal and stress conditions due to their higher PC1 but lower PC2 values (as depicted in Fig. 2).

While genotypes 6, 9, 12, and 26 exhibit lower performance or are more susceptible to heat under stress conditions due to their higher PC2 (positive) and lower PC1 (negative), genotype 9452 stands out with the highest PC1, positively influenced by stress indices such as STI, MRP, MP, and GMP. These genotypes have been identified as the most heat-tolerant. Utilizing heat tolerance indices like MP, GMP, HM, STI, and MRP, the studied wheat genotypes were categorized into seven distinct groups (refer to Table 7 and Figure 3). Cluster I encompasses the majority of genotypes (20), whereas Clusters VI and VII contain only one genotype each. Genotypes within the same cluster exhibit greater similarity, while those in different clusters display significant variations in stress tolerance index values. In this context, the highest values of MP, GMP, HM, STI, and MRP were observed in the genotype of Cluster VII, followed by those in Clusters II, IV, and I. Conversely, the lowest values were noted in the genotype of Cluster VI, succeeded by those in Clusters III and V. Thus, genotype 9452 of Cluster VII, possessing the highest values of tolerance indices, was deemed highly heat tolerant. This study involved screening stress indices through grain yield and mean grain yield to analyze heat tolerance across various wheat genotypes and also pinpointed genotypes with superior heat tolerance performance. Elevated temperatures were found to significantly diminish the grain yield of wheat genotypes.

Similar investigations (29) and (30) have echoed these findings. The stress levels in different wheat-growing regions vary due to environmental factors (31). There is a negative correlation between grain yield and heat stress, posing significant challenges for plant breeders in maintaining high yields. Wheat genotypes sown later are affected by heat stress at the anthesis and post-anthesis stages, experiencing temperatures approximately 3–4 °C higher than those sown normally. A pooled ANOVA has highlighted the significant impact of heat stress on the growth, development, and ultimately, the grain yield of wheat genotypes. Stress patterns differ markedly across various wheat-growing environments, indicating a genotype-environment interaction. Moreover, a pronounced genotype by environment interaction has been observed, demonstrating that each genotype responds uniquely to grain production and other yield parameters across two different environments. The significance of the mean sum of squares for all stress indices related to grain production across all genotypes underscores the diversity within genotypes regarding high-temperature tolerance (32). The variation among genotypes in different environments suggests a diversity in the wheat germplasm for heat tolerance. Plant breeders leverage this variability among cultivars to identify and select high-yielding genotypes under stress conditions.

According to various studies, ANOVA is a robust method for evaluating genotype performance through selection indices. It's particularly effective for pinpointing tolerant genotypes in stressful conditions. For instance, wheat stress tolerance indices have been widely used to identify genotypes resilient to high temperatures. A preference for smaller TOL values is evident, as larger numbers suggest greater stress susceptibility. Interestingly, as SSPI and TOL values diminish, tolerance improves, although these metrics fall short in distinguishing between genotypes with consistently high yields across different conditions. Selection based on TOL and SSPI tends to favor genotypes that perform less well under normal conditions but excel when stressed. For example, the genotype 'Millat 2011' showed minimal yield variation between normal and stressed conditions, indicated by its low TOL and PYR values, classifying it as heat sensitive. Selection criteria should consider both low TOL and grain yield to identify high-performing genotypes. This is supported by findings from Dorostkar et al. and Kumar et al., who observed similar patterns in wheat under both conditions. Erdemci and Shabani et al. suggest that STI is a superior parameter for screening chickpea genotypes for tolerance. Genotypes that excel in both normal and stressed environments exhibit higher STI, MP, and GMP values. Moreover, selections made using STI are likely to yield genotypes with enhanced grain yield and stress tolerance. However, selections based on MP tend to increase average performance across environments without distinguishing between stress-tolerant and high-yielding genotypes.

MP favours higher yield potential and lower stress tolerance 2. In our studies based on HM, MRP, GMP and STI genotypes HD 9452 had the highest values. The genotype HD 9452 was more productive under stress conditions than the remaining genotypes. Basavaraj et al.20 and Kamrani et al.11 also presented similar results and suggested higher yielding and heat tolerant genotypes could be selected on the basis of high values of MRP, GMP and STI. The genotype Millat 2011 could be selected as a heat tolerant genotype as it represented lowest value for SSPI and highest value for YSI. Similar results were observed by Basavaraj et al.20 in rice and suggested that SSI and YSI could be used to identify higher yielding genotypes under stress conditions rather than under normal conditions. The highest values for YI belonged to genotypes 9521 and 9707, so on the basis of higher values for YI these genotypes are stress tolerant genotypes. According to Ashraf et al.38 and Singh et al.39 the line would be tolerant to stress conditions that had a higher value of YI. A single approach based on values of different stress indices is not enough in selection of different heat tolerant or susceptible genotypes. Thus, to find the most suitable stress indices for heat stress tolerance, correlation coefficient was analysed between grain yields (Yp and Ys) of both conditions and heat stress indices.

The interrelation of study results, denoted as Yp and Ys, aligns with findings from Kamrani et al.11, indicating that high-performing genotypes are identifiable under both standard and heat-prone conditions. This suggests that normal condition outcomes are instrumental for indirect selection in heat-stressed environments. Grain yield exhibits a negative correlation with TOL, SSPI, and RSI under stress conditions, yet shows a positive correlation under normal circumstances. Conversely, YSI demonstrates a significant positive correlation with Ys and a negative one with Yp. Poudel et al.10 observed analogous patterns, proposing that lower TOL and SSI values alongside higher YSI values are indicative of stress-tolerant genotypes. Indices such as STI, YI, MP, GMP, and HM display robust positive correlations with grain yield (Yp and Ys), a finding corroborated by Ivić et al.40 in nitrogen-deficient wheat genotypes and further supported by Jha et al.41 who advocate for the use of these indices in identifying high-yielding genotypes across varying conditions. Principal Component Analysis (PCA) was employed to ascertain the contribution percentage of principal components and indices to the overall variance, considering grain yield in both normal and stress conditions alongside heat stress tolerance indices. While correlation coefficients serve well in analyzing bivariate relationships, multiple sources including Nouri et al.28 and Talebi et al.42 suggest that PCA offers a superior criterion over correlation coefficients for selecting optimal yielding genotypes in both normal and stressed states.

Principal Component Analysis (PCA) elucidates the relationship among all traits simultaneously while reducing the number of traits contributing to the most significant proportion of total variation. The analysis deduced that components with an eigenvalue exceeding 1 possess variation above the average, serving as a criterion for selecting components. Yield was the pivotal variable in this study, forming the basis of the analysis. PC1 exhibits a positive correlation with Ys, YI, MRP, HM, MP, GMP, STI, YSI, and Yp, designating it as a "yield potential and heat tolerance component" under varying conditions. Conversely, PC2 correlates strongly with SSPI, TOL, RSI, and PYR, thus termed a "stress susceptibility component." This component aids in identifying heat-sensitive genotypes. Correlation analyses by Puri et al. and Kamrani et al. have similarly categorized the first two principal components under normal and stress conditions. Genotypes that perform well typically show higher PC1 and lower PC2 values. Kaya et al. suggest that genotypes with high PC1 but low PC2 are stable and vice versa. In biplot analysis, the cosine of the angle between vectors indicates index correlations; an obtuse angle signifies a positive correlation, an acute angle indicates a negative correlation, and perpendicular vectors imply no correlation. The biplot reveals positive associations of Yp and Ys with YI, HM, STI, MRP, GMP, and MP; whereas Ys negatively correlates with TOL, SSPI, RSI, and PYR as depicted by obtuse and acute angles between their vectors respectively.

GMP showed zero correlation with RSI as both are at 90°. Based on the heat tolerant indices, like MP, GMP, HM, STI and MRP, all studied wheat genotypes were grouped into seven clusters. In this the highest value of MP, GMP, HM, STI and MRP was possessed by genotype of cluster VII followed by genotypes belonged to cluster II while minimum was exhibited by the genotype of cluster VI followed by genotypes of cluster Naghavi et al.45 also clustered the eight genotypes of maize into three classes by using stress tolerant indices like MP, GMP, STI and found that the genotypes with high value of these indices were stress tolerant genotypes which showed mean values were treated as semi tolerant to stress.Using grain yield (under both conditions) and stress tolerance indices. Tana et al.46 classified all studied genotypes in five clusters according to their performance and stress tolerance degree and found that a genotype with high values of MP, GMP, HM, STI and YSI is best performing and stress tolerant. So, genotypes with high values of MP, GMP, HM, STI and YSI might be used as parents in breeding programs to develop stress tolerant genotypes. Jha et al.41,47,48 generated different clusters of chickpea genotypes to select superior stress tolerance genotypes, based on various stress tolerance indices and other morphological traits and suggested that the genotypes belonging to distant group might be used in breeding programme for producing stress tolerance genotype in chickpea. I was also found that the stress indices, viz. MP, GMP, YI and SSI could be used in breeding programme for selecting superior genotypes to sustain chickpea yield under stressed conditions. GMP showed zero correlation with RSI as both are at 90°. Based on the heat tolerant indices, like MP, GMP, HM, STI and MRP, all studied wheat genotypes were grouped into seven clusters. In this the highest value of MP, GMP, HM, STI and MRP was possessed by genotype of cluster VII followed by genotypes belonged to cluster II while minimum was exhibited by the genotype of cluster VI followed by genotypes of cluster Naghavi et al.45 also clustered the eight genotypes of maize into three classes by using stress tolerant indices like MP, GMP, STI and found that the genotypes with high value of these indices were stress tolerant genotypes which showed mean values were treated as semi tolerant to stress.Using grain yield (under both conditions) and stress tolerance indices. Tana et al.46 classified all studied genotypes in five clusters according to their performance and stress tolerance degree and found that a genotype with high values of MP, GMP, HM, STI and YSI is best performing and stress tolerant. So, genotypes with high values of MP, GMP, HM, STI and YSI might be used as parents in breeding programs to develop stress tolerant genotypes. Jha et al.41,47,48 generated different clusters of chickpea genotypes to select superior stress tolerance genotypes, based on various stress tolerance indices and other morphological traits and suggested that the genotypes belonging to distant group might be used in breeding programme for producing stress tolerance genotype in chickpea. It was also found that the stress indices, viz. MP, GMP, YI and SSI could be used in breeding programme for selecting superior genotypes to sustain chickpea yield under stressed conditions.

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Table 1: List of genotypes with pedigree used in experiment

Sr. No.	Genotypes	Pedigree
1	Pissaba-12-2004	KAUZ/STAR
2	Ufaq 2002	V.84133/V83150
3	Anmol 91	KVZ/TRM//PTM/ANA
4	Kaghan 93	TTR/JUN
5	Pisaba 2008	KAUZ/PASTOR
6	Hashim 2008	JUP/ALD'S'//KLT'S'/3/VEE'S'/6/BEZ//TOB/8156/4/ON/3/6*TH
7	NIA SAARANG	SHA4/Weaver//Skauz*2/SRMA
8	Wattan 94	LU26/HD 2179
9	Baras 2009	PFAU/SERI//BOW
10	NIFA-BARSAT-10	FRET2
11	GOMAL 7	Atilla
12	Sariab 92	BB/GLL//CARP/3/PVN
13	Bhakhar 2002	P102/PIMA//F371/TTR/BOW/3/PVN
14	Saleem 2000	CHAM6//KITE/PGO
15	Moumal 2002	BUC or BUCS/4/TZPP/IRN46
16	Darawar 97	SASONO KOMOGI/NORIN//BOB'S'
17	Millat 2011	CHENAB2000/INQ-91
18	Janbaz-10	Gen*2//Buc/Filk/3/Buchin
19	NARC 2011	OASIS/SKAUZ//4*BCN/3/2*PASTOR
20	Punjab 2011	AMSEL/ATTILA//INQ-91/PEW'S'
21	78-4SIBW	N/A
22	9452	LU26/HD 2179
23	9705	SH-88/90A-204//MH97
24	9507	PRL/PASTOR//2236
25	9488	PSN/BOW
26	9517	KVZ/TRM//PTM/ANA
27	9479	FORLANI/ACC//ANA or Fln/ACS//ANA
28	9508	CROW'S'/NAC//BOW'S'
29	9703	PFAU'S'/SERI
30	9451	AU/UP301//GLL/Sx/3/PEW S/4/MAI S/MAY A S//PEWS
31	9021	Mentana/Mayo//4-11
32	9512	WLRG 3 1-8 (1993-94)/5039
33	9459-1	C 591/RN//JN/3/CHR/HD 1941
34	9189	HD2160/4/JN/GAGE//JN/KALYANSONA/3/V-18/C-273; HD-2160/WG-1025;
35	9877	LERMA-ROJO-64//NORIN-10/BREVOR/3/3*
36	9247	NP 890 /HD 2160
37	9687	Inq91/30th SAWSN 30 (1998-99)

38	9521	9244/PBW222
39	9495	9244/Iqbal2000
40	9526	9244/Parwaz94
41	9707	PT'S'/3/TOB/LFN//BB/4/BB/HD-832 5//ON/5/GV/ALD'S'//HPO
42	9505	PBW65/2*Pastor
43	9516	CHENAB2000/INQ-91
44	9704	MAYA/MON//KVZ/TRM
45	9519	DWL5023/SNB//SNB
46	9610	Pb96/Watan/MH-97
47	9520	PSN/BOW
48	9522	LUAN/KOH-97
49	9595	LU26'S'/Pb96
50	9622	5039/Rawal87

Table 2: Detail of experiment conducted during 2021-22 and 2022-23

Location	**2021-22**	**2022-23**
Location	GSF Dhakkar	GSF Dhakkar
Date of sowing	26 Oct-10 Dec	28 Oct-10 Dec

Table 3: Combined analysis of variance of grain yield under normal (Yp) and stress (Yp) conditions

	Mean Squares													
SOV	**Df**	**TOL**	**STI**	**SSPI**	**YI**	**YSI**	**RSI**	**MP**	**GMP**	**HM**	**MRP**	**PYR**	**YS**	**YR**
Replication	1	1574.1	0.004	6.25	0.006	0.0016	0.028	726.6	10.35.3	1484.3	0.007	15.93	2190.2	50.4
Genotypes	49	14185.8**	0.05**	45.41***	0.02***	0.01**	0.09***	8483.8*	8007.9*	77223*	0.06**	114.48*	6854.2**	16705.8*
Residuals	49	4300.9	0.004**	15.8	0.004	0.003	0.03	1524.8	1371.6	1308.5	0.011	33.99	1512.5	3667.2

Table 4: Grain yield/plot (g), Yp and Ys under normal and stress conditions and stress tolerance indices of different wheat genotypes.

Genotypes	**Yp**	**Ys**	**TOL**	**STI**	**SSPI**	**YI**	**YSI**	**RSI**	**MP**	**GMP**	**HM**	**MRP**	**PVR**
9452	1108.3	678.8	429.50	0.963	24.29	1.14	0.61	2.42	893.6	867.4	842.02	2.39	38.7
9521	893.67	700.63	193.0	0.801	10.91	1.17	0.78	1.89	797.13	791.26	785.44	2.18	21.60
9707	839.88	692.75	197.13	0.789	11.15	1.16	0.78	1.90	791.31	785.15	779.04	2.17	22.15
9522	914.50	683.75	230.75	0.800	13.05	1.14	0.75	1.98	799.13	790.75	782.47	2.18	25.23

9705	1053.6	564.3	489.2	0.761	27.6	0.94	0.54	2.76	809.0	771.1	735.0	2.14	46.43
Millat 2011	745.75	626	119.75	0.597	6.77	1.05	0.84	1.76	685.8	683.26	680.6	1.89	16.06
Sariab 92	719.8	468.5	251.3	0.431	14.2	0.78	0.65	2.27	594.19	580.74	567.6	1.60	34.9

STIstress tolerance index, MRPmean relative performance, HMharmonic mean, GMPgeometric mean, MPmean productivity, Ys grain yield of genotypes under heat stress condition, YI yield index, Yp grain yield of genotypes under normal condition, YSI yield stability index, PYRpercent yield reduction, RSIrelative stress index, TOLtolerance index, SSPIstress susceptibility percentage index

Table 5: Correlation Coefficient between grain yield (Yp-Ys) of wheat genotypes and stress tolerance indices.

	TOL	STI	SSPI	YI	YSI	RSI	MP	GMP	HM	MRP	PYR	Ys	Yp
TOL	1												
STI	0.354**	1											
SSPI	1**	0.354**	1										
YI	− 0.227*	0.828**	− 0.227*	1									
YSI	− 0.953**	− 0.104^{NS}	− 0.953**	0.464**	1								
RSI	0.959**	0.088^{NS}	0.959**	− 0.478**	− 0.982**	1							
MP	0.454**	0.992**	0.454**	0.765**	− 0.206*	0.197*	1						
GMP	0.354**	0.998**	0.354**	0.830**	− 0.104^{NS}	0.088^{NS}	0.994**	1					
HM	0.249*	0.992**	0.249*	0.885**	0.4^{NS}	− 0.023^{NS}	0.974**	0.994**	1				
MRP	0.353**	0.998**	0.353**	0.831**	− 0.099^{NS}	0.088^{NS}	0.994**	0.999**	0.992**	1			
PYR	0.953**	0.104^{NS}	0.953**	− 0.464**	− 1**	0.982**	0.206*	0.104^{NS}	− 0.4^{NS}	0.099^{NS}	1		
Ys	− 0.227*	0.828**	− 0.227*	1**	0.464**	− 0.478**	0.765**	0.830**	0.885**	0.831**	− 0.464**	1	
Yp	0.781**	0.859**	0.781**	0.431**	− 0.586**	0.582**	0.911**	0.860**	0.798**	0.860**	0.586**	0.431**	1

Table 6: Result of principal component analysis based on grain yield of genotypes and stress tolerance indices.

Components	**PC1**	**PC2**
Eigen value	7.11	5.59
Variance%	54.7	43
Commulative	54.7	97.7
STI	0.99	0.06
MRP	0.99	0.08
HM	0.99	0
GMP	0.99	0.09
MP	0.96	0.22
Ys	0.89	-0.43
YI	0.89	-0.43
Yp	0.89	0.62
YSI	0.76	-0.98
PYR	0.12	0.98
RSI	-0.12	0.98
TOL	-0.09	0.97
SSPI	0.19	0.97

Table 7: Cluster of 50 wheat genotypes

Clusters	Genotypes
Cluster I	20
Cluster II	9
Cluster III	3
Cluster IV	3
Cluster V	13
Cluster VI	1
Cluster VII	1

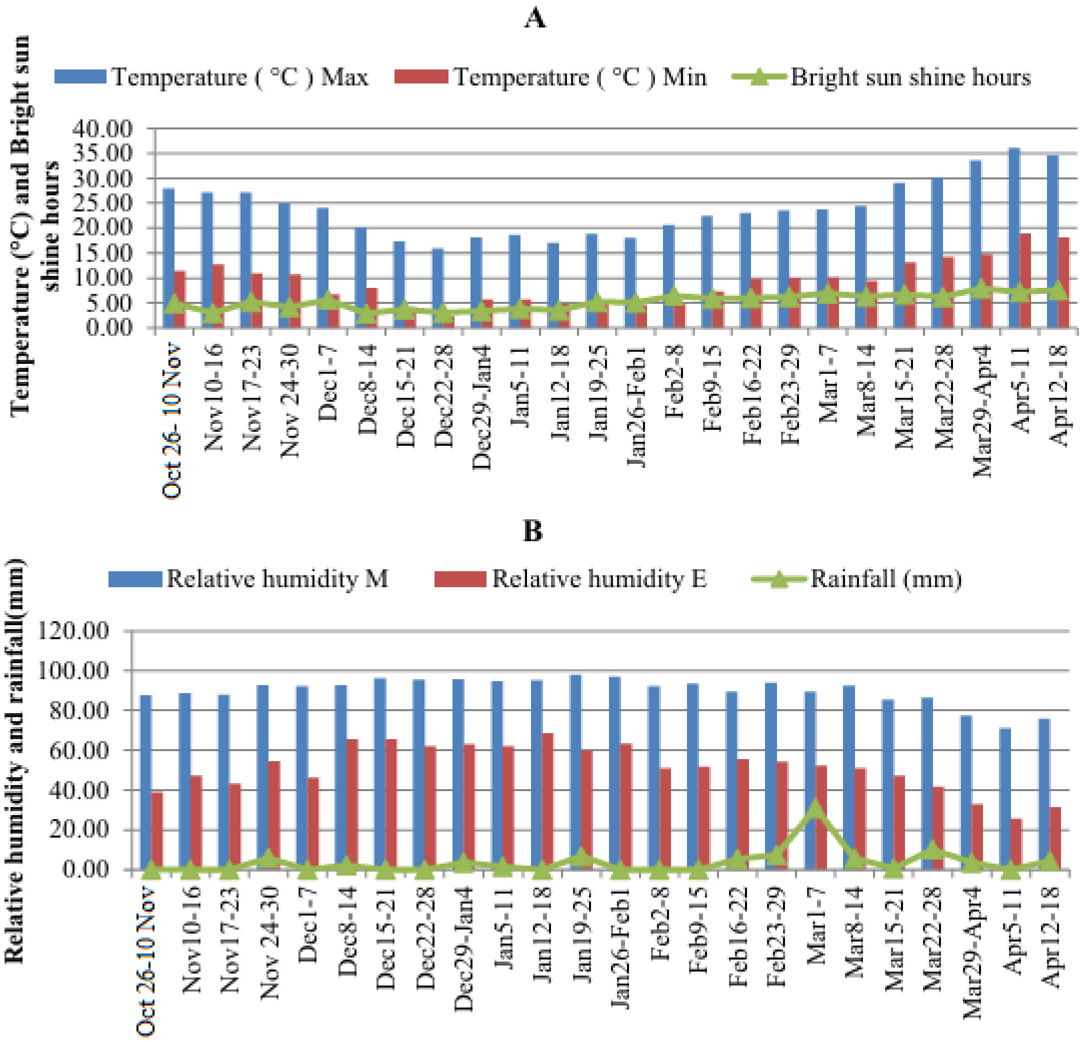

Figure 1. Pooled weekly weather parameters [minimum and maximum temperature (°C), bright sun shine hours (**A**), relative humidity (morning and evening) and rainfall (mm) (**B**)] during wheat growing season 2021-22 and 2022-23

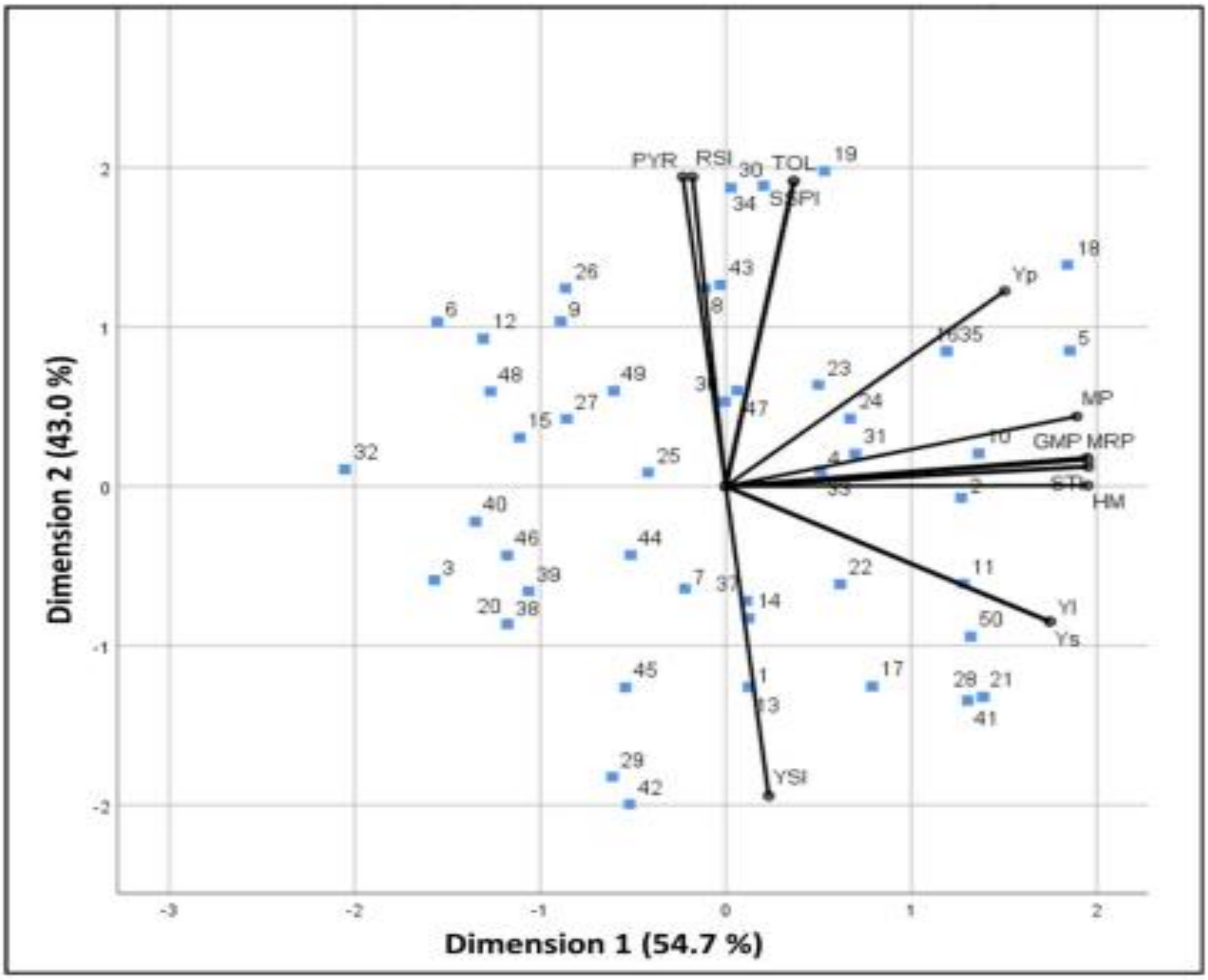

Figure 2. Biplot drawn based on PCA result showing correlation among traits. PC1 (Dimension 1) = First principal component, PC2 (Dimension 2) = Second principal component, STI = Stress tolerance index, MRP = Mean relative performance, HM = Harmonic mean, GMP = Geometric mean, MP = Mean productivity, Ys = Grain yield of genotypes under heat stress condition, YI = Yield index, Yp = Grain yield of genotypes under normal condition, YSI = Yield stability index, PYR = Percent yield reduction, RSI = Relative stress index, TOL = Tolerance index, SSPI = Stress susceptibility percentage index.

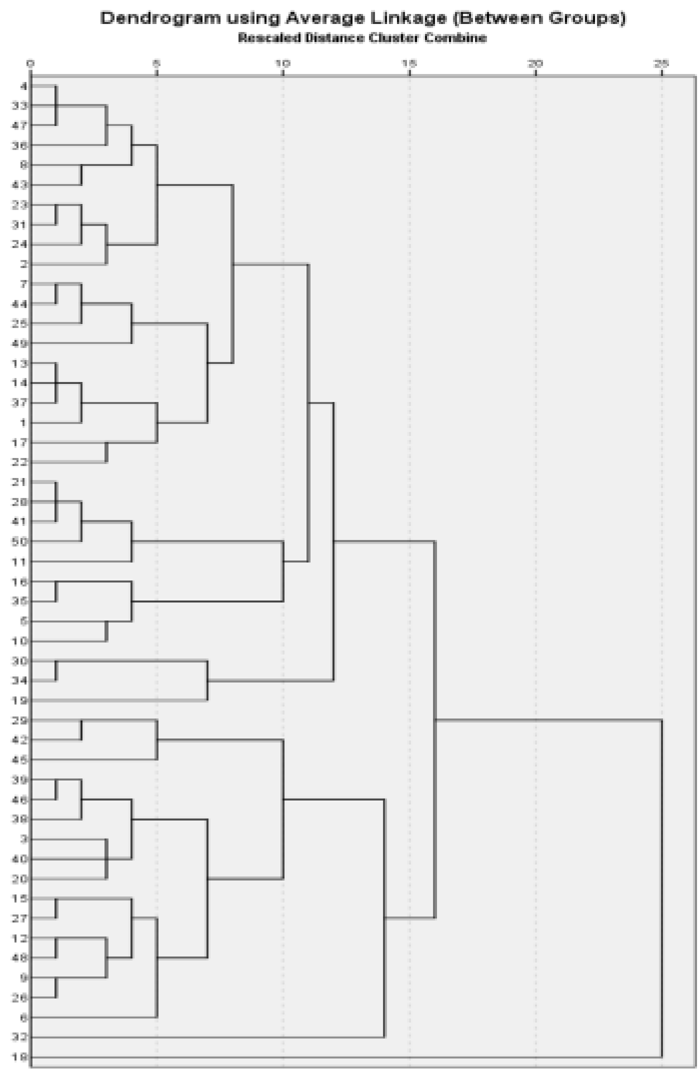

Figure 3: Dendogram of wheat genotypes representing heat indices