Article

Evaluation of Indian Durum Wheat Genotypes for Yield and Quality Traits Using Additive Main-Effects and Multiplicative Interaction (AMMI) Biplot Analysis under Terminal Heat Stress Conditions

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ABSTRACT

The abrupt increase of temperatures during and after the flowering period of wheat is defined as terminal heat stress, and it causes severe reductions in productivity. One hundred two durum wheat lines were evaluated against this stress for three consecutive cropping seasons (2014–2017) in Indore, Madya Pradesh (India). The main objectives were to assess their grain yield potential, stability, and rheological quality characteristics under these conditions, and identify other contributing traits to adaptation. Combined ANOVA across environments showed significant differences ($P < 0.01$) for all factors, and high broad sense heritability was recorded for hectoliter weight, 1000-grains weight, grain yield, number of grains per spike, spike length, days to maturity, total carotene and sedimentation values. Grain yield showed significant ($P < 0.01$) positive associated with biomass, harvest index, hectoliter weight and significant negative associations with day to heading and maturity. Genotypes showed explicit variation to environmental condition as supported by significant ($P < 0.01$) for genotype × environment interaction (GEI). The traits like early heading, maturing, high biomass and hectoliter weight were the most critical traits for adaptation under terminal heat stress. To determine effects of GEI data were subjected to GGE biplot analysis, which identified as the most stable and performing across seasons G-30 (GW 1240) for hectoliter weight and G-98 (Vijay) for grain yield. These entries can now be combined via breeding to develop superior heat stress tolerant varieties.

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KEYWORDS: durum wheat; terminal heat stress; yield stability; heritability; genotype × environment; Additive Main-Effects and Multiplicative Interaction (AMMI)

INTRODUCTION

Durum wheat (*Triticum turgidum* spp. *durum*) is the 10th most important cereal crops in the world that is grown on 8 to 10% of the total wheat-cultivated area [1,2]. Durum wheat is mostly cultivated in the Mediterranean basin [3] as it is used in the traditional diet in the form of pasta, couscous, bulgur and many local food products [4–6]. The largest durum wheat growers are the European Union, followed by Canada, Turkey, United States, Algeria, India, Mexico, Kazakhstan, and Syria [7–14]. India is one of the prime producers of durum wheat with some 1.5 million hectares dedicated to its cultivation each year, accounting for approximately 10% of total wheat production [8]. In India during rabi season 2021–22 total cultivated area of wheat was 33.2 million hectare with the record production of around 106 metric ton and total wheat growing area in Madhya Pradesh was 8.71 million hectare with total wheat production was 18 million metric tons whereas durum wheat covered around 1.3 million hectare, with production of 1.5 million metric ton (Progress report State Department of Agriculture Government of India 2023).

The atmospheric temperature plays a critical role in determining the growth and development of the crop. Temperatures exceeding 22 °C detrimental for durum wheat growth, and are hence commonly defined as “heat stress” [15–19]. When temperatures abruptly increase at the end of the growing seasons these are defined as “terminal heat stress”. In particular, when this occurs during or immediately after the flowering of the crops it can be extremely damaging [8,14,20,21]. In the optic of the globally raising temperatures, developing better varieties adapted to cope with terminal heat stress is critical to ensure productive farming can continue [22].

Due to the importance and difficulty of the challenge, many studies have been conducted to assess the response of genotypes to this stress in search of novel sources of tolerance [23–27]. The identification of stable and high yielding genotypes is critical to achieve sustainable durum wheat farming in arid and semi-arid regions [28,29], especially when accompanied by strategic agronomical practices [30,31]. Grain yield in wheat is influenced by genotype (G), environment (E), and their interaction Genotype × environment (GEI) [29,32]. Genotypes that respond consistently to different environmental conditions are defined as “stable” and tend to be less influenced by GEI [33]. Because of the unpredictability of climatic conditions, farmers are extremely interested by “stable” varieties capable of tolerating more extreme variations. The identification of traits contributing to stability are important for breeding new cultivars with improved adaptation to the environmental constraints [34–36]. It was reported that the additive main effects and multiplicative interaction Additive Main-Effects and Multiplicative Interaction (AMMI) model help to distinguish the GEI pattern from the random error components [37,38]. Thus, the present study was conducted to assess the grain yield stability and performance of 102 durum wheat genotypes under terminal heat stress condition during three cropping seasons to identify stable genotypes.

MATERIALS AND METHODS

Genetic Material

Based on the earlier performance under various environmental conditions, 102 genetically diverse durum wheat genotypes were selected from the germplasm developed by the ICAR-Indian Agriculture Research Institute, Regional Station, Indore, India (Supplementary Table S1).

Field Experiments

The field trials were carried out during three consecutive rabi seasons 2014–15, 2015–16, and 2016–17 at the ICAR-Indian Agricultural Research Institute, Regional Station, Indore, Madhya Pradesh India. The experimental field is situated between 22°37' N latitude to 75°50' E longitude at 557 m above Mean Sea Level (MSL) having semi-arid and tropical climate with temperatures shifting from 23 °C to 41 °C and 7 °C to 29 °C in summer and winter seasons, separately, in January before flowering 7 °C to 24 °C and in February after flowering from 23 °C to 31 °C (Figure 1). In this area, most of the rainfall is received during south-west monsoon, i.e., between June to September, with occasional showers in winter. The sowing was done on the 7th of December each season, which corresponds to late sown conditions as a way to maximize exposure to higher temperatures during the flowering transition. Sowing was done in beds having length of 2.5 m in two row plots with a row to row spacing of 18 cm. The experimental design was a randomize block design (RBD) with three replications. Four gravity irrigations of 30 mm were provided during the crop cycle: germination irrigation just after sowing, vegetative stage between 30 to 40 days after sowing, flowering time 55 to 60 days after sowing, and milking stage 80 to 90 days from date of sowing. Recommended agronomical practices were followed to ensure no inputs deficiencies and minimize external effects. All agronomic parameters were recorded (days to heading [39], days to maturity, spike length, number of grains/spike, grain yield/plant, harvest index, and biomass) and several rheological traits (hectoliter weight, yellow pigment, sedimentation value, and 1000 grain weight).

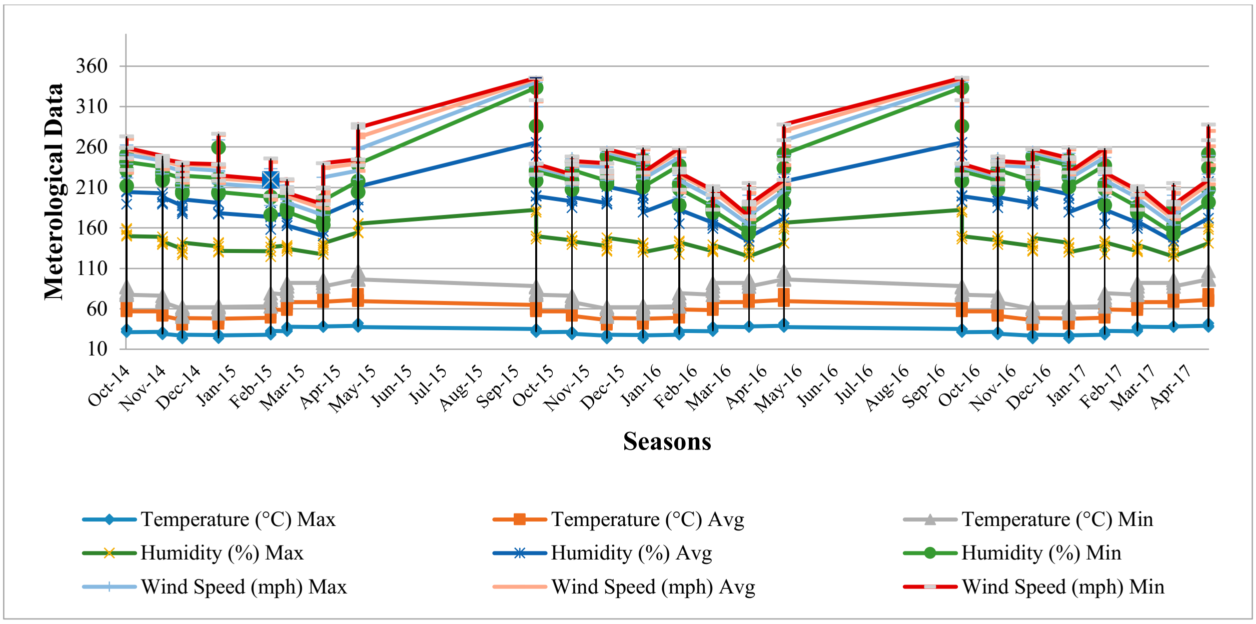

Figure 1. Temperature (°C), Humidity (%), Wind Speed (mph) during crop cycle over the years.

Statistical Analysis

Genstat release 16.1 [40] was used for computing descriptive statistics and correlation analysis. The combined analysis of variance (ANOVA) was performed using Genstat release 16.1 [40], considering genotypes as fixed effects, while years and replications were considered as random effects. The broad sense heritabilities were calculated for each trait using the standard equation [41]. The Additive Main-Effects and Multiplicative Interaction (AMMI) model [42] was run using the Genstat software version 16.1 [40]. The GGE biplot [43,44], was constructed using entry means from each environment for grain yield and quality traits using Genstat software version 16.1 [40]. The GGE biplots model was calculated as follows:

$$(Y_{ij} - \overline{Y}j) = \lambda_1\xi_{i1}\eta_{j1} + \lambda_2\xi_{i2}\eta_{j2} + e_{ij} \quad (1)$$

Where, Y_{ij} = average yield of i^{th} genotype in j^{th} environment, $\overline{Y}j$ = average yield over all genotypes in j^{th} environment and $\lambda_1\xi_{i1}\eta_{j1}$ and $\lambda_2\xi_{i2}\eta_{j2}$ = collectively the first and second principal component (PC1 and PC2); λ_1 and λ_2 = singular values for the first and second principal components, PC1 and PC2, respectively; ξ_{i1} and ξ_{i2} = PC1 and PC2 scores, respectively for the i^{th} genotype; η_{j1} and η_{j2} = PC1 and PC2 scores, respectively for j^{th} environment; and e_{ij} = residual of the model associated with the i^{th} genotype in the j^{th} environment.

RESULTS

The descriptive results for the combined analysis across seasons are presented in Table 1. Mean value of selected traits based on BLUEs of genotypes 2014–2017 showed diversity among the genotypes. (Supplementary Table S2). The set of genotypes tested generated a potential genetic gain of 20.8% for grain yield over the mean, and rates ranging from 3.8% for Days to maturity to 38.0% for total carotene.

Table 1. Mean, range, standard error, genetic advance, genetic advance over mean for different traits in durum wheat under terminal heat stress condition.

Traits	Mean	Max	Min	SE±	Genetic advance	GA over mean (%)
DF (days)	74.8	81.8	61.7	0.6	6.6	8.8
DM (days)	113.1	116.2	101.9	0.4	4.3	3.8
SL (cm)	7.3	9.5	5.8	0.0	1.1	15.2
NG	51.6	68.8	33.6	2.9	12	23.3
BM (g)	55.9	71.3	42.5	7.6	8.1	14.5
HI (%)	34.8	45.1	27.1	4.3	6.8	19.6
TGW (g)	48.3	59.7	39.2	1.7	7.8	16.1
HW (g)	78.4	82.1	70.6	1.1	4.0	5.1
T. Car. (ppm)	4.5	7.7	2.7	0.1	1.7	38.0
SDS (mL)	32.4	43.2	22.3	1.6	6.9	21.3
GY (g)	18.8	26.8	13.9	0.4	3.9	20.8

Max: Maximum; Min: Minimum; GA: genetic advance; DF: day to heading; DM: days to maturity; SL: spike length; NG: number of grains/spike; BM: biomass; HI: harvest index; TGM: 1000 grain weight; HW: hectoliter weight; T. Car.: total carotene; SDS: sedimentation value; GY: grain yield/plant.

Table 2. Combined analysis of variance for 102 durum wheat genotypes across three cropping seasons under heat stress conditions.

Statistic	DF	DM	SL	NG	BM	HI	TGW	HW	T. Car.	SDS	GY
H^2	0.88	0.72	0.74	0.77	0.54	0.31	0.78	0.86	0.71	0.70	0.77
GV	10.9**	4.7**	0.4**	36.9**	21.2**	4.2**	16.0**	4.6**	0.8**	12.7**	4.0**
G × E	4.4**	5.3**	0.4**	31.6**	51.9**	26.9**	13.2**	1.9**	1.0**	15.5**	3.6**
RV	0.6	0.4	0.1	2.9	7.6	3.8	1.7	1.1	0.1	1.6	0.4
GM	74.8	113.1	7.3	51.6	55.9	34.8	48.3	78.4	4.5	32.4	18.8
LSD	3.2	3.2	0.8	8.1	8.7	4.7	5.3	2.2	1.4	5.4	2.7
CV (%)	1.0	0.6	3.0	3.3	4.9	5.6	2.7	1.3	8.5	3.9	3.3

** significant at 5% and 1% level of probability, respectively; H^2: Heritability; GV: Genotypic Variance; G × E: Genotypic × Environment; RV: Residual Variance; GM: Grand Mean; LSD: Least significant difference; CV: Coefficient of variation; DF: day to heading; DM: days to maturity; SL: spike length; NG: number of grains/spike; BM: biomass; HI: harvest index; TGW: 1000 grain weight; HW: hectoliter weight; T. Car.: total carotene; SDS: sedimentation value; GY: grain yield/plant.

In Table 2 is summarized the descriptive statistics for the combined analysis. All the studied traits over the years revealed significant effects ($P < 0.01$) for the years. The coefficient of variation (CV) for the investigated traits across environments varied between 0.58% (days to maturity) to 8.49% (total carotene). The lowest CV was observed for number of grains per spike (3.33%), followed by sedimentation value (3.94%), biomass (4.94%), harvest index (5.26%), and highest for total carotene (8.49%). The heritability ranges from 0.31 (harvest index) to 0.88 (days to heading) across the environments. The heritability for grain yield across environments was 0.77, indicating the influence of environment on grain yield, but also indicating that efficient selection and genetic gain can be made. High estimates of heritabilities were observed for hectolitre weight (0.86), followed by 1000 grain weight (0.78), grain yield (0.77), number of grains per spike (0.77), spike length (0.74) and other traits like days to maturity, total carotene and SDS values were an indicator that these traits have a strong genetic component under limited environmental influence.

Phenotypic Correlation among the Traits under Terminal Heat Stress

Phenotypic correlations between grain yield and the other traits are presented in Table 3 (Supplementary Figure S1). The most significant (P < 0.01) contributing traits were biomass (0.63), harvest index (0.45), hectoliter weight (0.23), while significant (P < 0.01) negative correlation were identified with day to heading (−0.17) and days to maturity (−0.18). As it can be expected, day to heading showed highly positive association with days to maturity (0.80) but also number of grains/ spike (0.26), total carotene (0.29), and a negative association with spike length (−0.26) and 1000-grains weight (−0.41). The number of grains/spike showed positive association with hectoliter weight (0.41), total carotene (0.26). and sedimentation value (0.24). Biomass showed negative association with harvest index (−0.39).

Table 3. Phenotypic correlation coefficients between mean yield and other traits across three cropping seasons under heat stress conditions.

Traits	DF	DM	SL	NG	BM	HI	TGW	HW	T. Car.	SDS
DM	0.80**									
SL	−0.26**	−0.26**								
NG	0.26**	0.15 ns	0.04 ns							
BM	−0.13 ns	−0.06 ns	0.19*	0.19*						
HI	−0.03	−0.10 ns	−0.12 ns	−0.10 ns	−0.39**					
TGW	−0.41**	−0.28**	0.14 ns	−0.18*	0.11 ns	−0.03 ns				
HW	0.05 ns	−0.03 ns	−0.21**	0.41**	0.19*	0.04 ns	0.03 ns			
T. Car.	0.29**	0.32**	0.06 ns	0.28**	0.05 ns	−0.06 ns	−0.20*	0.06 ns		
SDS	0.08 ns	0.04 ns	0.02 ns	0.24**	−0.08 ns	0.17*	−0.02 ns	0.21*	0.29**	
GY	−0.17*	−0.18*	0.13 ns	0.11 ns	0.63**	0.45**	0.07 ns	0.23**	0.01 ns	0.09 ns

*, ** significant at 5% and 1% level of probability, respectively; ns: non-significant; DF: day to heading; DM: days to maturity; SL: spike length; NG: number of grains/spike; BM: biomass; HI: harvest index; TGW: 1000 grain weight; HW: hectoliter weight; T. Car.: total carotene; SDS: sedimentation value; GY: grain yield/plant.

Stability Analysis for Grain Yield and Other Trait by Additive Main-Effects and Multiplicative Interaction (AMMI) Biplot Analysis

Additive Main-Effects and Multiplicative Interaction (AMMI) was performed for grain yield to assess GEI (Supplementary Table S3). Biplot is the most powerful interpretive tool for Additive Main-Effects and

Multiplicative Interaction (AMMI) model. We constructed a biplot for each trait where the main effects and IPCA scores are plotted against each other for genotypes and environments (Supplementary Table S3).

DF: The distribution of the environments indicates that the environments used are distinct for this trait. PCA 1 and PCA 2 were both significant and accounted for 63.4% and 36.6% of the phenotypic variance, respectively. The biplot placed indicated that G-11 (Bijaja Red), G-47 (HI 8653), G-8 (B 4447-BA) and G-81 (NIDW 70) were the most stable genotypes under terminal heat stress condition (Figure 2a,b).

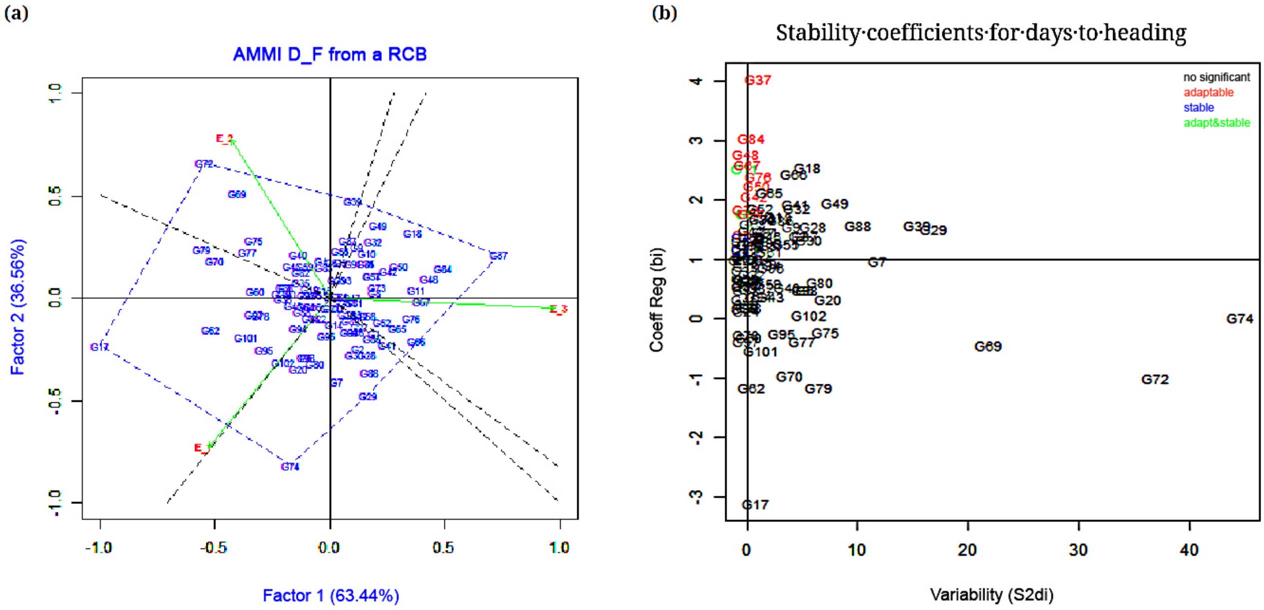

Figure 2. (**a**) The "which-won-where" view of the GGE biplot based on the G × E data for days to flowering. It explained 100% of the total G + GE. The genotypes are labeled as 1 to 102 and the environments are labeled as E1 to E3. (**b**) The biplot display of days to heading (DtH), biplot explains variability and regression coefficient of genotypes, it also explains adaptability and stability of the genotypes for days to heading, under terminal heat stress conditions.

SL: PCs of Additive Main-Effects and Multiplicative Interaction (AMMI) biplot for spike length showed that PCA 1 and PCA 2 were significant. PC1 and PC2 accounted for 54.4% and 45.6% of variance respectively. It means that by using PC1 and PC2, the analysis could explain 100% variation (Supplementary Table S3). The genotypes G-19 (DWL 5023), G-24 (GW 2), G-26 (GW 1139), G-4 (HI 8550), G-40 (HI 8498), G-42 (HI 8591), G-44 (HI 8627), G-45 (HI 8638), G-48 (HI 8663), G-51 (HI 8691) and G-6 (Amrut) were the most adaptable genotypes for spike length, similarly G-27 (GW 1170), G-4 (AKDW 4240) and G-90 (Raj 6516) were the most stable genotypes and G-4 (AKDW 4240) was the most adaptable and stable genotypes for spike length yield under terminal heat stress condition.

NG: PCs of Additive Main-Effects and Multiplicative Interaction (AMMI) biplot for number of grains/spike showed that PCA 1 and PCA 2 were significant. PC1 and PC2 accounted for 52.3% and 47.7% of variance respectively. It means that by using PC1 and PC2, the analysis could explain 100 % variation (Supplementary Table S3). The distribution of the environments in the biplot with variable environment means and IPCA scores indicate that the environments behaved very distinct compared each other and selecting of the adaptable and high yielding genotypes among these environments will be useful for terminal heat stress in durum wheat. Among the environments, E2 had short vectors and they did not exert strong interactive forces while E1 and E3 with long vectors were more differentiating environments. The genotypes near the origin are not sensitive to environmental interaction and those distant from the origin are sensitive and have more G × E interactions. The genotypes G-1 (A-9-30-1), G-100 (WH 912), G-3 (AKDW 4151), G-38 (HI 7747), G-39 (HD 4709), G-5 (Altar), G-52 (HI 8722), G-53 (IWP 5004-1), G-56 (IWP 5013), G-74 (MPO 215), G-86 (PDW 233) and G-99 (WH 896) were the most adaptable genotypes for number of grains/spike, similarly G-12 (Bijaga Yellow) and G-55 (IWP 5013) were the most stable genotypes for number of grains/spike under terminal heat stress condition (Figure 3a,b).

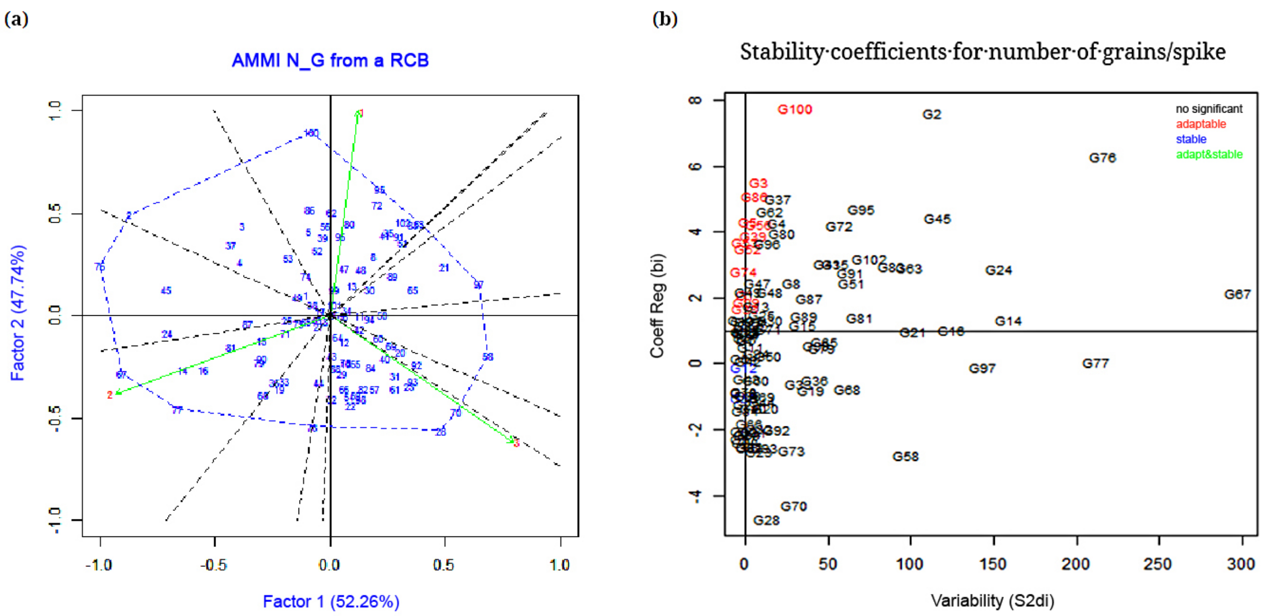

Figure 3. (**a**) The "which-won-where" view of the GGE biplot based on the G × E data for days to flowering. It explained 100% of the total G + GE. The genotypes are labeled as 1 to 102 and the environments are labeled as E1 to E3. (**b**) The biplot display of number of grains per spike (NG), biplot explains variability and regression. coefficient of genotypes, it also explains adaptability and stability of the genotypes for number of grains per spike under terminal heat stress conditions.

BM: PCs of Additive Main-Effects and Multiplicative Interaction (AMMI) biplot for biomass showed that PCA 1 and PCA 2 were significant. PC1 and PC2 accounted for 74.6% and 25.4% of variance respectively. It means that by using PC1 and PC2, the analysis could explain 100% variation (Supplementary Table S3). Among the environments, E2 had short vectors and they did not exert strong interactive forces while E1 and E3 with long vectors were more differentiating environments. The genotypes near the origin are not sensitive to environmental interaction and those distant from the origin are sensitive and have more G × E interactions. The genotypes G-25 (GW 1114), G-27 (GW 1170), G-30 (GW 1240), G-31 (GW 1244), G-37 (HG 110), G-40 (HI 8498), G-51 (HI 8691), G-55 (IWP 5013), G-6 (Amrut), G-62 (Line 1172), G-77 (N 59), G-82 (NIDW 295), G-89 (Raj 6069) and G-90 (Raj 6516) were the most adaptable genotypes for biomass, similarly only G-12 (Bijaga yellow) was the most stable genotype for biomass under terminal heat stress condition.

HI: PCs of Additive Main-Effects and Multiplicative Interaction (AMMI) biplot for harvest index showed that PCA 1 and PCA 2 were significant. PC1 and PC2 accounted for 66.8% and 33.2% of variance respectively and IPC3 contribute 0.0% variation of the total with Pr. *F* value more than 0.00. It means that by using PC1 and PC2, the analysis could explain 100 % variation (Supplementary Table S3). Among the environments, E2 had short vectors and they did not exert strong interactive forces while E1 and E3 with long vectors were more differentiating environments. The genotypes near the origin are not sensitive to environmental interaction and those distant from the origin are sensitive and have more G × E interactions. The genotypes G-10 (Baxi 228-18), G-15 (DBP 01-09), G-25 (GW 114), G-27 (GW 1170), G-5 (Altar 84), G-50 (HI 8671), G-6 (Amrut), G-71 (Mandsaur local), G-74 (MPO 215), G-77 (N 59), G-89 (Raj 6069), G-9 (Bansi local) and G-97 (VD 97-15) were the most adaptable genotypes for harvest index, similarly G-33 (HD 4502), G-41 (HI 8550), G-77 (N 59) and G-91 (Raj 6562) were the most stable genotypes and G-77 (N 59) was the most adaptable and stable genotypes for harvest index under terminal heat stress condition.

TGW: PCs of Additive Main-Effects and Multiplicative Interaction (AMMI) biplot for 1000 grain weight showed that PCA 1 and PCA 2 were significant. PC1 contribute 52.9% variation to the total whereas PC2 contribute 47.1% to the total variation. It means that by using PC1 and PC2, the analysis could explain 100% variation (Supplementary Table S3). Additive Main-Effects and Multiplicative Interaction (AMMI) biplot placed genotypes G-10 (Baxi 228-18), G-11 (Bijaga Red), G-14 (CPAN 6236), G-29 (GW 1225), G-31 (GW 1244), G-44 (HI 8627), G-45 (HI 8638), G-46 (HI 8645), G-47 (HI 8653), G-48 (HI 8663), G-66 (MACS 2846), G-68 (MACS 3063), G-71 (Mandsaur local) and G-91 (Raj 6562) were the most adaptable genotypes for 1000 grain weight, similarly G-67 (MACS 3061) and G-82 (NIDW 70) were the most stable genotypes and G11 (Bijaga Red) and G-8 (B 4447-BA) were the most adaptable and stable genotypes for 1000 grain weight under terminal heat stress condition (Figure 4a,b).

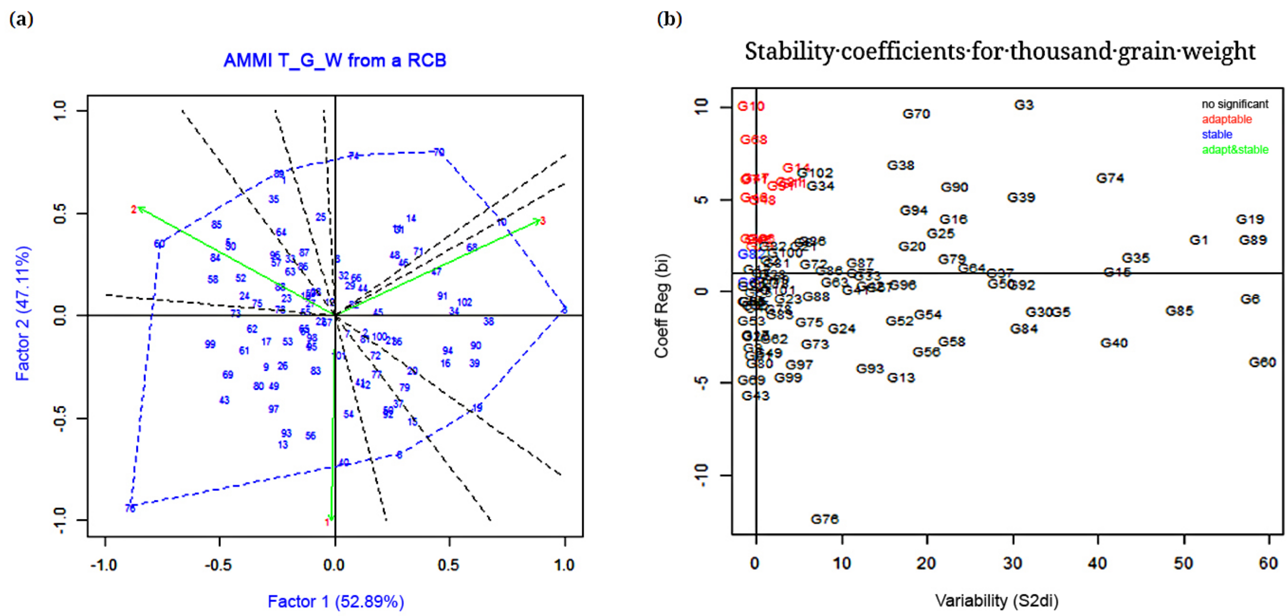

Figure 4. (**a**) The "which-won-where" view of the GGE biplot based on the G × E data for TGW. It explained 100% of the total G + GE. The genotypes are labeled as 1 to 102 and the environments are labeled as E1 to E3. (**b**) The biplot display of 1000 grain weight, biplot explains variability and regression coefficient of genotypes, it also explains adaptability and stability of the genotypes for 1000 grain weight under terminal heat stress conditions.

HW: PCs of Additive Main-Effects and Multiplicative Interaction (AMMI) biplot for hectoliter weight showed that PCA 1 and PCA 2 were significant. PC1 and PC2 accounted for 69.9% and 30.1% of variance respectively. It means that by using PC1 and PC2, the analysis could explain 100% variation (Supplementary Table S3). Among the environments, E1 had short vectors and they did not exert strong interactive forces while E2 and E3 with long vectors were more differentiating environments. The genotypes G-10 (Baxi 228-18), G-15 (DBP 01-09), G-25 (GW 114), G-27 (GW 1170), G-5 (Altar 84), G-50 (HI 8671), G-6 (Amrut), G-71 (Mandsaur local), G-74 (MPO 1215), G-77 (N 59), G-89 (Raj 6069), G-9 (Bansi local) and G-97 (VD 97-15) were the most adaptable genotypes Hectoliter weight, similarly G-22 (Guji 'S'), G-26 (GW 1139), G-30 (GW 1240), G-50 (HI 8671), G-68 (MACS 3063), G-83 (NP 4) and G-87 (PDW 245) were the most stable genotypes and G-30 (GW 1240) was the most adaptable and stable genotypes for hectoliter weight under terminal heat stress condition.

T. Car.: For total carotene, Additive Main-Effects and Multiplicative Interaction (AMMI) biplot analysis between the mean values and the mean of IPCA scores (Figure 5a,b) indicated that there is no much distinct behavior among the environments. PCs of Additive Main-Effects and Multiplicative Interaction (AMMI) biplot showed that PCA 1 and PCA 2 were significant. PC1 and PC2 accounted for 66.9% and 33.1% of variance respectively. It means that by using PC1 and PC2, the analysis could explain 100% variation (Supplementary Table S3). Additive Main-Effects and Multiplicative Interaction (AMMI) biplot placed genotypes G-18 (Dohad local), G-19 (DWL 5023), G-24 (GW 2), G-25 (GW 1114), G-30 (GW 1240), G-67 (MACS 3061), G-71 (Mandsaur local), G-74 (MPO 215), G-77 (N 59), G-78 (NI 5759), G-96 (V 21/23) were the most adaptable genotypes for total carotene under terminal heat stress condition.

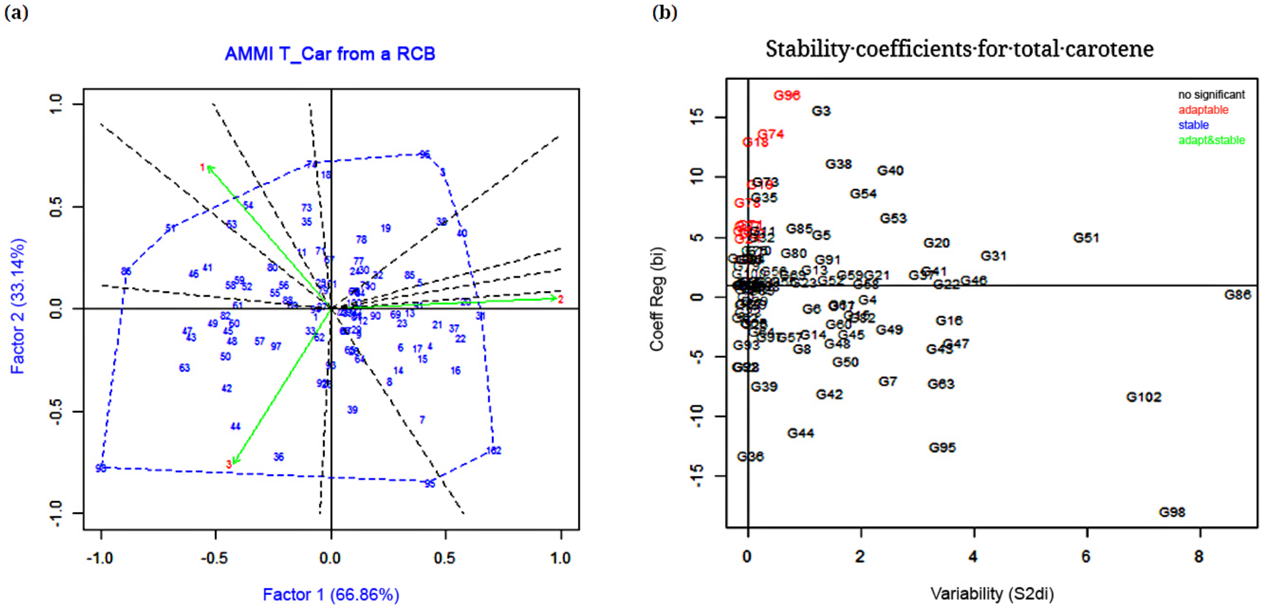

Figure 5. (**a**) The "which-won-where" view of the GGE biplot based on the G × E data for total carotene. It explained 100% of the total G + GE. The genotypes are labeled as 1 to 102 and the environments are labeled as E1 to E3. (**b**) The biplot display of total carotene (T. car.), biplot explains variability and regression. coefficient of genotypes, it also explains adaptability and stability of the genotypes for total carotene under terminal heat stress conditions.

SDS value: For sedimentation value, Additive Main-Effects and Multiplicative Interaction (AMMI) biplot analysis between the mean values and the mean of IPCA scores (Figure 6a,b) indicated that there is no much distinct behavior among the environments. PCs of Additive Main-Effects and Multiplicative Interaction (AMMI) biplot showed that PCA 1 and PCA 2 were significant. PC1 and PC2 accounted for 60.1% and 39.9% of variance respectively. It means that by using PC1 and PC2, the analysis could explain 100% variation (Supplementary Table S3). Additive Main-Effects and Multiplicative Interaction (AMMI) biplot placed genotypes G-19 (DWL 5023), G-24 (GW 2), G-27 (GW 1170), G-31 (GW 1244), G-32 (GW 1245), G-34 (HD 4672), G-5 (Altar 84), G-63 (MACS 9), G-72 (Meghdoot), G-89 (Raj 6069), G-90 (Raj 6516) and G-95 (Trinakria) were the most adaptable genotypes for sedimentation value, similarly G-19 (DWL 5023) and G-52 (HI 8722) were the most stable genotypes and G-19 (DWL 5023) was the most adaptable and stable genotypes for sedimentation value under terminal heat stress condition.(Figure 6a,b).

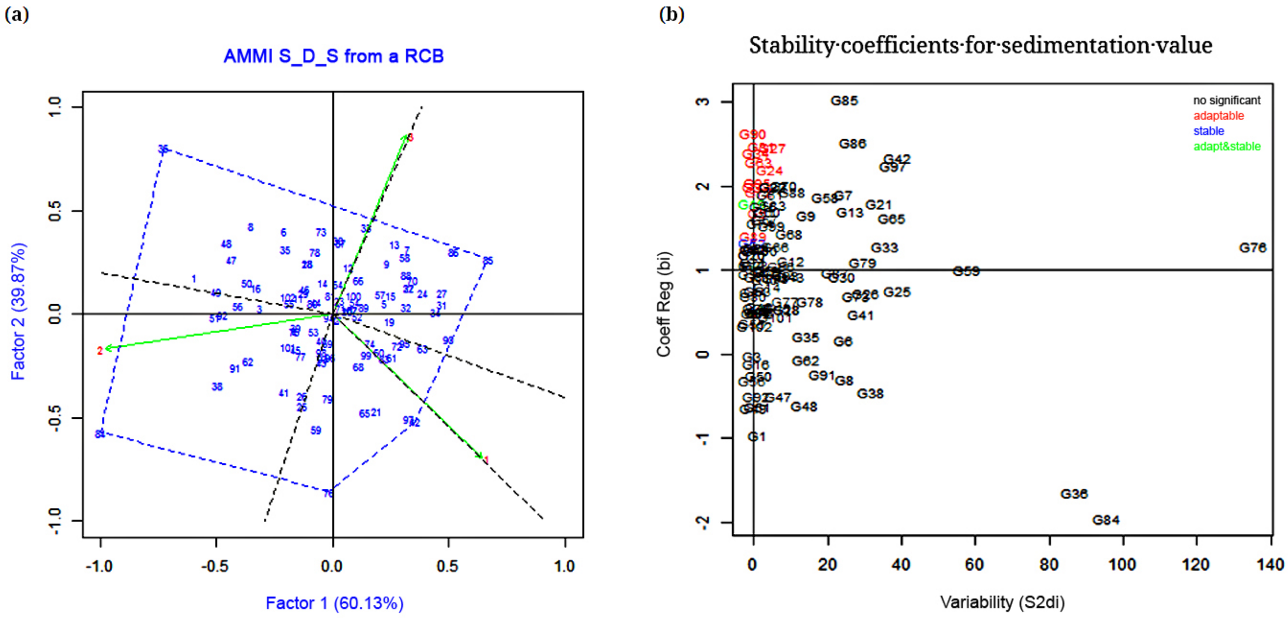

Figure 6. (**a**) The "which-won-where" view of the GGE biplot based on the G × E data for sedimentation value. It explained 100% of the total G+GE. The genotypes are labeled as 1 to 102 and the environments are labeled as E1 to E3. (**b**) The biplot display of sedimentation value (SDS), biplot explains variability and regression. coefficient of genotypes, it also explains adaptability and stability of the genotypes for sedimentation value under terminal heat stress conditions.

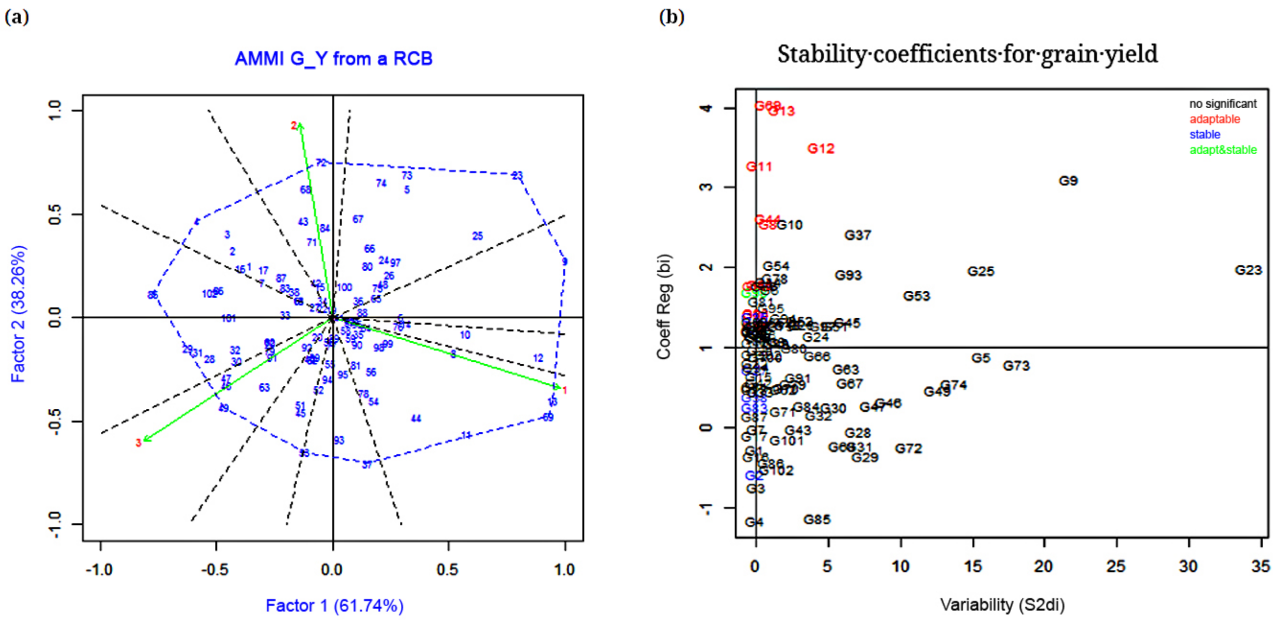

Figure 7. (**a**) The "which-won-where" view of the GGE biplot based on the G × E data for grain yield. It explained 100% of the total G + GE. The genotypes are labeled as 1 to 102 and the environments are labeled as E1 to E3. (**b**) The biplot display of grain yield (GY), biplot explains variability and regression. coefficient of genotypes, it also explains adaptability and stability of the genotypes for grain yield under terminal heat stress conditions.

Grain yield/plant: PCs of Additive Main-Effects and Multiplicative Interaction (AMMI) biplot for grain yield/plant showed that PCA 1 and PCA 2 were significant. PC1 and PC2 accounted for 61.7% and 38.3% of variance respectively. It means that by using PC1 and PC2, the analysis could explain 100% variation (Supplementary Table S3). Among the environments, E2 had short vectors and they did not exert strong interactive forces while E1 and E3 with long vectors were more differentiating environments. The genotypes near the origin are not sensitive to environmental interaction and those distant from the origin are sensitive and have more G × E interactions.

The genotypes G11 (Bijaga Red), G12 (Bijaga yellow), G-13 (CDW 04), G-44 (HI 8627), G-56 (IWP 5070), G-64 (MACS 1967), G-69 (MACS 3125), G-8 (B 447-BA), G-90 (Raj 6516), G-96 (V 21/23), G-98 (Vijay) and G-99 (WH 912) were the most adaptable genotypes for grain yield, similarly G-2 (A 206), G-27 (GW 1170), G-38 (HI 7747), G-83 (NP 4) and G-98 (Vijay) were the most stable genotypes and G-98 (Vijay) was the most adaptable and stable genotypes for grain yield under terminal heat stress condition. (Supplementary Table S4) (Figure 7a,b). Diversity of most stable genotypes were observed for various traits under terminal heat stress over the years (Table 4).

Table 4. Performance of genotypes for various traits over the years under terminal heat stress conditions.

Overall Yield	Early DtH	BM	TGW	SL	T. Car.	SDS	NG
HI 8627	Bijaja Red	GW 1114	Baxi 228-18	DWL 5023	Dahod local	DWL 5023	A-9-30-1
Bijaga yellow	HI 8653	GW 1170	Bijaga Red	GW 2	DWL 5023	GW 2	WH 912
CDW 04	B 4447-BA	GW 1240	CPAN 6236	Gw 1139	GW 2	GW 1170	AKDW 4151
IWP 5070	NIDW 70	HG 110	GW 1225	HI 8550	GW 1114	GW 1244	HI 7747
MACS 1967		HI 8498	HI 8627	HI 8498	GW 1240	GW 1245	HD 4709
MACS 3125		HI 8691	HI 8645	HI 8591	MACS 3061	MACS 9	Altar
Raj 6516		IWP 5013	HI 8653	HI 8627	MPO 215	Meghdoot	HI 8722
V 21/23		Line 1172	HI 8663	HI 8638	N 59	Raj 6069	IWP 5004-1
HI 7747		Raj 6069	MACS 2846	HI 8663	NI 5759	HD 4672	PDW 233
NP 4		Raj 6516	MACS 3063	HI 8691	V 21/23	HI 8722	WH 896

DISCUSSION

High temperature occurring during reproduction and grain filling period reduce wheat productivity [20,45,46]. The use of delayed sowing ensured that flowering and grain filling stages occurred under warmer conditions (Figure 1) [18]. Our results confirmed that genetic diversity exists for the response to terminal heat stress, with some genotypes better suitable to tolerate this stress. High heritability values were exhibited for most traits, suggesting that genetic gain is possible for them. This is accordance with what previously reported [47,48]. Low heritability values of traits like biomass and harvest index suggest that selection for these characters would not be effective due to predominant effects of non-additive components and the high influenced by the environmental factors [33,49–52].

Maximum expected genetic advance was observed for total carotene, number of grains per spike, sedimentation value, grain yield/plant and harvest index promoting these for breeding selection [53]. Especially, those traits with high heritability and high genetic advance are the most interesting targets for breeders [54–56]. Bijaga Red, Bijaga yellow, CDW 04, HI 8627, IWP 5070, MACS 1967, MACS 3125, B 447-BA, Raj 6516, V 21/23, Vijay and WH 912 were the most adaptable genotypes for grain yield, were the most adaptable genotypes for grain yield, similarly A 206, GW 1170, HI 7747, NP 4 and Vijay were the most stable genotypes and Vijay was the most adaptable and stable genotypes for grain yield under terminal heat stress condition [57,58].

Under terminal heat stress, our correlation study confirmed that genotypes heading and maturing earlier tend to yield significantly more. Furthermore, high biomass production was confirmed to be a critical trait for adaptation, together with hectoliter weight [59–61]. However, it is valuable to underline that grains number and TGW were not important to determine overall performances of genotypes under terminal heat stress [62,63]. Hence, breeders interested in developing varieties better adapted to terminal heat stress should target short duration types capable of producing high biomass and converting it to yield via seeds having high hectoliter weight, but not TGW [64–71]. Our results also suggest genotypic-dependent heat stress effects on grain quality attributes as suggested by [72–75].

Stability Analysis for Grain Yield and Other Trait by Additive Main-Effects and Multiplicative Interaction (AMMI) Biplot Analysis

Combined analysis of variance showed that both genotype and environment mean sum of squares were significant for grain yield as it was in the ADDITIVE MAIN-EFFECTS AND MULTIPLICATIVE INTERACTION (AMMI) model. Biplot analysis was conducted and visualized to determine the differences among the environments, to evaluate stable and wide adaptable genotypes, and to evaluate the environments which differentiates the genotypes. In this biplot, the usual interpretation of a biplot assay is that if a genotype or an environment has IPCA score nearly zero, it has small interaction effects and found to be stable, results of present study are in conformity with [76–84]. The distribution of the environments in the biplot with variable environment means and IPCA scores indicate that the environments behaved very distinct compared to each other and selection of the adaptable and high yielding genotypes among these environments will be useful for late heat stress in durum wheat. In the current study, environments E1 and E3 had long vectors which resulted in most variation to differentiate the genotypes [85–95]. A 206, GW 1170, HI 7747, NP 4 and Vijay were the most adaptable and stable genotypes over the years. On the basis of adaptation and stability, genotypes G-11 (Bijga Red), G-8 (B 4447-BA) for day to heading, G-97 (VD 97-15) for days to maturity, G-4 (AKDW 4240) for spike length, G-77 (N 59) for harvest index, G-30 (GW 1240) for hectoliter weight, G-19 (Bansi local for sedimentation value) and G-98 (Vijay) for grain yield were highly adapted and most stable for different traits across the environments, and can be used in convergent durum wheat breeding program to develop heat stress tolerant varieties.

SUPPLEMENTARY MATERIALS

The following supplementary materials are available online at https://doi.org/10.20900/cbgg20230004. Supplementary Table S1: List of genotypes used in the experiment. Supplementary Table S2: Mean value of selected traits based on BLUEs of genotypes 2014–2017. Supplementary Table S3: Analysis of variance of principle components of biplot genotype and location of the traits across three cropping seasons under heat stress conditions. Supplementary Table S4: Performance of genotypes for adaptability, stability and both genotypic adaptability and stability for all the selected traits under terminal heat stress conditions. Supplementary Figure S1: The biplot based on the correlation data for grain yield with other yield contributing traits. It explained 69.74% of the total G + GE where PC1 and PC2 accounted for 42.36% and 27.38% of variance respectively.

DATA AVAILABILITY

The dataset of the study is available from the authors upon reasonable request.

AUTHOR CONTRIBUTIONS

AG: Performed field evaluations and data analyses and writing original draft; SVSP & AJ: Guided during the whole experiment; FB: Provided a critical review of the manuscript and approved the final manuscript.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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