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GENETIC AND STABILITY ANALYSES FOR THE SELECTION OF TERMINAL HEAT STRESS TOLERANT WHEAT (*Triticum aestivum*) GENOTYPES IN BANGLADESH

M.T. ANWAR, T. CHAKI, and G.H.M. SAGOR*

Department of Genetics and Plant Breeding, Bangladesh Agricultural University, Mymensingh-2202, Bangladesh
Corresponding author's emails: sagorgpb@gmail.com, sagorgpb@bau.edu.bd
Email addresses of co-authors: tahsinulanwar@gmail.com, ayushmitachaki@gmail.com

SUMMARY

The high temperature during crop growing seasons is prevalent in the Indo-Gangetic region, causing heat stress to the plants. Heat stress in wheat is a threat to food security and agricultural sustainability. Finding a heat-stress stable wheat genotype is a timely demand. A field study scrutinized 60 genotypes, designed with five different sowing dates, each with 10-day intervals, to identify the stable one. All the growth parameters showed significant responses to terminal heat stress effects. Wheat yield declined by 20%–57% with the successive heat-stress increases with late sowing dates. Most plant growth parameters had a similar or slight variation in genotypic coefficient of variation (GCV) and phenotypic coefficient of variation (PCV). The higher PCV in pollen sterility, chlorophyll content, and the number of filled grains than GCV indicates environmental influence on the expression of the characters studied. These parameters also showed a direct positive effect on crop yield when analyzed in their path coefficients. Genotype performance in yield incurred heat-stress tolerance index tests and revealed that Sourav, Gourav, SA-8, Chyria 3, CB-47, and Sabia genotypes had suitable tolerance, stress-susceptibility, and high-yield stability indexes, indicating higher yields in stress condition. AMMI analysis also showed a significant variation, and the genotypes SA-8, Chyria 3, Pavan, DSN-117, and Sonalika were the most stable. The most unstable genotypes were SA-2, Kheri, and FYN-PVN. The genotypes SA-8, Chyria 3, Pavan, DSN-117, and Sonalika can benefit further breeding as sources of genetic material to develop heat-tolerant, high-yielding wheat varieties.

Keywords: Wheat, heat stress, heat tolerance indices, stability model (AMMI), stable genotypes

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Key Findings: Heat stress significantly affected all the yield-contributing parameters, causing yield reduction at late sown dates by 20%–57% than the optimum planting date. Yield-contributing parameters which had high heritability also influenced environmentally, among the 60 genotypes of wheat SA-8, Chyria 3, Pavan, DSN-117 and Sonalika showing stable performance under different heat-stress conditions, opposite to the SA-2 genotype. The selected materials can further benefit as source materials to develop heat-tolerant, high-yielding wheat varieties.

INTRODUCTION

After rice (*Oryza sativa*), wheat (*Triticum aestivum* L.) is the cereal crop with the second-highest nutritional value (Bhatt *et al.,* 2016). It is crucial for human nutrition and industrial uses. Crop production worldwide incurs serious threats from heat stress due to high ambient temperatures (Kumar *et al.,* 2019). Since the middle of the 19th century, the earth's surface temperature has risen at a rate of 1.09 °C (Ferdous *et al.,* 2023). A prediction of a 1 °C temperature increase would result in a 6%, 3.2%, and 7.4% decline in global wheat, rice, maize, and soybean yields, respectively (Zhao *et al.,* 2017). An anticipated average global temperature will rise by 0.9 °C-1.2 °C by the end of the 21st century (Siegert *et al.,* 2020). Wheat is very heat-stress susceptible from a morphological viewpoint because post-anthesis heat stress negatively impacts wheat grain development. Continuous heat stress lasts the entire wheat growing season, whereas terminal heat stress begins at reproductive growth stages, primarily from heading to maturity stages (Prasad *et al.,* 2008). In wheat, the anthesis and grain-filling phases of terminal heat stress affect flowering, pollen viability, availability and translocation of photosynthates to the developing kernel, and starch synthesis and its deposition within the seed, which results in lower grain number, grain weight, and grain quality (Kumar *et al.,* 2019).

According to Karttenberg *et al*. (2015), with a predicted 2 °C rise in temperatures by the middle of the 21st century due to global warming, crops may sustain more thermal stress soon. Likewise, heat stress during the grain-filling stages significantly impacts grain quality (Spiertz *et al*., 2016). The majority of wheat varieties grown in Bangladesh are sensitive to high temperatures; hence, the anticipated climatic changes threaten the yield's safety. Bangladesh will need to have a thorough understanding of the physiological reactions of plants to high temperatures, the mechanisms of heat tolerance, and potential strategies for improving crop thermo-tolerance; however, limited data on varieties exist in Bangladesh. Heat tolerance indices usually serve in the selection of heat-tolerant cultivars in wheat. Information on late sowing and grain yield and its components can help plant breeders increase selection efficiency in breeding programs. In this context, the presented research commenced under terminal heat-stress conditions to identify the most stable and tolerant genotypes that can benefit as source materials to develop heat-tolerant, high-yielding wheat varieties.

MATERIALS AND METHODS

Plant material, experimental layout, and growing conditions

The collected 60 wheat genotypes came from the Genetics and Plant Breeding Department, Bangladesh Agricultural University (BAU) (Table 1). The experiment began following a randomized complete block design (RCBD) with three replications. First sowing transpired on optimum time (T1: 21 November 2022), and terminal heat stress imposition was sowing wheat genotypes in 10-day intervals four times after the optimum time of sowing, on 1 (T2), 11 (T3), 21 (T4), and 31 (T5) December 2022. Data of yield and yield-contributing parameters' recording continued on different stages of growth and maturity. The mean value computation of the characteristics comprised taking the values of individual plants.

Table 1. List of wheat genotypes used in this study.

Genotype	Genotype	Genotype	Genotype
Sonalika	BL-1020	Sabia	BAW 960
Ananda	NK-5	Pavan	BAW 456
Barkat	KT-1-40	Chyria 3	BAW 966
Balaka	PV-79	Opata	BAW 1004
Prodip	KAV-2	Sawghat	BAW 1008
Sufi	DSN-117	Ning 3517	FDS-5
Mayour	SA-2	O-4	Bijoy
Peacock	SA-3	CB-51	Shatabdi
Protiva	SA-7	CB-47	BAW 1006
Sourav	SA-8	D-141	BAW 1027
Gourav	NE-3	D-72	DSN-76
Sohora	BAW 457	TP-2	SADH-12
Kheri	BAW 677	PT-1	SADH-14
Wuhan	BAW 897	K-9107	SADH-22
Kalyan Sona	BAW 898	FYN/PVN	SADH-24

Supplemental Table 1. Ranking of the genotypes according to ASV value.

Ranking	Genotype No.	Genotype Name	PC1	PC2	ASV value
1	37	SA-2	-0.1046	0.0283	0.1762
2	18	Chyria 3	-0.1109	-0.0049	0.1845
3	17	Pavan	0.1226	0.0686	0.2150
4	36	DSN-117	-0.0660	-0.2355	0.2598
5	1	Sonalika	-0.1624	0.1082	0.2909
6	39	Sourav	-0.1869	0.0490	0.3146
7	28	PT-1	0.0689	0.3083	0.3289
8	52	Bijoy	0.1532	-0.2655	0.3680
9	50	BAW 1008	-0.1767	-0.2315	0.3740
10	26	D-72	-0.0690	0.3872	0.4038
11	41	NE-3	-0.0342	0.4008	0.4048
12	9	Protiva	0.1515	-0.3270	0.4128
13	51	FDS-5	0.1137	-0.3725	0.4177
14	49	BAW 1004	0.2598	0.1006	0.4435
15	35	KAV-2	-0.2522	0.1522	0.4460
16	12	Sonora	0.1978	0.3130	0.4540
17	33	KT-1-40	0.2801	0.0027	0.4657
18	4	Bolaka	-0.1860	0.4107	0.5141
19	53	Shatabdi	0.1400	0.4686	0.5232
20	60	SADH-24	0.2965	0.2542	0.5546
21	6	Sufi	0.3152	0.2448	0.5784
22	20	Shughat	-0.3309	0.1858	0.5807
23	45	BAW 898	-0.3425	-0.1688	0.5939
24	42	BAW 457	0.3125	0.3147	0.6075
25	48	BAW 966	-0.3653	-0.0506	0.6094
26	7	Mayor	0.0742	0.6028	0.6153
27	44	BAW 897	-0.3737	-0.1609	0.6418
28	22	O 4	-0.3680	0.2305	0.6538
29	2	Ananda	-0.3919	0.0737	0.6557
30	55	BAW 1027	0.3439	-0.3682	0.6801
31	57	SADH-12	-0.4123	0.0977	0.6924
32	43	BAW 677	-0.4324	0.1186	0.7286
33	31	BL-1020	0.2655	0.5867	0.7343

Supplemental Table 1. (cont'd.)

Ranking	Genotype No.	Genotype Name	PC1	PC2	ASV value
34	46	BAW 960	0.3243	-0.5122	0.7437
35	15	Kalai sona	-0.0238	-0.7485	0.7496
36	59	SADH-22	-0.4490	-0.1225	0.7565
37	24	CB-47	-0.4728	0.2508	0.8251
38	5	Prodip	0.4945	-0.0950	0.8277
39	29	K-9107	-0.4961	0.0908	0.8298
40	34	PV-79	0.4935	-0.1307	0.8308
41	14	Wahan	0.4381	-0.4283	0.8450
42	27	TP-2	-0.5232	-0.0766	0.8733
43	10	SA-7	-0.5045	-0.2498	0.8752
44	32	NK-5	-0.4884	0.3373	0.8793
45	8	Peacock	-0.2866	-0.7521	0.8903
46	23	CB-51	0.5073	-0.2934	0.8929
47	54	BAW 1006	-0.5514	-0.0698	0.9193
48	11	Gourav	0.4257	0.5887	0.9206
49	19	Opata	-0.5370	-0.4242	0.9885
50	56	DSN-76	-0.6816	0.0170	1.1333
51	47	BAW 456	0.6524	-0.4225	1.1641
52	21	Ning 3517	0.6458	0.4677	1.1712
53	3	Barkat	-0.7490	-0.3368	1.2900
54	38	SA-3	0.7617	0.3662	1.3183
55	16	Sebia	-0.8051	0.1502	1.3469
56	25	D-141	0.7368	-0.5648	1.3489
57	58	SADH-14	0.7536	0.6224	1.3990
58	30	FYN-PVN	0.6754	0.8366	1.4003
59	13	Kheri	-0.9787	-0.7928	1.8100
60	40	SA-8	1.9085	-1.0301	3.3359

Estimation of components of variation and genetic parameters

Different genetic parameters focusing on the optimum treatment incur calculation according to Johnson *et al*. (1955), Hanson *et al*. (1956), and Singh (1995) (Table 2).

Stress tolerance indices

The stress tolerance indices computations employed the following formulas:

1. Tolerance Index (TOL) = Y_P - Y_S (Rosielle and Hamblin, 1981)
2. Stress Susceptibility Index (SSI) = $\frac{1-\frac{Y_s}{Y_p}}{1-\frac{Y_s}{Y_p}}$ (Fischer and Maurer, 1978)
3. Yield Stability Index (YSI) = $\frac{Y_s}{Y_p}$ (Bouslama and Schapaugh, 1984)
4. Mean Productivity (MP) = $\frac{Y_s+Y_p}{2}$ (Rosielle and Hamblin, 1981)
5. Geometric Mean Productivity (GMP) = $\sqrt{Y_s \times Y_p}$ (Ramirez and Kelly, 1998)
6. Stress Tolerance Index (STI) = $\frac{Y_p \times Y_s}{\overline{Y}_p^2}$ (Fernandez, 1992)

Where:
Y_p = Grain yield of genotypes under normal conditions
Y_s = Grain yield of genotypes under stress conditions

Table 2. Estimation of genetic parameters in wheat.

Parameters	Genotypic variance	Phenotypic variance	SD of Phenotype	Heritability	Genetic advance	GA in % of mean	GCV	PCV
Plant height	42.87	44.47	6.67	96.40	13.24	52.97	0.26	0.27
Canopy temperature	17.25	17.30	4.16	99.75	8.55	34.19	0.17	0.17
Chlorophyll	83.75	84.11	9.17	99.57	18.81	75.24	0.37	0.37
Days of 50% flowering	192.40	192.40	13.87	100.00	28.57	114.29	0.55	0.55
Days to germination	99.22	99.23	9.96	99.99	20.52	82.07	0.40	0.40
Pollen viability (%)	302.37	308.07	17.44	99.44	35.72	142.88	0.70	0.70
Pollen sterility (%)	300.68	307.46	17.53	97.79	35.32	141.30	0.69	0.70
No. of tillers/plant	1.76	1.77	1.33	99.43	2.72	10.89	0.05	0.05
No. of spikelets/spike	134.46	140.54	11.85	95.67	23.36	93.46	0.46	0.47
Filled spikelets/spike	156.26	159.83	12.52	99.63	25.70	102.81	0.50	0.50
No. of filled spikelets/spike	14.75	15.03	3.88	98.14	7.84	31.35	0.15	0.16
100-grain weight (g)	0.84	1.16	1.08	72.16	1.60	6.41	0.04	0.04
Yield per plant (kg)	13.76	13.98	3.74	98.42	7.58	30.32	0.15	0.15
Total straw weight (kg)	40.58	40.58	6.37	99.99	13.12	52.49	0.25	0.25

Supplemental Table 2. Serial number of the genotypes used in Figures 8-10.

Genotype name	Genotype No.	Genotype name	Genotype No.	Genotype name	Genotype No.
SA-2	37	Sufi	6	Wahan	14
Chyria 3	18	Shughat	20	TP-2	27
Pavan	17	BAW 898	45	SA-7	10
DSN-117	36	BAW 457	42	NK-5	32
Sonalika	1	BAW 966	48	Peacock	8
Sourav	39	Mayor	7	CB-51	23
PT-1	28	BAW 897	44	BAW 1006	54
Bijoy	52	O 4	22	Gourav	11
BAW 1008	50	Ananda	2	Opata	19
D-72	26	BAW 1027	55	DSN-76	56
NE-3	41	SADH-12	57	BAW 456	47
Protiva	9	BAW 677	43	Ning 3517	21
FDS-5	51	BL-1020	31	Barkat	3
BAW 1004	49	BAW 960	46	SA-3	38
KAV-2	35	Kalai sona	15	Sebia	16
Sonora	12	SADH-22	59	D-141	25
KT-1-40	33	CB-47	24	SADH-14	58
Bolaka	4	Prodip	5	FYN-PVN	30
Shatabdi	53	K-9107	29	Kheri	13
SADH-24	60	PV-79	34	SA-8	40

Genotype environment interaction (AMMI model analysis)

AMMI analysis proceeded using the PBTools and GEA-R (Angela *et al*., 2015), and the AMMI stability value (ASV) calculation engaged the method formulated by Purchase *et al*. (2000).

Data analysis

Data analysis used the STAR, Statistix 10, PBTools, Minitab, and R programs (Sales *et al*., 2013). MS Office Excel helped manage data and prepare necessary graphs. Assessing the Genotype Environment Interaction proceeded with software R.

RESULTS

Growth performance of the wheat genotypes

High-temperature-induced modifications in plants may provide a better understanding of the change in existing physiological processes or altering patterns of development in wheat. Optimum (T1) and late-sowing conditions (T2–T5) of wheat genotypes under heat stress showed significant differences in morphophysiological characters (Figure 1). Normal growth conditions significantly ($p < 0.01$) took fewer days to germinate with 50% flowering compared with late planting treatments (T2 to T5). The canopy temperature (Figure 1d), number of unfilled grains (Figure 1i), and the percentage of sterile pollen statistically took less time in T1 than other treatments. With the delay in seed sowing, the germination days were late by 29%–32%; therefore, the 50% flowering completion rate was 2%–5%. Since the late sowing induced delays in flowering, the T4 required a longer time than T5. The canopy temperature was low at T1. However, it slowly increased in late sowing conditions throughout the growing seasons. Similarly, the percentage of sterile pollen grains was also few at T1, but with the increase in sowing length, the pollen sterility and canopy temperature increased by 32%–86% and 2%–4%, respectively.

Align to pollen sterility, the number of unfilled grains/spike of the studied genotypes increased with late sowing (Figure 1i). The number of tillers/plant, the number of spikelets/spike, and the number of filled grains were also higher in T1 than other treatments. The number of tillers/plant was superior in T1, but T5 had higher tillers than T4 (Figure 1f). A similar result also showed in canopy temperature and a 100-grain weight, where T1 had a higher number, but T5 had a better value than T4. With the increase of time in seed sowing, the crop yield reduced, where T1 had a higher crop yield than others, being minimal in T5. The chlorophyll content was immense in T1, yet, similar to crop yield, it suddenly increased in T2 and T4, as statistically the same with T1 (Figure 1m). The crop yield decreased by 20% to 57% with the increase of sowing time.

Genetic parameters and mean performances of the wheat genotypes

The yield and yield-contributing parameters probe studied the effect of heat stress on wheat genotypes, with the results presented in Figure 1. The heritability estimates of 99.46%, accompanied by an expected genetic advance of 82.07%, were evident for days to germination. Canopy temperatures ranged from 33.2 °C to 37.56 °C, with a mean value of 34.64 °C. The highest chlorophyll content appeared in genotype NE-3 (47.80), followed by PV-79 (47.10) and SA-8 (46.5). Pollen fertility ranged from 48% (SA-3) to 95.8% (BL-1020), with a mean of 75.01%. BL-1020 (95.8%) was the best performer in terms of its mean performance, followed by NK-5 (94.2%), SA-7 and BAW 677 (92.8%), and BAW 898 (92.6%). Pollen sterility ranged from 4.2% (BL-1020) to 52% (SA-3), averaging 24.44%. BL-1020 (4.2%) was best performing based on mean performance, followed by NK-5 (5.8%) and SA-7 (7.2%). The mean value of the number of spikelets/spike was 49.11, ranging from 31.0 (BL-1020) to 72.0 (BAW 960). Heritability was 95.67%, accompanied by a genetic advance in percent of mean at 93.46%. The average filled grains per spike recording was 42.08, from 24 (BL-1020) to 68

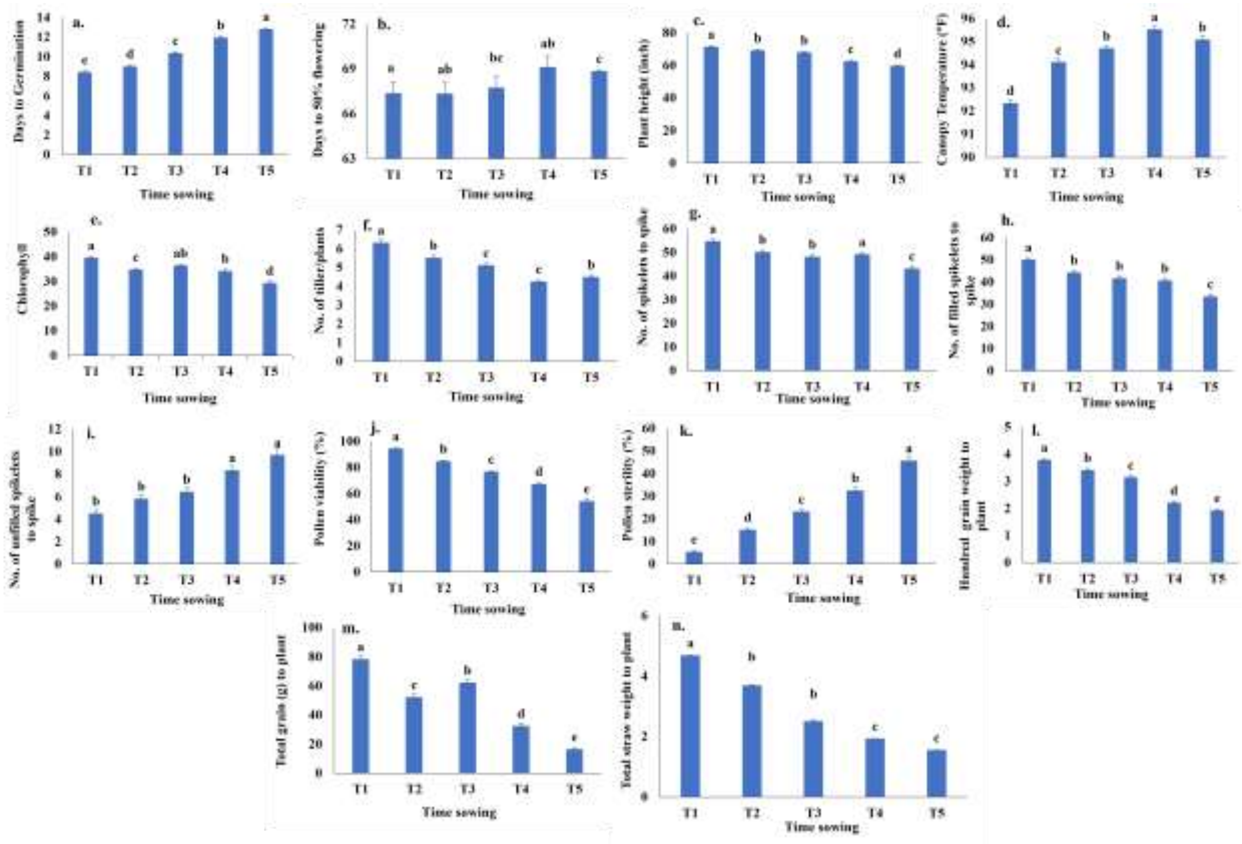
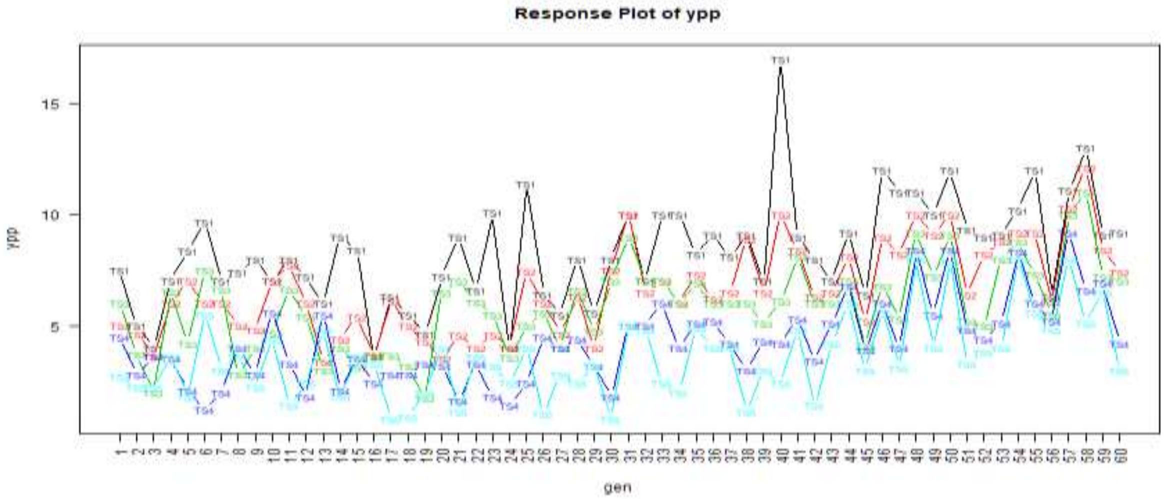


Figure 1. Differences in plant growth parameters (a) Days to germination (b) Days to 50% flowering (c) Plant height (d) Canopy temperature (e) Chlorophyll content (f) Tillers per plant (g) Spikelets per spike (h) Filled spikelets per spike (i) Unfilled spikelets per spike (j) Pollen viability (k) Pollen sterility (l) Hundred-grain weight (m) Yield per plant (n) Total straw weight/plant of wheat. Bars (mean ± se) with different letters indicate significant differences at $p < 0.05$.



Supplemental Figure1. Response of genotypes at different sowing dates (values = genotype number; AMMI stability value ASV).

(BAW 960). Differences occurred for the 100-grain weight, which ranged from 1.44 g (SA-3) to 5.12 g (SA-2) and a mean value of 2.89 g. A high heritability of 72.16% with high genetic advance was apparent for said trait.

Heat stress tolerance indices

Heat stress tolerance indices' determination ensued on the grain yield of genotypes under control (T1) and heat stress conditions (T5). Discussions on the heat stress tolerance indices, viz., tolerance index (TOL, Figure 2), stress susceptibility index (SSI, Figure 3), yield stability index (YSI, Figure 4), mean productivity (MP, Figure 5), geometric mean productivity (GMP, Figure 6), and stress tolerance index (STI, Figure 7) follow. The lower value of TOL was apparent in T1 than in T5, with a similar result for all the genotypes (Figure 2). The genotype D-141 had a TOL of 6.4, 9, and 7.4 in T2, T3, and T4 treatments, respectively, indicating the most heat susceptible. The varieties Sabia, CB-47, and Ananda similarly performed at different heat-stress conditions on every sowing date. At the 5th sowing date, Sabia (0.3), followed By Kheri (1.2), CB-47 (1.6), Barkat (1.8), K-9107 (2.4), Sourav (2.6), Opata (2.64), TP-2 (2.7), Ananda (2.8), and O4 (3.0), had the lowest TOL values. Still on the 5th sowing date, Sabia (0.13), Kheri (0.32), Sourav (0.6), CB-47 (0.65), K-9107 (0.69), Sufi (0.7), Sughat (0.72), Barkat (0.73), O-4 (0.73), BAW 1006 (0.40), DSN-76 (0.44), BAW 966 (0.51), SADH-12 (0.52), SADH-22 (0.53), NK-5 (0.58), BAW 1008 (0.64), BAW 897 (0.65), BAW 677 (0.74), KAV-2 (0.75), NE-3 (0.87), and Balaka (0.7) had the lowest SSI values. Thus, it is definite from the results that the variety Sabia, followed by Sourav, CB-47, D-72, and Barkat, had low heat susceptibilities under late sowing (Figure 3) terminal heat-stress conditions. Sabia (0.92), Kheri (0.8), Sourav (0.63), CB-47 (0.6), K-9107 (0.57), Sufi (0.57), Sawghat (0.56), Barkat (0.55), O-4 (0.55), Balaka (0.51), BAW 1006 (0.78), DSN-76 (0.76), SADH-12 (0.72), SADH-22 (0.71), NK-5 (0.69), BAW 1008 (0.66), BAW 897 (0.65), KAV-2 (0.60), BAW 677 (0.60), and NE-3 (0.53) had the highest YSI values (Figure 4). Sabia and DSN-76 were the varieties which maintained consistency in performance throughout the growing season. The genotypes D-141 (7.7), Sufi (7.6), Sabia (6.6), Kalyan Sona (6.0), Sourav (5.7), Sawghat (5.6), Peacock (5.5), Kheri (5.4), Wuhan (5.4), and Barkat (5.3) had the highest MP values (Figure 5) under stress condition. Hence, an inference is that D-141 and CB-51 varieties showed high productivity in almost every heat-stress situation. During stress conditions, BAW 1008 (0.97), SADH-12 (0.91), BAW 966 (0.90), BAW 1006 (0.83), BAW 1027 (0.69), BAW 960 (0.69), SADH-14 (0.68), and SADH-22 (0.61) had the highest STI values (Figure 7).

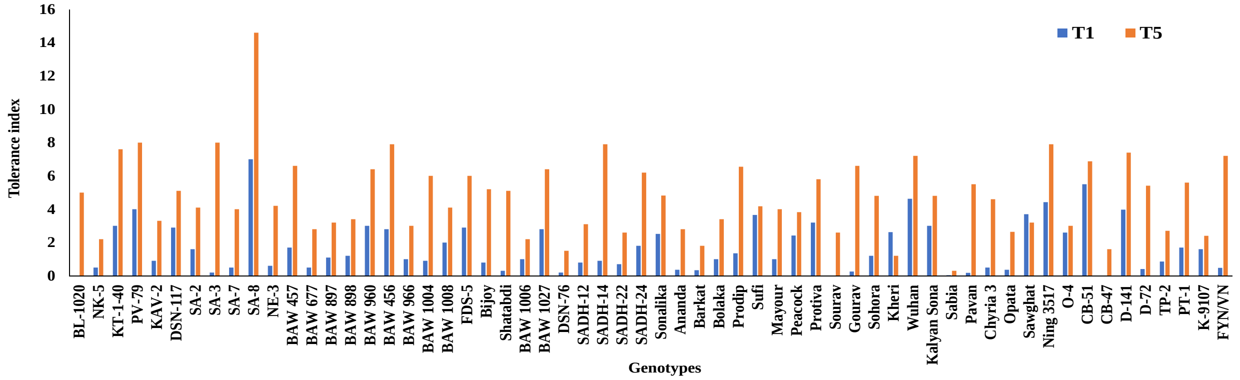


Figure 2. Tolerance index (TOL) of 60 wheat genotypes under control (T1) and (T5) terminal heat stress conditions.

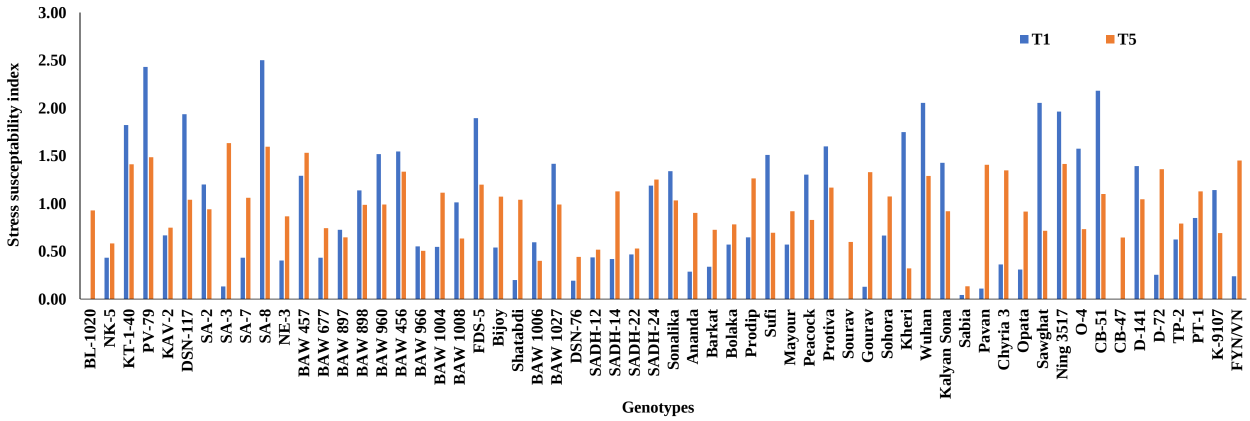


Figure 3. Stress susceptibility index (SSI) of 60 wheat genotypes under control (T1) and (T5) terminal heat stress conditions.

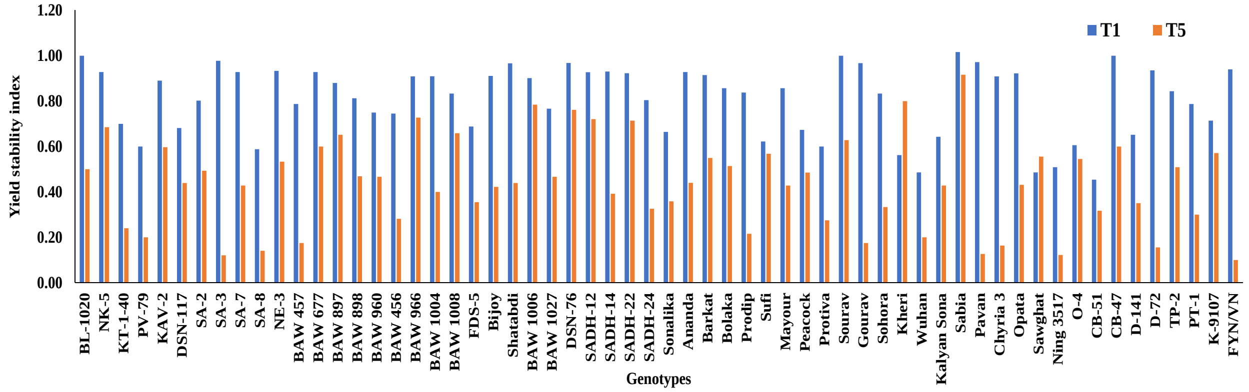


Figure 4. Yield stability index (YSI) of 60 wheat genotypes under control (T1) and (T5) terminal heat stress conditions.

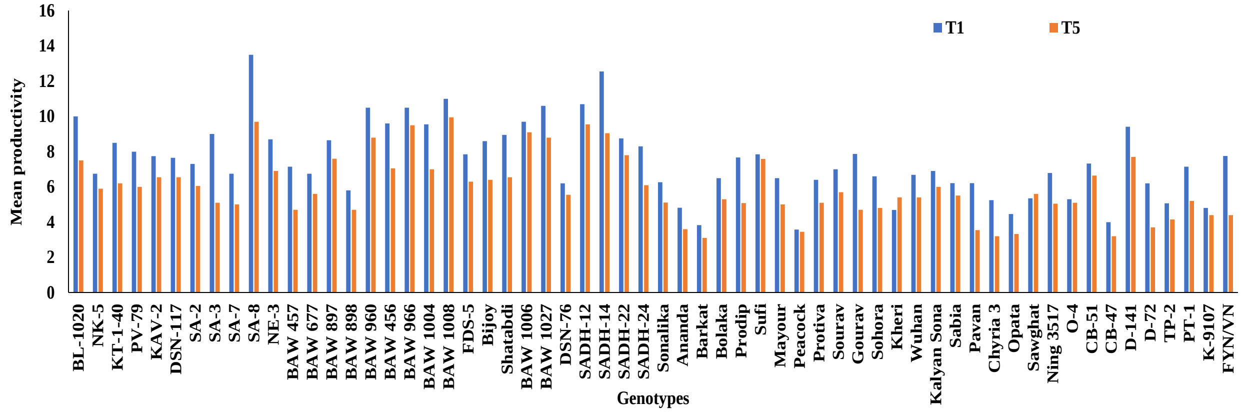


Figure 5. Mean productivity of 60 wheat genotypes under control (T1) and (T5) terminal heat stress conditions.

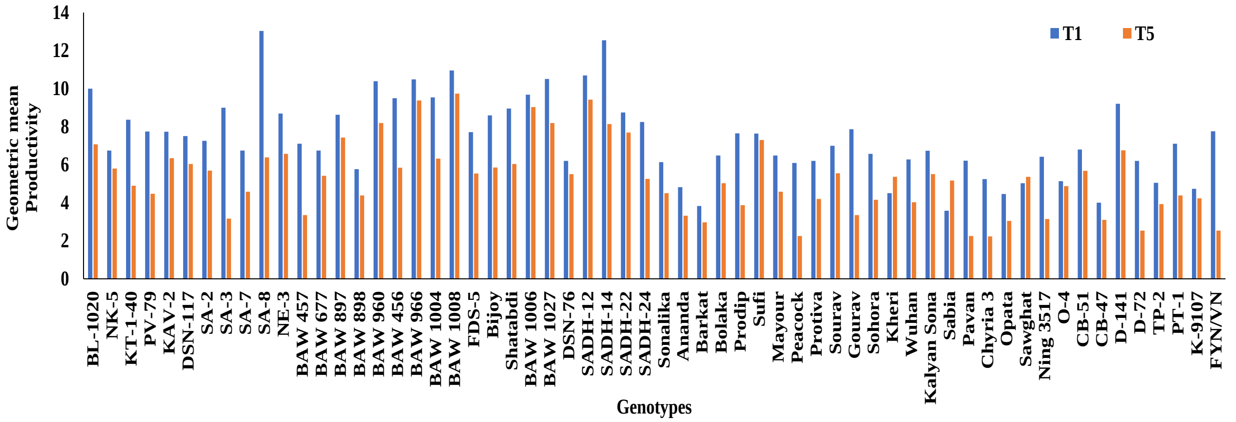


Figure 6. Geometric mean productivity (GMP) of 60 wheat genotypes under control (T1) and (T5) terminal heat stress conditions.

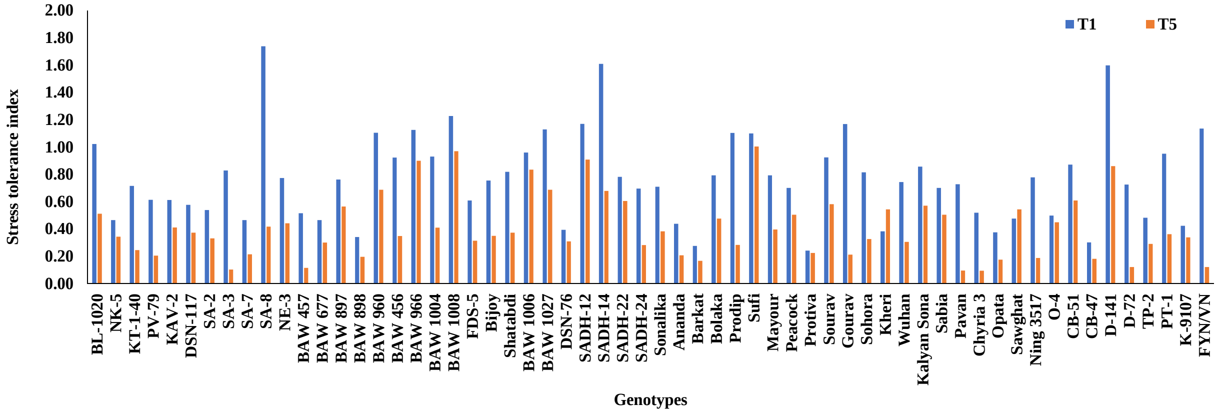


Figure 7. Stress tolerance index of 60 wheat genotypes under control (T1) and (T5) terminal heat stress conditions.

Direct and indirect effects of different traits on grain yield

The path coefficient analysis (Table 3) for grain yield emanated with a set of independent characters. Although all the parameters had a direct positive or negative effect on grain yield, the effect of each parameter on the activity of other parameters was also present, termed indirect effects (Table 3). Days to germination, canopy temperature, pollen sterility, the number of spikelets per spike and unfilled spikelets/spike, and total straw weight negatively affected grain yield. A negative direct effect indicates the reciprocal relation of the cited parameters with crop yield. Traits, days to 50% flowering, plant height, the number of tillers per plant, chlorophyll content, pollen viability, number of filled spikelets per spike, and 100-grain weight caused positive direct effects on grain yield. The positive impact of the parameters on crop yield indicates the parallel relations with crop yield.

Stability analysis using AMMI model

The result of the ANOVA of the AMMI model revealed that grain yield incurs a significant ($p < 0.001$) effect from the environment, genotype, and genotype-environment interaction, which explained 42.17%, 39.33%, and 18.5% of the occurring variation,

Table 3. Direct and indirect effects of yield-contributing and heat-tolerant related characteristics on yield per plant of wheat.

Traits	PH	CT	CH	DTF	NOTPP	NOSPS	FS	NUFS	HGW	TSW	DOG	PV	PS	YPP
PH	0.0003	0.00476	-0.00151	-0.00192	0.01881	-0.06287	-0.06051	-0.00805	0.15564	-0.00104	0.00326	0.02042	-0.03104	0.15518
CT	-0.00002	-0.07496	-0.00429	-0.02529	-0.00978	-0.06984	-0.12384	0.02516	-0.01617	0.00306	-0.00149	-0.00297	0.00457	-0.1658
CH	-0.00001	0.00795	0.04039	0.03495	0.00291	0.09513	0.0327	0.03405	0.05304	0.00162	0.00121	0.00774	0.0016	0.0153
DTF	0	0.00985	0.00733	0.19243	0.01438	-0.10768	0.04831	-0.03455	-0.17672	-0.00247	0.01205	-0.00011	0.0047	0.01771
NOTPP	0.00003	0.00381	0.00061	0.01437	0.19252	0.01367	0.02283	-0.01069	0.02402	0.00515	0.01719	0.00075	0.00318	0.24131
NOSS	-0.00003	0.00797	0.00585	0.03154	-0.00401	-0.65698	0.71995	-0.00433	0.05374	-0.00535	-0.00892	0.01055	0.00091	0.04449
FS	-0.00002	0.01119	0.00159	0.0112	0.0053	0.56986	0.83001	-0.10801	0.02231	-0.00334	-0.01081	0.01286	0.00767	0.17182
NUFS	-0.00001	-0.00872	0.00636	0.03073	-0.00951	0.01314	-0.41443	-0.21633	-0.05146	0.00008	0.00434	-0.01171	-0.0175	-0.2523
HGW	0.00011	0.00277	-0.00489	-0.07759	-0.01055	0.08055	-0.04225	-0.0254	0.43888	0.0042	0.00027	0.00082	-0.01438	0.37031
TSW	0.00001	0.00382	-0.00109	0.00795	-0.01656	-0.05867	0.04631	-0.00028	-0.03073	-0.0603	-0.00883	0.01083	0	-0.1085
DOG	0.00001	0.00142	0.00063	0.02965	0.04233	-0.07496	-0.11471	0.01201	-0.00149	0.00677	-0.0782	0.00005	0.01543	0.1458
PV	0.00008	0.00292	0.00411	-0.00029	0.00189	0.09112	0.14036	-0.03331	0.00473	-0.00853	0.00005	0.07607	-0.00912	0.08442
PS	0.00005	0.00184	-0.00035	-0.00487	-0.00329	0.00322	-0.03428	-0.02038	0.03392	0	-0.0065	0.00374	-0.18519	-0.17781

Here, PH=Plant Height, CT=Canopy Temperature, CH= Chlorophyll, DTF=Days to 50% Flowering, NOTPP=No. of Tiller Per Plant, NOSPS=No. of Spikes Per Plant, FS= No. of Filled Spike, NUFS= No. of Unfilled Spikes, HGW= Hundred-Grain Weight, TSW= Total Straw Weight, DOG= Days of Germination, PV= Pollen Viability, PS= Pollen Sterility, YPP= Yield Per Plant.

Table 4. ANOVA of the AMMI model.

Source of variation	DF	SS	MS	F Value	PROB(F)	% Explained	% Cumulative
ENV*GEN	236	1151.754	4.88032	7.13	0	18.5	100
GEN	59	2448.739	41.50406	6.07	0	39.33	81.5
PC2	60	235.3669	3.92278	7.56	0	20.44	76.1
PC1	62	651.2788	10.5045	2.02	0	56.55	56.55
ENV	4	2625.622	656.4056	9.6	0	42.17	42.17
Residuals	600	0	0	NA	NA	0	0

respectively, as shown in Table 4. In the AMMI biplot, the genotypes that cluster together behave similarly across the environments (Figure 8). The SA-2, Chyria 3, Pavan, DSN-117, Sonalika, and SA-7 wheat genotypes clustered together and performed equally under both terminal heat stress and ideal conditions. The yield in a heat-stressed environment is lower than average, whereas the harvest is higher than average in a favorable setting. The wheat genotypes SA-3, Chyria 3, Pavan, and Sonalika were the most stable among the tested genotypes. The wheat genotypes SA-8, Kheri, FYN-PVN, SADH-14, and D-141 were relatively unstable. In particular, SA-8 was the most suitable to an optimum environment, with Kheri and Opata adapted to the terminal heat-stressed environment.

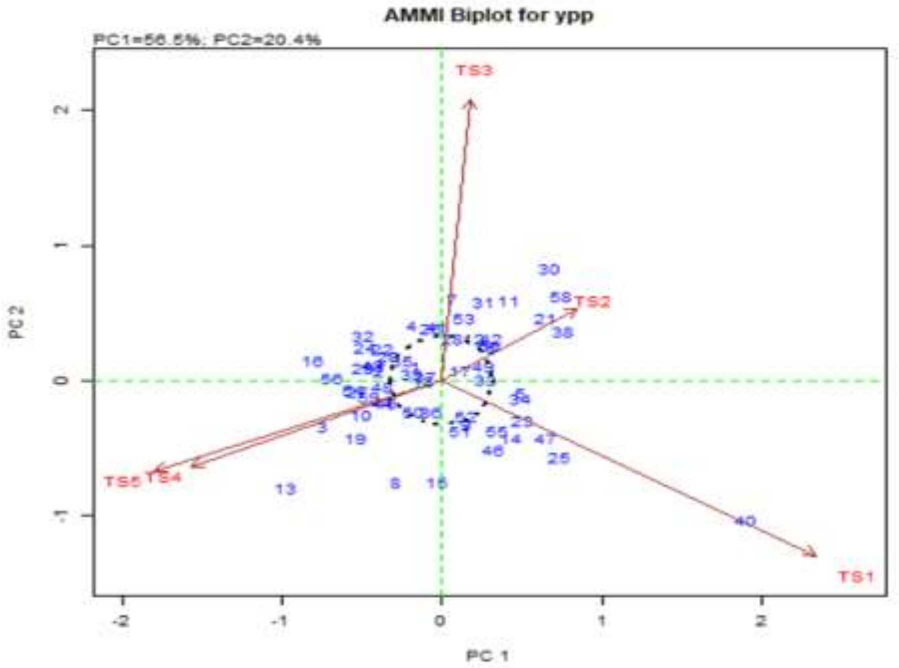


Figure 8. AMMI Biplot for 60 genotypes (values = genotype number).

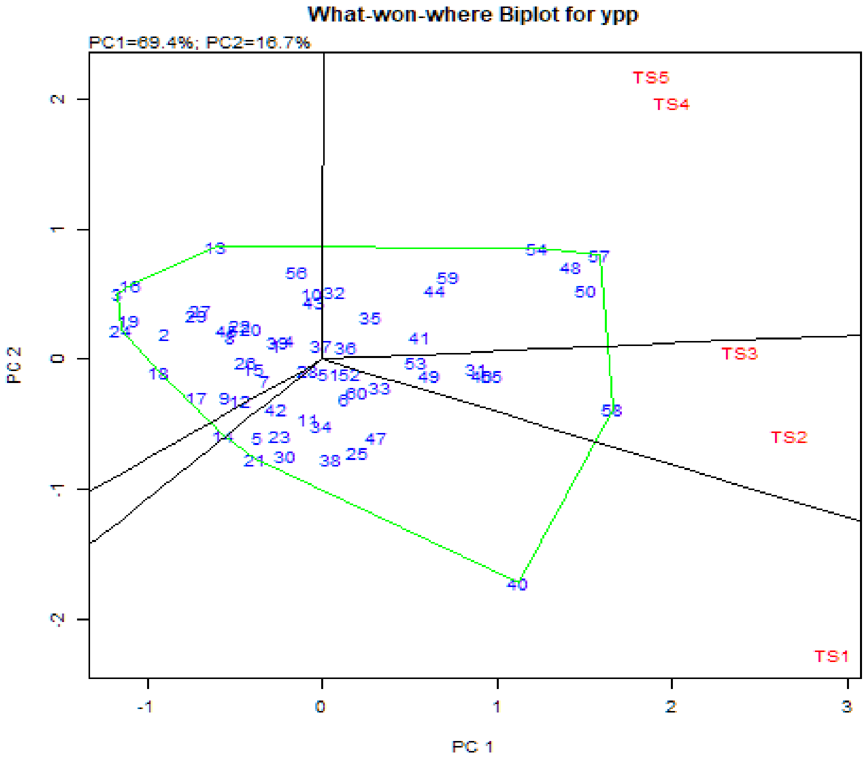


Figure 9. *What-won-where* model for 60 genotypes (values = genotype number).

GGE biplot analysis using the 'What-won-where' model and AMMI Stability Value (ASV)

The polygon creation started with connecting the markers farthest from the point of origin, ensuring that it encompasses all other pointers. According to the polygon view, the 60 wheat genotypes fall into six sectors, and the five different sowing times fall into three sectors (Figure 9). The SA-8, SA-3, BAW 456, and D-141 wheat genotypes were distinct in the segment with the best environment. The genotype SA-8 had the utmost distance from the origin, and this sector's vertex line implied that SA-8 specifically adapted to an ideal surrounding, with less stability in other settings. Similarly, the area with a terminal heat-stressed environment consists of SADH-12, BAW 1008, BAW 966, and BAW 1006, all well-performing in this environment. In addition, the SADH-12 had the maximum distance from the origin, with a location in the vertex line of this sector, indicating that it was the most responsive in a heat-stressed terminal environment. Thus, the 'what-won-where' pattern of the trial revealed line SA-8 as the winning genotype in the control condition, while line SADH-12 was bold in the heat-stressed environment. Furthermore, the polygon views revealed wheat genotypes SA-2, Chyria 3, Paven, and DSN-117 are near the biplot's origin, indicating the same rankings of these genotypes in all test environments and are the most stable lines. Moreover, the presence of wheat genotypes SA-8, Kheri, FYN-PVN, SADH-14, D-141, Sebia, SA-3, and Barkat in the sector with no test environment indicates that these lines have poor adaptation to all environments. According to the AMMI stability value (ASV) ranking, the most stable genotypes are Sonalika, Chyria 3, Pavan, DSN-117, and SA-2. The most unstable genotypes were SA-8, Kheri, and FYN-PVN (Supplemental Figure 1).

DISCUSSION

Significant differences in plant growth parameters under different sowing dates were prominent in this study. Heat stress condition increases the number of unfilled grain and pollen sterility. Hossain *et al*. (2013) reported that a temperature higher than the optimum condition at the germination stage delayed the grains' germination time and also changed pollen viability. It may be due to ambient temperature severely affecting embryonic cells in wheat, which reduces crop stands by impairing seed germination and emergence (Essemine *et al*., 2010). The warm environment produces lower biomass than plants grown under optimum or low temperatures. Under heat stress, plant starts to degenerate their protein; thus, this mechanism may induce few tillers per plant. The high temperature suppresses the plant growth through leaf senescence, reducing photosynthesis. The results are similar to the findings of Rahman *et al*. (2018). The decrease in the number of tillers, in turn, lowers the overall crop yield (Khan *et al.,* 2020). Heat stress damaged pollen cells and microspores, causing male sterility (Freeha *et al.,* 2008; Koolachart *et al*., 2019; Shaukat *et al*., 2021).

Canopy temperature, pollen fertility, and chlorophyll content had direct positive effects on crop yield and adverse relations with late-sown treatments, as found in this study. Significant increases in floral abortion, pollen sterility, and loss of seed set in peanut, wheat, rice, and maize were evident (Kiss *et al*., 2019) when exposed to heat stress during the flowering stage. Positive direct effects of these characteristics suggested that the features directly affect crop grain yield, and selecting these traits for high-grain crops would be effective. These results indicated similarity with the findings of Mohsin *et al*. (2009). High-temperature stress resulted in a loss of pollen fertility by retarding pollen tube growth, besides poor anther dehiscence. With a decreased effectiveness of enzymes involved in starch production, the starch content of grain can drop by as much as one-third of the total endosperm starch when exposed to high temperatures (Liu *et al.,* 2011). When plants sustain high temperatures, they release a reactive element called reactive oxygen species (ROS), which disrupts cell activity by damaging the lipid, protein, and DNA, causing a decrease in membrane thermostability by 54% (Cossani and Reynolds, 2012), negatively affecting the photosynthesis, the most heat sensitive process (Pandey *et al*., 2010). An increase in temperature of 1 °C–2 °C reduces seed mass by accelerating the seed growth rate and shortening grain-filling periods in wheat (Nahar *et al*., 2010). (A high heritability for chlorophyll content had been central in an earlier section). It may be because heat stress causes a reduction in total chlorophyll content by disrupting the structure and function of chloroplasts thylakoids (Shanmugam *et al*., 2013).

Canopy temperature varies on different sowing dates. The high temperature at late-sown treatments increases canopy temperature, ultimately affecting grain yield. In this experiment, optimum-sown treatment T1 had the lower canopy temperature, which rose in the late-sown treatments of T2, T3, and T4. The number of grains per spikelet and yield per plant all gained effects from heat stress as the harvest was higher under optimum time sowing but started decreasing with a delay in seed sowing (Ayeneh *et al*., 2002). The analysis of the effect of heat stress by Rahman *et al*. (2018) found that heat stress negatively impacted the growth and development of wheat. Heat stress changed the morphology and reduced the plant growth and development, hampering crop yield and affecting the duration of the grain-filling period. The 50% flowering was higher in T4 than in T5; inversely, the canopy temperature was higher in T5 than in T4.

The higher temperature might induce an early flowering, a detritus reason for yield loss. Mohammadi *et al*. (2017) evaluated the effect of temperatures on grain formation and development in 10 spring wheat genotypes and observed that heat stress at post-anthesis affects head traits in wheat. A significant correlation was visible between chlorophyll content and grain yield under heat and drought stress, decreasing the drought intensity by reducing chlorophyll content (Din *et al*., 2010). All these reciprocal relations reduced plant yield with a delay in the planting date than in an optimum planting date. Stress tolerance indices attain measurements by the grain yield of genotypes under normal and heat-stress conditions. Many researchers have used heat stress tolerance indices of grain yield to identify the genotypes that are tolerant to heat (Sharma *et al*., 2013). Canopy temperature and the number of tillers per plant had the lowest heritability. Meanwhile, GCV and PCV closely correlated, indicating that the gene responsible for these traits could not function correctly under heat stress conditions. Rahman *et al*. (2018) found that high temperature reduces chlorophyll content by 6%–24% in different wheat varieties; the lower chlorophyll reduced photosynthesis rate, producing more unfilled grains, which was also in line with this study result.

The PCV value is close to the GCV value for all the parameters (Table 1), indicating the minimum influence of the environment on the attributes. The parameter with high heritability indicates the additive gene effects. Hossain *et al.* (2013) reported poor establishment and low yield in many crops, including wheat, due to heat stress. The higher the genetic advance, the higher the effect of the additive gene. The characteristics, days to germination, days to 50% flowering, flag leaf width, spike length, and total straw weight had close linkages with the genotypic variation with the heritability (Table 1). It also suggests that the effect of environment and genes can be better based on the values stated in Table 3. The high genotypic and phenotypic variation indicates the genetics and environment's effects on trait expression.

The heat tolerance parameters provided the performance of different genotypes under heat stress. A best-performing genotype is unidentifiable from these data. Thus, we require using the AMMI model for an accurate yield estimate (Zobel *et al.,* 1988), which summarizes the relationship between the genotype and environment, providing a basis for better use of other models (Gauch, 1988). The AMMI revealed a chief part of the variation in yield as explained by the environment, which indicates ecosystems were diverse. This finding is similar to Bhardwaj *et al*. (2020). Also, the vectors of genotypes with PC1 close to the origin (zero) have general adaptability, whereas those with larger PC1 specifically adapted to an environment. The AMMI model revealed that SA-2, Chyria 3, Pavan, DSN-117, Sonalika, and SA-7 clustered close, which performed similarly in terminal heat stress and optimum environment. The result indicated they were relatively stable lines in yield, which are broadly adapted lines. The most effective and succinct way of summarizing the genotype and genotype-environment interaction of the dataset is the polygon view of the GGE biplot, which visualizes the 'what-won-where' pattern of a multi-environment dataset (Yan and Kang, 2003). The 'what-won-where' design of the trail revealed the line SA-8 as a winning line in the optimum time sowing environment, while the SADH-12 is a winning line in the heat-stressed environment. Similar to this research, Thungo *et al.* (2020) also identified the highly responsive genotype of wheat in the heat-stressed environment using the 'what-won-where' model of GGE biplot, noting the vertex genotype as a winning genotype in the corresponding setting. Also, Neisse *et al.* (2018) ably identified a high-yielding and specifically adapted variety to a specific environment, deploying the 'what-won-where' model. Quantitative stability measure is essential to quantify and rank genotypes according to their yield stability (Kendal, 2019). However, the AMMI model does not provide a quantitative stability measure. Purchase (1997) introduced the ASV ranking, identifying SA-2, Chyria 3, Pavan, DSN-117, and Sonalika as the most stable genotypes.

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REFERENCES

Angela P, Mateo V, Gregorio A, Francisco R, Jose C, Juan B (2015). GEA-R (Genotype × Environment Analysis with R for Windows) Version 4.1, hdl:11529/10203, CIMMYT Research Data and Software Repository Network, V16, GEA-R_v4.1_BASE_ setup.exe. Mexico.

Ayeneh A, Van Ginkel M, Reynolds MP, Ammar K (2002). Comparison of leaf, spike, peduncle and canopy temperature depression in wheat under heat stress. *Field Crops Res.* 79(2-3): 173-184.

Bhardwaj V, Sood S, Kumar V, Gupta VK (2020). BLUP and stability analysis of multienvironment trials of potato varieties in sub-tropical Indian conditions. *Heliyon*. 6.

Bhatt B, Chandra R, Ram S, Pareek N (2016). Long-term effects of fertilization and manuring on productivity and soil biological properties under rice (*Oryza sativa*)–wheat (*Triticum aestivum*) sequence in Mollisols. *Archives Agron. Soil Sci. 62*(8): 1109-1122.

Bouslama M, Schapaugh Jr WT (1984). Stress tolerance in soybeans. I. Evaluation of three screening techniques for heat and drought tolerance. *Crop Sci.* 24(5): 933-937.

Cossani CM, Reynolds MP (2012). Physiological traits for improving heat tolerance in wheat. *Plant Physio.* 160(4): 1710-1718.

Din RU, Subhani M, Ahmad N, Hussain M, Rehman AU (2010). Effect of temperature on development and grain formation in spring wheat. *Pak. J. Botany*. 42: 899-906.

Essemine J, Ammar S, Bouzid S (2010). Impact of heat stress on germination and growth in higher plants: Physiological, biochemical and molecular repercussions and mechanisms of defence. *J. Biolo. Sci.* 10: 565-572.

Ferdous J, Mahjabin F, al Asif MA, Riza IJ, Jahangir MMR (2023). Gaseous losses of nitrogen from rice field: Balancing climate change and sustainable rice production. *Intechopen.*

Fernandez GC (1992). Effective selection criteria for assessing plant stress tolerance. In Proceeding of the International Symposium on Adaptation of Vegetables and other Food Crops in Temperature and Water Stress, Aug. 13-16, Shanhua, Taiwan. 257-270.

Fischer RA, Maurer R (1978). Drought resistance in spring wheat cultivars. I. Grain yield responses. *Austra. J. Agri. Rese.* 29(5): 897-912.

Freeha A, Abdul W, Farrukh J, Muhammad A (2008). Influence of foliar applied thiourea on flag leaf gas exchange and yield parameters of bread wheat (*Triticum aestivum*) cultivars under salinity and heat stresses. Int. J. Agri. Biol. 10(6): 619-626.

Gauch HG (1988). Model selection and validation for yield trials with interaction. Biometrics. 44: 705-715.

Hanson CH, Robinson HF, Comstock RE (1956). Biometrical studies of yield in segregating populations of Korean lespedeza. *Agron. J.* 48(6): 268-272.

Hossain A, Sarker MAZ, Saifuzzaman M, Teixeira da Silva JA, Lozovskaya MV, Akhter MM (2013). Evaluation of growth, yield, relative performance and heat susceptibility of eight wheat (*Triticum aestivum* L.) genotypes grown under heat stress. Int. J. Plant Prod. 7(3): 615-636.

Johnson HW, Robinson HF, Comstock RE (1955). Estimates of genetic and environmental variability in soybeans. *Agron. J.* 47(7): 314-318.

Karttenberg AF, Giorgi H, Grassl GA, Meehl JFB, Mitchll RJ, Stouffer T, Tokioka A, Weaver J, Wigley TML (2015). Climate models—projection of future climate. In: J.T. Houghton (ed.). The science of climate change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge: Cambridge University*. 289-357.

Kendal E (2019). Comparing durum wheat cultivars by genotype yield trait and genotype trait biplot method. *Chil. J. Agric. Res.* 79 (4).

Khan ADEEL, Ahmad M, Shah MKN, Ahmed M (2020). Performance of wheat genotypes for Morpho-physiological traits using multivariate analysis under terminal heat stress. *Pak. J. Bot.* 52(6): 1981-1988.

Kiss T, Ba´nyai J, Balla K, Mayer M, Berki Z, Horva´ thA´ (2019). Comparative study of the developmental traits and yield components of bread wheat under field conditions in several years of multi-sowing time experiments. *Crop Sci.* 59: 591-604.

Koolachart R, Jogloy S, Vorasoot N, Wongkaew S, Holbrook CC, Jongrungklang N, Kesmala T, Suriharn B (2019). Association of aflatoxin contamination and root traits of peanut genotypes under terminal drought. *SABRAO J. Breed. Genet*. 51(3): 234-251.

Kumar S, Dwivedi VK, Tyagi NK (2019). Genetic variabiliy in some metric traits and its contribution to yield in wheat (*Triticum aestivum L.*). *Progressive Agriculture*. 3: 152-153.

Liu P, Guo W, Jiang Z, Pu H, Feng C, Zhu X, Little CR (2011). Effects of high temperature after anthesis on starch granules in grains of wheat (*Triticum aestivum* L.). *J. Agri. Sci.* 149(2): 159-169.

Mohammadi R, Armion M, Zadhasan E, Ahamdi MM, Amir A (2017). The use of AMMI model for interpreting genotype-environment interaction in durum wheat. *Exp. Agric.* 54 (5): 670-683.

Mohsin T, Khan N, Naqvi FN (2009). Heritability, phenotypic correlation and path coefficient studies for some agronomic characters in synthetic elite lines of wheat. *J. Food Agri. Environ.* 7(3-4): 278-282.

Nahar K, Ahamed KU, Fujita M (2010). Phenological variation and its relation with yield in several wheat (*Triticum aestivum L.*) cultivars under normal and late sowing mediated heat stress condition. *Notu. Sci. Biolo.* 2: 51-56.

Neisse AC, Kirch JL, Hongyu K (2018). AMMI and GGE Biplot for genotype-environment interaction: A medoid–based hierarchical cluster analysis approach for high–dimensional data. *Biom. Lett.* 55 (2): 97-121.

Pandey IB, Pandey RK, Dwivedi DK, Singh RS (2010). Phenology, heat unit requirement and yield of wheat (*Triticum aestivum*) varieties under different crop-growing environment. *Indian J. Agri. Sci.* 80(2): 136-140.

Prasad PV, Pisipati SR, Ristic Z, Bukovnik URSKA, Fritz AK (2008). Impact of nighttime temperature on physiology and growth of spring wheat. *Crop Sci.* 48(6): 2372-2380.

Purchase JL (1997). Parametric analysis to describe G x E interaction and yield stability in winter wheat. Ph.D. Dissertation. Dept. of Agronomy, Faculty of Agriculture, University of the Free State, Bloemfontein, South Africa. 148.

Rahman MM, Hasan MA, Chowdhury MF, Islam MR, Rana MS (2018). Performance of wheat varieties under late planting-induced heat stress condition. *Bang. Agron*. J. 21(1): 9-24.

Ramirez-Vallejo P, Kelly JD (1998). Traits related to drought resistance in common bean. *Euphytica.* 99(2): 127-136.

Rosielle AA, Hamblin J (1981). Theoretical aspects of selection for yield in stress and non-stress environment. *Crop Sci.* 21(6): 943-946.

Sales N, Bartolome V, Caneda A, Gulles A, Morantte RIZ, Nora L, ... Ye G (2013). PB Tools software for Plant Breeding. International Rice Research Institute, College, Los Banos, Laguna.

Shanmugam S, Kjaer KH, Ottosen CO, Rosenqvist E, Kumari Sharma D, Wollenweber B (2013). The alleviating effect of elevated CO_2 on heat stress susceptibility of two wheat

(*Triticum aestivum L.*) cultivars. *J. Agron. Crop Sci.* 199(5): 340-350.

Sharma A, Rawat R, Verma J, Jaiswal J (2013). Correlation and heat susceptibility index analysis for terminal heat tolerance in bread wheat. *J. Central Euro. Agri*. 14(2):57-66.

Shaukat S, Kousar I, Fatima S, Shukat R, Ali A, Ahmad J, Akhtar N, Nadeem M, Farooq J, Ramzan M (2021). Evaluation of spring wheat genotypes for terminal heat stress. *SABRAO J. Breed. Genet.* 53(2): 239-247.

Siegert M, Alley RB, Rignot E, Englander J, Corell R (2020). Twenty-first century sea-level rise could exceed IPCC projections for strong-warming futures. *One Earth*. *3*(6): 691-703.

Singh KN, Singh SP, Singh GS (1995). Relationship of physiological attributes with yield components in bread wheat (*Triticum aestivum* L.) under rain-fed condition. *Agri. Sci. Digest*. (Karnal) India. 15: 11-14.

Spiertz JHJ, Hamer RJ, Xu H, Primomartin C, Don C, Pelvander P (2016). Heat stress in wheat (*Triticum aestivum L.*): Effects on grain growth and quality traits. *Euro. J. Agron.* 25: 89-95.

Thungo Z, Shimelis H, Odindo A, Mashilo J (2020). Genotype-by-environment effects on grain quality among heat and drought tolerant bread wheat (*Triticum aestivum* L.) genotypes. *J. Plant Interact*. 15: 83-92.

Yan W, Kang MS (2003). GGE Biplot Analysis, a Graphical Tool for Breeders, Geneticists, and Agronomists. CRC Press, Washington, DC.

Zhao C, Liu B, Piao S, Wang X, Lobell DB, Huang Y, Huang M, Yao Y, Bassu S, Ciais P, Durand JL (2017). Temperature increase reduces global yields of major crops in four independent estimates. *PANS. 114*(35): 9326-9331.

Zobel RW, Wright MJ, Gauch HJ (1988). Statistical analysis of a yield trial. *Agron. J.* 80: 388-393.