PLANT SCIENCE TODAY
Vol 12(3): 1-11
https://doi.org/10.14719/pst.7607

eISSN 2348-1900

RESEARCH ARTICLE

Genotype × environment interaction and stability analysis of CMS- Based wheat hybrids under terminal heat stress

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Received: 05 February 2025; Accepted: 07 July 2025; Available online: Version 1.0: 12 August 2025; Version 2.0: 27 August 2025

Cite this article: Goyal VK, Shukla RS, Singh SK, Pandey S, Hussain ME. Genotype × environment interaction and stability analysis of CMS- Based wheat hybrids under terminal heat stress. Plant Science Today. 2025; 12(3): 1-11. https://doi.org/10.14719/pst.7607

Abstract

The current study aimed to ascertain the performance of hybrid wheat under different environmental conditions. Sixteen newly developed CMS-based hybrids were used as the experimental material. Stability for grain yield performance and genotype × environment (G × E) interaction was studied in 16 hybrids made by using line × tester design of hybrid wheat by evaluating them across three temperature regimes viz., 20th November, 30th November and 10th December following randomized block design with twice replications during rabi 2018-19 at Seed Breeding Farm, Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur (M.P.). Genotype × environment interaction was analyzed using Eberhart and Russell's additive main effect and multiplicative interaction (AMMI) model, as well as the genotype and genotype × environment interaction (GGE) stability model analysis. There was considerable variation in grain yield among both genotypes and environments. The AMMI and GGE biplots explained 83.31 % and 94.7 % of the observed genotypic variation for grain yield, respectively. The hybrid G15 (CMS94 × Res-37) was the most stable across the environments in terms of grain yield. They can be considered potential genotypes for cultivation under terminal heat stress after evaluation in multilocation trials. Hence, the hybrids mentioned above could be used to accelerate wheat improvement programs for different cropping systems.

Keywords: cytoplasmic male sterility; hybrid wheat; regression coefficient; stability

Introduction

Wheat (*Triticum aestivum* L.) is the world's second most important staple food crop, with more than 35 % of the world's population relying on it, second only to rice. India is the second -largest wheat producer in the world, with a production level of 101.20 Mt. Madhya Pradesh is the second-largest producer of wheat with an area, production and productivity of 6.69 M ha hectares, 17.58 MT and 2627 kg/ha, respectively (1). Heat stress has a significant impact on wheat yield because of its high sensitivity. Global wheat production is expected to decrease by 6 % for every 1 °C increase in temperature (2). Even a 1 °C temperature increase over the mean temperature during the reproductive stage may lead to a higher loss in grain yield (3, 4). The effects of drought and high-temperature stress on grain yield are complex and multifaceted. The processes such as nutrient assimilation and their mobilization to various reproductive organs, accumulation of stem reserves, gametogenesis, fertilization, embryogenesis, endosperm and seed development are critical in determining grain yield. The presence of these stresses at any growth stage can affect grain yield. The seed filling stage is critical for determining average seed weight, seed composition and, therefore, the final quantitative and qualitative yield (5, 6).

In recent times, India's wheat area has been increasing in the North-Western Plains Zone (NWPZ) and North-Eastern Plains Zone (NEPZ), primarily due to delayed planting resulting from rice-wheat crop rotation (7). As a consequence, the crop is exposed to high-temperature stress at the post-anthesis phase. So, there is a dire need to breed lines under these circumstances to enhance yield. Consequently, to maintain the continuous rise in future wheat production, we must pave the way to combat the severe challenges ahead, such as drastic irregularities in climatic conditions.

However, breeding for yield stability for a wide range of different environmental conditions has always been important. In any breeding program, identifying phenotypically stable genotypes for yield is necessary, as they perform more or less uniformly under different environmental conditions. In the case of hybrids developed for terminal heat stress, genotype-by-season and genotype-by-season-by-temperature interactions are critical for achieving the potential grain yield. There is no practical way to select hybrids solely based on their performance in a single environment, as hybrid grain yield has a complex quantitative inheritance and is influenced by the surrounding environment. Therefore, it is imperative to evaluate wheat hybrids for grain yield stability across multiple seasons and environments. Thus, the study evaluated wheat hybrids for high yield and stability under variable temperature regimes across seasons.

Materials and Methods

Plant materials

The present study was conducted at the Seed Breeding Farm, Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur (M.P.), during the Rabi seasons of 2017-18 and 2018-19. The experimental material of the study received from Genetics Division, IARI, New Delhi and IIWBR, Karnal, consisted of sixteen CMS lines (A-line) i.e., CMS82A, CMS83A, CMS84A, CMS85A, CMS86A, CMS87A, CMS88A, CMS89A, CMS90A, CMS91A, CMS92A, CMS94A, CMS95A, CMS96A, CMS2041A; their maintainer lines and one restorer (R-line) i.e. Res37 and Five standard check i.e., HI 1544, GW 322, MP 3382, LoK-1, GW 366 and their 16 F1's. MP 3382 stress-tolerant check was included in the study (8).

Experimental sites

The experiment was carried out at the seed breeding farm of JNKVV, Jabalpur, India. Geographically, JNKVV lies between 22°49′ and 20°80′ N latitude and 78°21′ to 80°58′ E longitude and at an altitude of 411.78 m above sea level.

Methodology

The F_1s were made by crossing sixteen male sterile lines (A-lines) with one restorer (R line) during *Rabi* 2017-18 at the Seed breeding farm of JNKVV, Jabalpur, India. These crosses were then evaluated along with a standard check-in randomized complete block design with two replications in three different environments, E1, E2 and E3, i.e., 20th November, 30th November and 10th December, respectively, during rabi 2018-19. The environment E3, in a late-sown condition, flowered at high temperatures, resembling a terminal heat stress condition. A four-row plot, 2.5 m in length, was allotted randomly to each hybrid. The row-to-row and plant-to-plant distances were 22.5 cm and 10 cm, respectively.

Data collection

Data were recorded for yield and yield-related traits. Days to 50 % heading and days to maturity were measured on a plot basis. Plant height, number of tillers per plant, number of spikes per plant, spike length, spike weight, number of spikelets per spike, number of grains per spike, thousand-grain weight, grain yield per plant, biological yield per plant and harvest index were measured at maturity.

Statistical analysis

Replicated phenotypic data collected across environments were subjected to stability analysis. To study the adaptability and yield stability of the hybrids and checks across different environments, additive main effects and multiplicative interaction (AMMI) analysis was performed (9). The basic model for AMMI is based on the additive variance, which is derived from the multiplicative variance and principal component analysis (PCA). AMMI stability value (ASV) was calculated for each hybrid and check according to the relative contribution of the PC axis scores (IPCA1 and IPCA2) to the interaction sum of squares (SS). Research indicates the estimation of ASV (10). The genotype selection index (GSI) was calculated as the sum of the rankings based on yield and the ASV (11). The most effective and succinct way to summarise the dataset's genotype and genotype × environment interaction is the polygon view of the GGE biplot, which visualizes the 'which-won where' pattern of a multi-environment dataset (12). AMMI and GGE analyses were carried out using the software GEA-R version 4.1.

Results

Yield and yield-related traits

In the present study, 16 hybrids were evaluated through pooled analysis. A wide range of variation was recorded for all the traits *viz.,* grain yield per plant (19.60 g to 96.83 g), days to 50 % heading (70.67 to 88.33), days to maturity (98.17 to 123.83), plant height (83.83 cm to 101.67 cm), number of tillers per plant (15.76 to 54.86), number of spike per plant (14.96 to 53.81), spike length (9.98 cm to 13.05 cm), spike weight (2.48 g to 3.99 g), number of spikelets per spike (16.23 to 22.58), number of grains per spike (45.44 to 65.17), thousand-grain weight (32.71 g to 54.82 g), biological yield per plant (56.59 g to 238.20 g) and harvest index (28.95 to 49.01).

Grain yield per plant showed a marked reduction in performance in the third set of sowing, i.e., heat stress (E3) (Fig. 1). The terminal heat stress tolerant check variety MP 3382 (37.08 g) outperformed all other checks, viz., HI 1544 (29.62 g), GW273 (23.04 g), Lok-1 (32.17 g) and GW 366 (24.44 g) in terms of grain yield. The replicated data from three environments were assessed and compared with the check (MP 3382) using a significant pair-wise mean comparison.

Correlations among the studied traits across the individual environments were represented in Fig. 2. Grain yield per plant showed a significant correlation with all associated yield traits such as biological yield/plant (0.9587), number of tillers/plant (0.9579), number of spikes/plant (0.9571), number of spikelets/spike (0.9131), number of grains/spike (0.8963), spike length (0.8481), spike weight (0.7199), days to heading (0.5685) and days to maturity (0.4859) among three environments.

Analysis of variance

Stability analysis by ER model

Genotype and environment interactions were found to be significant for all the traits in pooled analysis (Table 1). For grain yield per plant, hybrid G15 (CMS94 × Res-37) had a higher mean than the population means and the regression coefficient was very close to unity, with a deviation from regression near zero; hence, this hybrid is ideal and stable. However, hybrids such as G10 (CMS89 × Res-37), G9 (CMS88 × Res-37) and G21 (CMS2041 × Res-37) exhibited a higher mean value and a regression coefficient less than unity, with an S2di value near zero. These hybrids, which are recorded as above-average stable, may perform better in unfavourable environments. However, all the remaining hybrids with any regression coefficient (bi) value associated with a high value of S^2di were unstable (Table 2).

AMMI biplot analysis

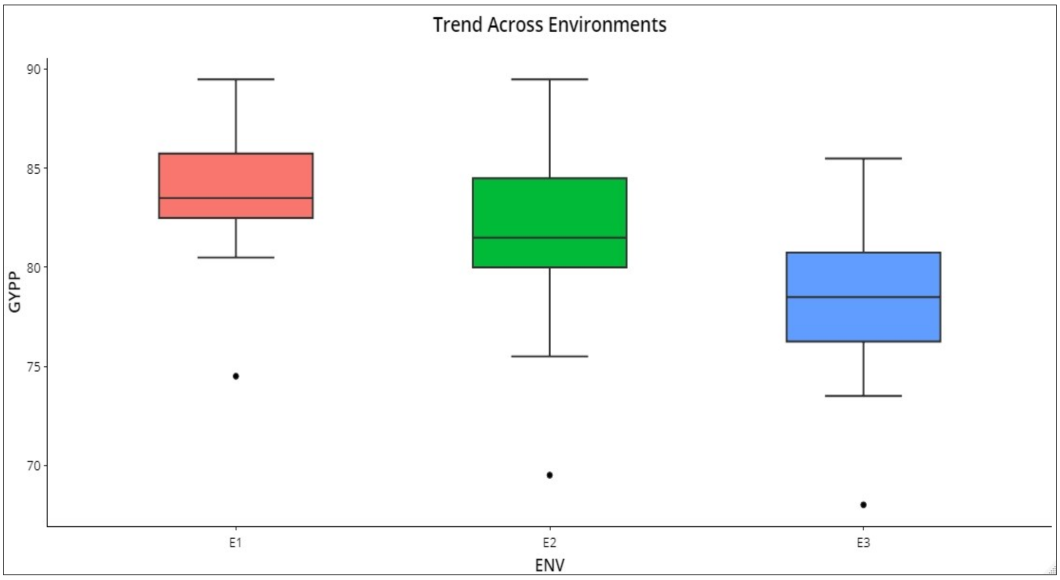

Fig. 1. Box plot representation of genotypes' performance for GYPP across the environments.

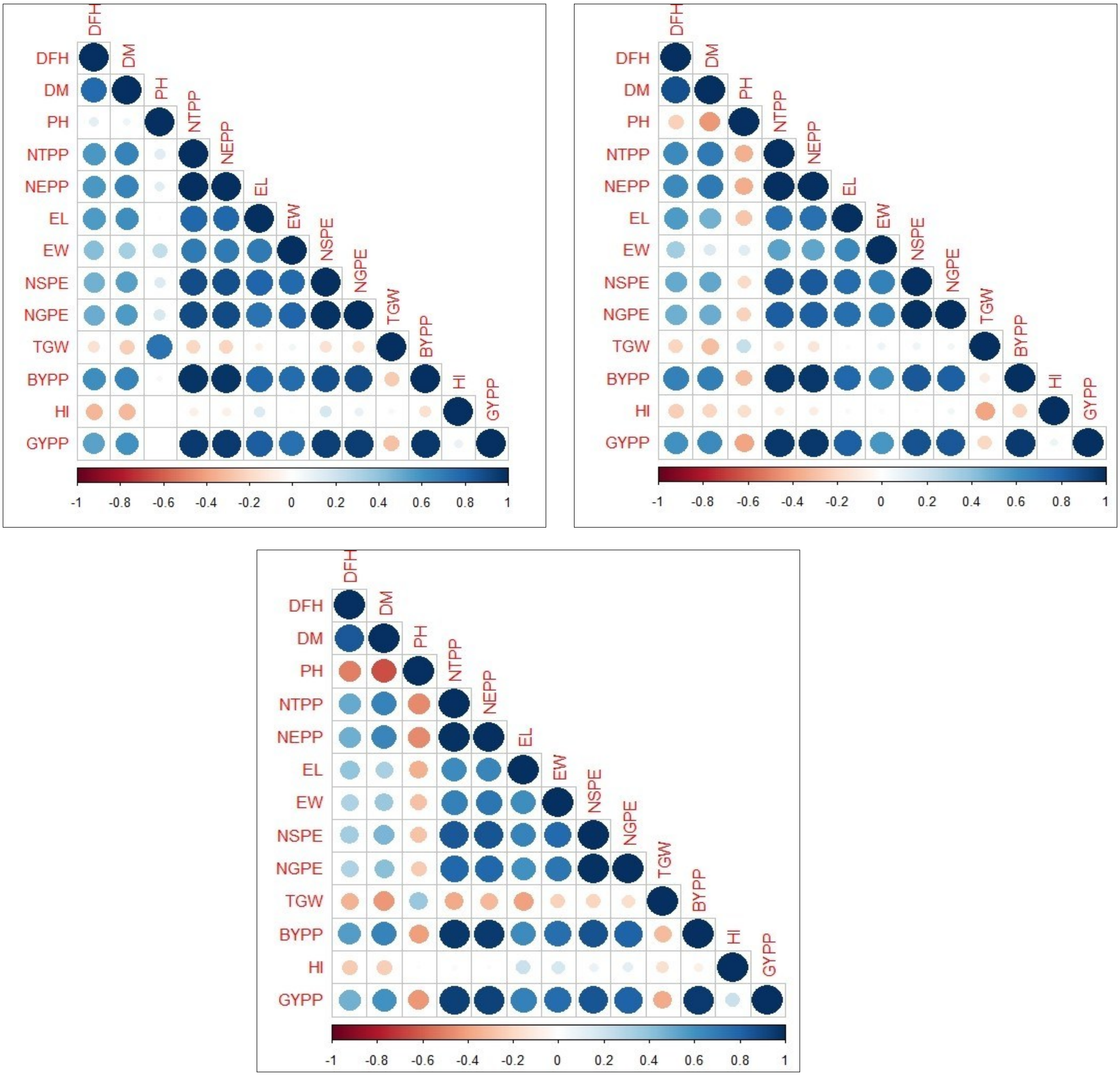

Fig. 2. Phenotype correlation coefficient analysis using the Pearson method for all traits under study across the environments-E1 (Left), E2 (Middle), E3 (Right).

Table 1. Analysis of variance for yield and yield components in wheat hybrids

Source of Variations	D.F.	Mean sum of squares												
		DH	DM	PH	NTPP	NSPP	SL	SW	NSPS	NGPS	TGW	BYPP	HI	GYPP
Hybrids	20	39.15**	39.45**	66.04**	489.11**	471.72**	2.05**	0.35**	12.63**	122.05**	100.20**	10626.28**	63.53**	1694.26**
Env.+ (hyb. × Env.)	42	8.57**	15.42**	24.78**	65.28**	66.20**	0.85**	0.07**	0.29**	3.265**	5.71	949.92**	4.19	161.61**
Environments (Lin.)	1	281.28**	583.15**	277.40**	1406.60**	1410.52**	26.03**	1.98**	8.19**	91.46**	20.53	21288.50**	8.79	3907.25**
Hyb. × Env.(Lin.)	20	2.33	1.67	20.7	63.12**	64.53**	0.28	0.05**	0.13	1.63*	4.17	806.44**	4.23	133.91**
Pooled deviation	21	1.53**	1.47**	16.64**	3.47**	3.77**	0.19**	0.01	0.07**	0.61**	6.48	118.06**	3.93**	9.62**
Pooled error	60	0.28	0.33	0.85	1.05	1.01	0.07	0.01	0.02	0.11	5.57	16.79	0.33	2.28
Total	62	18.44	23.17	38.09	202	197.01	1.24	0.16	4.27	41.58	36.19	4071.32	23.33	656.01

*, ** indicate level of significant at 5 % and 1 %, respectively; DH - Days to heading; DM - Days to maturity; PH - Plant height; NTPP - Number of tillers per plant; NSPP - Number of spikes per plant; SL - Spike length; SW - Spike weight; NSPS - Number of spikeletes per spike; NGPS - Number of grains per spike; BYPP - Biological yield per plant; TGW - Thousand grain weight; HI - Harvest index; GYPP - Grain yield per plant

Table 2. Stability parameters for grain yield per plant of wheat hybrids across three environments

S. No.	Hybrids	GYPP		
		Mean	βi	S^2di
1	CMS82 × Res-37	41.79	0.3	14.54**
2	CMS83A × Res-37	19.59	0.1	-0.52
3	CMS84 × Res-37	67.91	1.47*	-2.16
4	HI 1544	34.74	0.44	3.73
5	CMS85 × Res-37	64.01	1.61	7.142*
6	CMS86 × Res-37	39.99	0.83	0.99
7	CMS87 × Res-37	53.55	0.91	27.50**
8	GW 273	28.07	0.39	4.14
9	CMS88 × Res-37	92.46	0.7	1.63
10	CMS89 × Res-37	73.13	0.2	-0.98
11	CMS90 × Res-37	96.83	1.72**	-2.21
12	CMS91 × Res-37	64.43	0.56	10.45*
13	MP 3382	39.22	0.12	1.76
14	CMS92 × Res-37	89.62	2.39	33.518**
15	CMS94 × Res-37	72.51	1.04	-2.18
16	Lok-1	35.85	0.24	6.84*
17	CMS95 × Res-37	58.33	1.88	0.19
18	CMS96 × Res-37	90.28	2.85	50.88**
19	CMS97 × Res-37	57.46	2.43*	-1.71
20	GW 366	27.42	0.44	0.32
21	CMS2041 × Res-37	83.56	0.28	1.49
	Population Mean	58.61		
	S.E(±)		2.19	0.22

* &** indicates significance at 5 % and 1 % level, respectively

The AMMI analysis of variance of grain yield showed that 83.1 % of the total sum of squares was attributable to genotype, only 9.60 % to the environment and 7.08 % to G × E effects. The multiplicative variance of the treatment sum of squares due to interaction was partitioned into three significant interaction principal components. The first two PCs explained 95.10 % and 4.89 % of the GE interaction, respectively, representing a total of 100 % of the interaction (Table 3). The presence of a significant GE interaction necessitates the analysis of the stability of wheat genotypes over environments.

Grouping of environments

Grain yield analysis of wheat revealed that the average environment ranged from 50 g (E3) to 69.04 g (E1). Twelve genotypes showed above-average yield in the E1 environment. Ten genotypes in the E2 environment and ten genotypes in the E3 environment outperformed the average yield of their corresponding genotypes in each environment. The present study showed that environment E1 had the longest vector, indicating it was more discriminative compared to the other two environments. The Average Environment Axis (AEA) view compares the environments with an ideal environment. The environment E3 had the smallest angle with the AEA; hence, the E3 environment is highly representative (Fig. 3). The Average Environment Coordinate (AEC) axis projected the stability of the accessions. A small perpendicular line to the AEC axis indicates the highly stable genotypes. In contrast, the increase in the length of the vertical line denotes a decrease in the stability of the genotypes. Genotypes (G2, G4, G7, G15 and G11) were highly stable with low to good yielding ability. The genotype G19 was highly unstable because it was far away from the AEC axis, followed by G18 (CMS96A × Res-37) and G17 (CMS95A × Res-37). The elite hybrid wheat lines: G3 (CMS84A × Res-37), G5 (CMS85A × Res-37), G11 (CMS90A × Res-37) and G15 (CMS94A × Res-37) are above average yielders with more stability (Fig. 4).

Genotype response to wider adaptation

AMMI analysis revealed that the interaction component IPCA 1 accounted for 95.10 % of the total interaction sum of

Table 3. AMMI analysis of variance for mean grain yield of 21 genotypes from three different environments

	Degrees of freedom	Sum of squares	Mean sum of squares	F-value	Explained (%)
Environments	2	7814.518	3907.259**	875.9585**	9.6065
Genotypes	20	67770.62	3388.531**	759.6662**	83.31136
Genotype × Environment	40	5761.055	144.0264**	32.28891**	7.08214
IPCA1	21	5479.009	260.9052**	57.60391**	95.10427
IPCA2	19	282.046	14.84452**	3.27744**	4.89573
IPCA3	17	0	0	0	0
Residuals	63	281.0148	4.46055	NS	0

**significant at 5 % probability level; Ns- non-significant

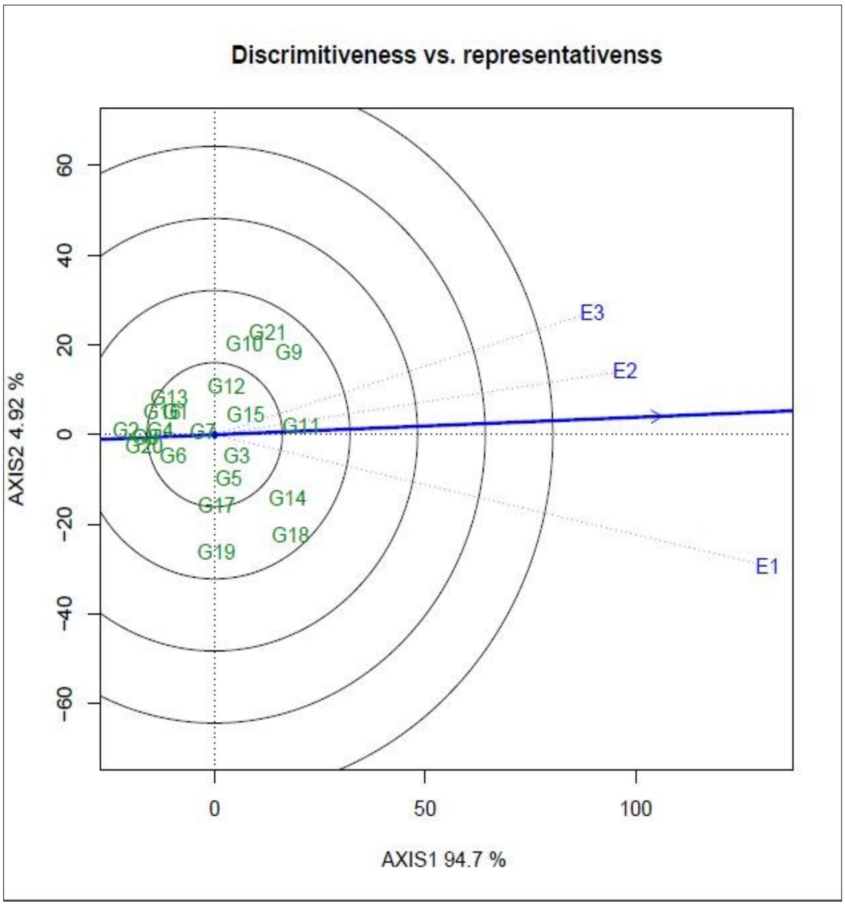

Fig. 3. GGE biplot based on environment focused scaling for the comparison of three environments in relation to average environment axis (AEA) (Blue line that passes through the biplot origin and the average environment).

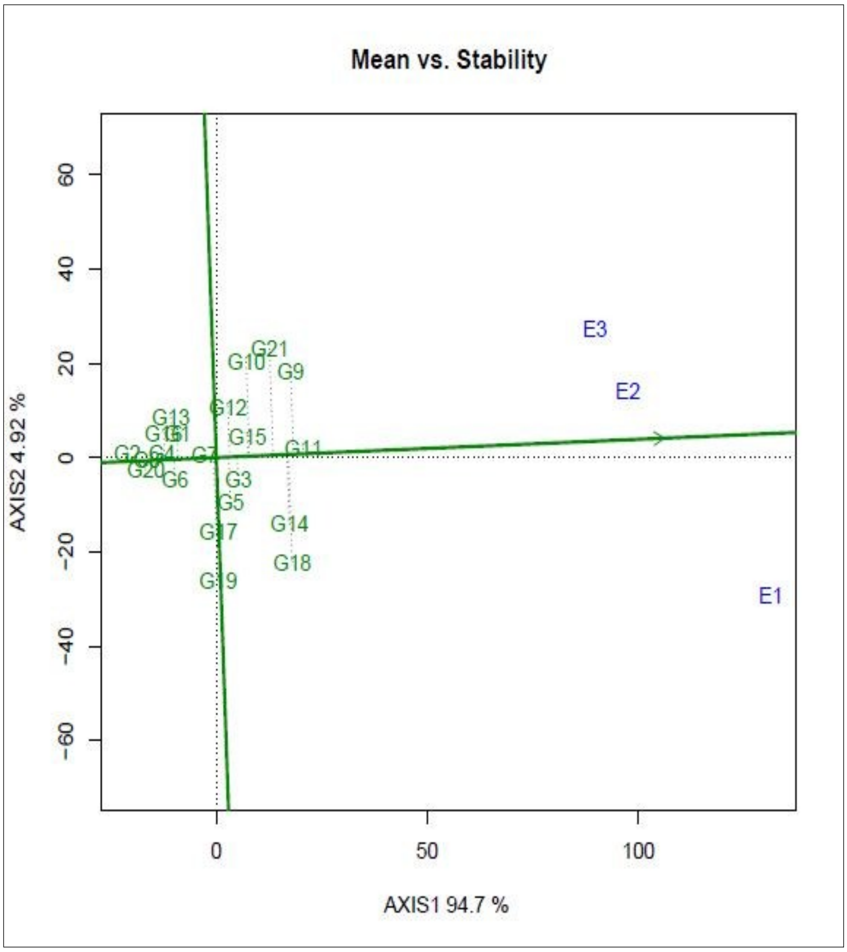

Fig. 4. Average environment coordinate (AEC) view based on environment focused scaling for the pooled mean performance and the stability of wheat hybrids.

squares, whereas IPCA 2 accounted for 4.89 %. The performance of genotypes in a specific environment, as well as the overall performance across all the test environments, can be effectively analyzed in the presence of two or more PCA axes. IPCA 1 scores for grain yield over three environments were plotted against genotype and environment scores along with the environments (E1, E2 and E3) (Fig. 4a). The genotypes plotted on the right side of the central axis, formed based on the grand mean, exhibited high yield compared to those on the left side of the axis. Eight genotypes that exhibited the above-average performance with a positive interaction effect were present in quadrant I. Four genotypes in quadrant IV also showed the above-average performance, but had an adverse interaction effect. Of the eight genotypes, along with environment E3, those falling under quadrant III showed below-average performance with an adverse interaction effect. Approximately 3 genotypes (G6, G7 and G15) had IPCA 1 scores closer to zero, ranging from -0.46 to 1 (Table 4), which remained stable across all test environments (E1, E2 and E3). A set of five genotypes was found to be less stable, as it explained moderately larger scores.

For the maximum exploration of GEI, the IPCA 1 scores are visualized against IPCA 2 in the form of a graph (Fig. 5). The G15 genotype with IPCA 2 value 0.02 located nearer to the centre of the biplot, produced a highly stable grain yield across all the test environments (Fig. 6). Furthermore, the biplot showed a highly interactive environment as E1 as well as the genotypes (G19 and G18) that contributed largely to the GEI. The genotypes G18 and G14 particularly performed well in E1. The genotype G7 was particularly adapted to E2, whereas genotype G1 had a greater interaction with E3. According to ASV, a low ASV of any genotype indicates stability across environments, while those with high ASV values are less stable. The hybrids G15 (CMS94 × Res-37), G6 (CMS86 × Res-37), G7 (CMS87 × Res-37), G3 (CMS84 × Res-37) and G12 (CMS91 × Res-37) were found to be the most stable hybrids with ASV values of 1.81 to 17.25, whereas G18 (CMS96 × Res-37) and G14 (CMS92 × Res-37) were the most unstable hybrids with ASV values of 70.09 and 53.01, respectively (Table 4). The genotype selection index (GSI) integrates both yield and stability across environments. The lowest GSI is considered the most stable with a high grain yield. Based on low GSI value, G15 (CMS94 × Res-37), G3 (CMS84 × Res-37), G11 (CMS90 × Res-37), G12 (CMS91 × Res-37) and G19 (CMS97 × Res-37) were found to be the most stable with high yield potential (Table 4). The genotypes G9, G15, G3, G11 and G12 and G19 outperformed the checks in E1, E2 and E3.

Genotype response to specific adaptation

Locating the most suitable accession for each environment can be done using a 'which-won-where' pattern analysis. In this, a polygon is produced by joining the genotypes far away from the origin consisting of all the other genotypes inside the polygon (Fig. 7). The polygon is further portioned into eight different sectors using the rays (red line) that were starting from the biplot origin and passing perpendicular to the sides of the polygon. The genotypes in an industry tend to be similar in performance compared to those in other sectors. Environment E1 is more suitable for the following genotypes,

Table 4. Mean grain yield, AMMI stability value (ASV) and genotype selection index (GSI) of wheat hybrids

Hybrids/Environment	Codes	E1	E2	E3	Mean	IPCA 1`	IPCA 2	ASV	GSI	rASV	rYSI	Mean
CMS82 × Res-37	G1	46.17	37.94	41.28	41.79	-0.33	-0.44	23.46	24.00	10.00	14.00	41.79
CMS83A × Res-37	G2	20.34	20.46	18.00	19.60	-0.32	0.46	32.85	39.00	18.00	21.00	19.60
CMS84 × Res-37	G3	83.16	65.45	55.13	67.91	0.24	0.10	16.90	13.00	5.00	8.00	67.91
HI 1544	G4	38.73	35.90	29.62	34.75	-0.30	0.10	20.96	26.00	8.00	18.00	34.75
CMS85 × Res-37	G5	81.78	58.61	51.67	64.02	0.34	-0.14	23.68	21.00	11.00	10.00	64.02
CMS86 × Res-37	G6	49.18	37.04	33.77	39.99	-0.08	-0.17	5.40	17.00	2.00	15.00	39.99
CMS87 × Res-37	G7	61.50	56.29	42.88	53.56	-0.08	0.42	5.64	16.00	3.00	13.00	53.56
GW 273	G8	31.43	29.40	23.40	28.08	-0.33	0.10	23.07	28.00	9.00	19.00	28.08
CMS88 × Res-37	G9	100.32	89.61	87.46	92.46	-0.14	-0.21	10.08	6.00	4.00	2.00	92.46
CMS89 × Res-37	G10	74.96	73.66	70.79	73.14	-0.42	-0.05	29.22	21.00	15.00	6.00	73.14
CMS90 × Res-37	G11	114.83	93.78	81.90	96.83	0.38	0.13	26.34	13.00	12.00	1.00	96.83
CMS91 × Res-37	G12	69.29	66.28	57.73	64.43	-0.25	0.21	17.26	15.00	6.00	9.00	64.43
MP 3382	G13	40.00	40.60	37.08	39.23	-0.46	0.01	32.35	33.00	17.00	16.00	39.23
CMS92 × Res-37	G14	116.33	80.46	72.10	89.63	0.76	-0.24	53.02	24.00	20.00	4.00	89.63
CMS94 × Res-37	G15	83.50	70.44	63.60	72.51	0.03	-0.01	1.82	8.00	1.00	7.00	72.51
Lok-1	G16	37.57	37.83	32.17	35.85	-0.41	0.11	28.49	31.00	14.00	17.00	35.85
CMS95 × Res-37	G17	77.50	56.17	41.33	58.33	0.45	0.27	31.27	27.00	16.00	11.00	58.33
CMS96 × Res-37	G18	122.13	79.23	69.50	90.28	1.00	-0.27	70.09	24.00	21.00	3.00	90.28
CMS97 × Res-37	G19	82.61	53.63	36.17	57.47	0.73	0.30	51.52	31.00	19.00	12.00	57.47
GW 366	G20	32.50	25.33	24.44	27.42	-0.28	-0.22	19.53	27.00	7.00	20.00	27.42
CMS2041 × Res-37	G21	86.00	84.60	80.10	83.57	-0.38	0.03	26.63	18.00	13.00	5.00	83.57
Mean		69.04	56.79	50	58.61							

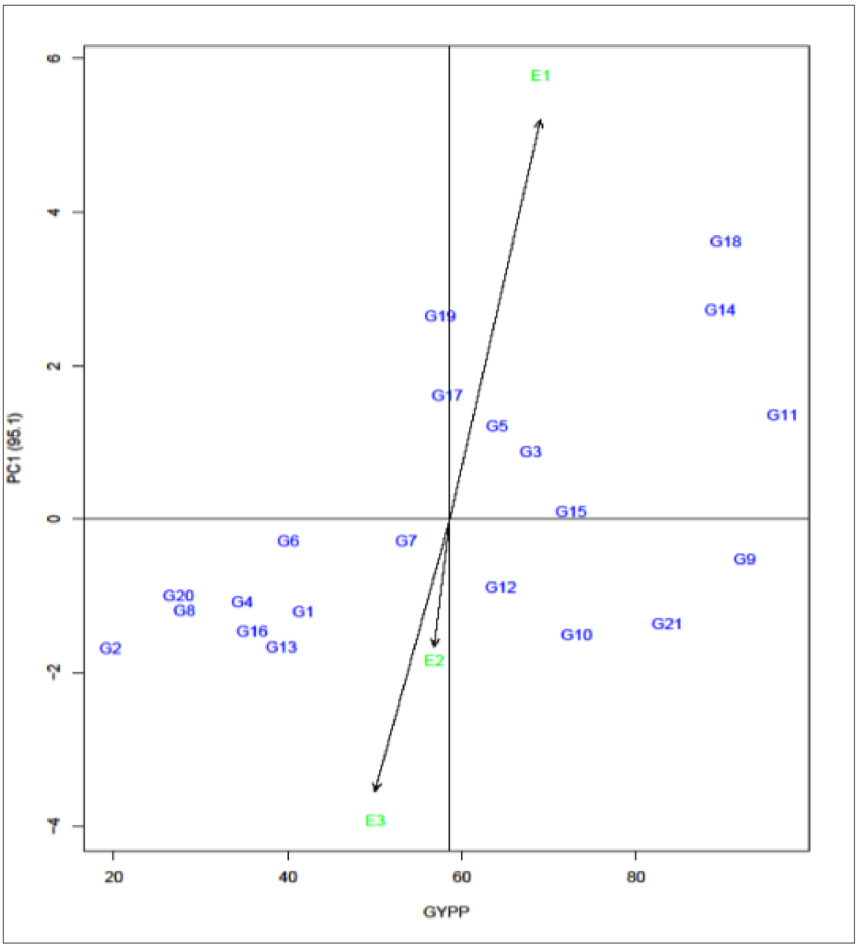

Fig. 5. AMMI I biplot showing main effects and IPCA 1 interaction effects of wheat hybrids and three environments on grain yield of wheat.

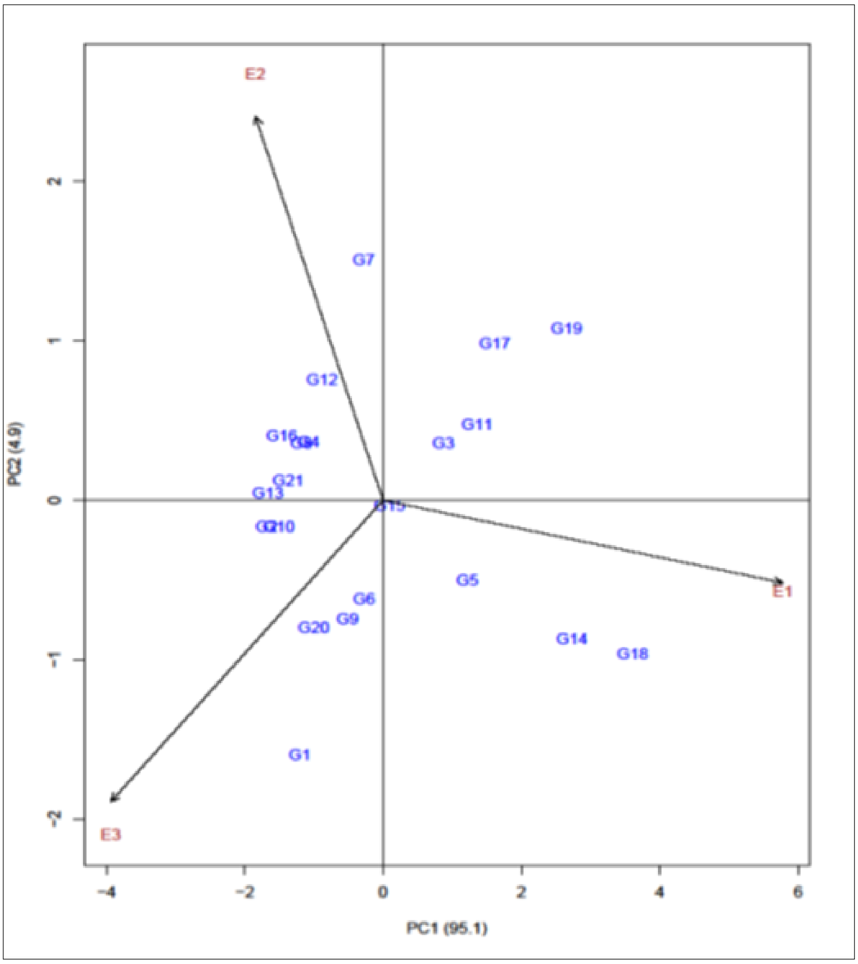

Fig. 6. AMMI II biplot of the first two principal components (IPCA1 Vs IPCA2) of interaction effects.

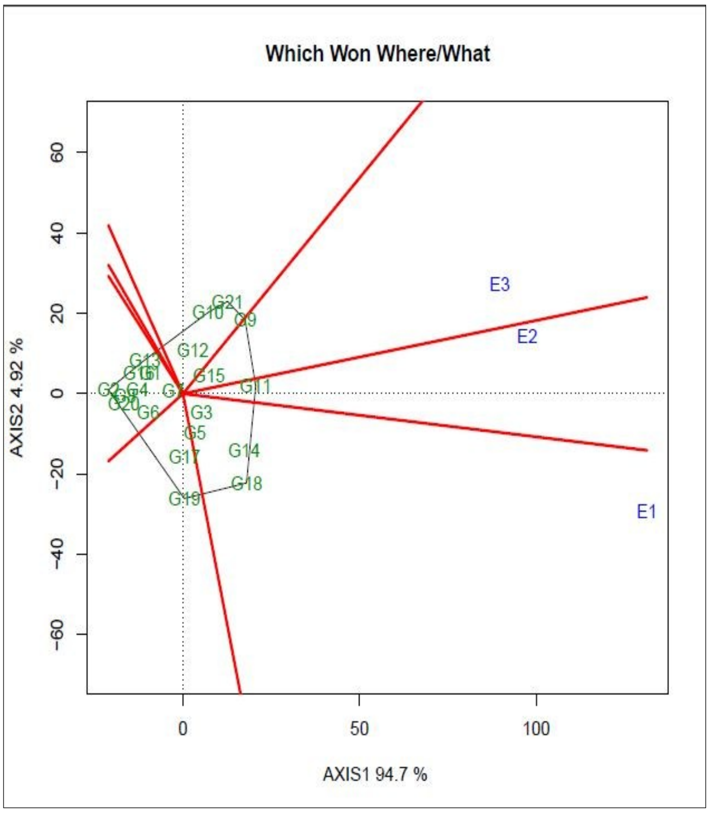

Fig. 7. The winning pattern of wheat hybrids across three environments, based on symmetrical scaling, showing the winning genotype in each environment.

viz., G14, G18 and G3, which are located in the same industry, whereas climate E2 is highly desirable for G11. Few of those genotypes that performed well in E3 were G9 and G15. The genotypes plotted at each vertex of the polygon were the best-performing genotype in the environment nearer to the vertex. In this case, the elite hybrid wheat line G18 (CMS96A × Res-37) vector is characterized by the longest distance from the origin and is the vertex line of the sector, implies line G18 (CMS96A × Res-37) with specific adaptation in the irrigated environment (E1) but lower stability in the overall environment. Similarly, G11 and G9 were the peak genotypes that are highly suitable for the environments E2 and E3, respectively. The genotypes G11 and G9 outperformed the checks in E2 and E3.

Discussion

Terminal heat stress, particularly during the reproductive stage , is a major constraint to wheat hybrid cultivation during the dry season, decreasing spikelet fertility and, subsequently, grain yield. Hence, a long-term goal of the current breeding program should be the generation of wheat hybrids with high yield heterosis and stability under different temperature regimes. In the present study, analysis of variance revealed significant genotype × environment differences for single plant yield. The effect of genotype × environment interaction on phenotypic expression was caused by the shift in sowing date, resulting in various temperature regimes throughout the crop's growth and development period. In the case of single plant yield, a reduction in yield due to heat stress was evident for all genotypes under study.

Genotype and environment interactions were significant for all the traits in the pooled analysis, indicating sufficient variability among the hybrids. The selection for yield improvement is a complex phenomenon that should be determined by accounting for both genotypes and environmental interactions. Stability models facilitate the study of the G × E interaction, enabling the identification of specifically adapted genotypes for particular environments and generally adapted genotypes for all test environments (13, 14). The best-performing and most stable accessions identified will be utilized for pre-breeding purposes to develop promising wheat genotypes.

The significance of the G × E interaction is tested against the pooled deviation to verify that hybrids do not differ for the environmental index (15-19). Stability analysis is one of the most desirable parameters of a genotype for wider adaptation. Hence, it is suggested that actual testing under variable environments, including both favourable and unfavourable conditions, would be advantageous in identifying stable genotypes. During selection, attention should be paid to the phenotypic stability of characters directly related to grain yield in hybrid wheat. Consequently, genotypes with good buffering ability and predictable behaviour in fluctuating environments are most desirable soon. They may be recommended for that particular environmental condition to accelerate wheat production in the climate-changing scenario.

The AMMI model is commonly used in stability analysis because it enables the model to fit into multi-environment evaluation, allows for partitioning of the G × E interaction and explains patterns and relationships between genotypes and environments (20, 21). In the present study, the significant yield variation explained by genotypes indicated substantial genetic variability among genotypes, with significant differences between genotype means contributing to most of the variation in grain yield (22, 23). The AMMI biplot has the primary effect, represented by grain yield, on the abscissa and IPCA1 is the ordinate. Genotypes or environments that lie on the same vertical line have the same yield and those that lie on the same horizontal line have the same interaction pattern. Additionally, the vectors of genotypes with IPCA1 close to the origin (zero) exhibit general adaptability, whereas those with larger IPCA1 values are specifically adapted to a particular environment. In this study, environments two and three, which are heat-stressed, have a lower-than-average yield, while the irrigated, timely sowing environment has a higher-than-average yield. In the AMMI biplot, genotypes that cluster together exhibit similar behaviour across environments. Based on the performance of genotypes across different environments, AMMI 1 classified the genotypes as most stable and high yielding genotypes (G15), less stable and high yielding genotypes (G9 and G11) and most stable and low yielding genotypes viz., G6 and G7. From the AMMI 2 biplot, the highly interactive environment (E1) and genotypes (G19 and G18) were identified. The precise adaptation of genotypes to the appropriate environment has also been visualized with the help of a biplot. E1 was more suitable for the genotype G18. The genotype G7 exhibited high-yielding potential in E2, whereas genotype G1 showed a positive interaction with E3. Numerous studies on wheat have reported that the environment explains the largest portion of the total sum of squares, often ranging from 40 % to over 80 %, highlighting the overwhelming influence of diverse growing conditions on crop performance.

However, stability *per se* should not be used as the only criterion for selection since the most stable genotypes may not necessarily give the best yield performance (24). Hence, approaches that incorporate mean yield and stability in a single index are needed. There are different selection criteria for the simultaneous selection of yield and stability (11, 25-28). Based on GSI, the following genotypes, namely G15 (CMS94A × Res-37) and G9 (CMS88A × Res-37), were identified as stable and high-yielding across all test environments under study. The sector with an irrigated, timely sowing environment consists of elite hybrid wheat lines: G3 (CMS84A × Res-37), G5 (CMS85A × Res-37), G14 (CMS92A × Res-37) and G18 (CMS96A × Res-37), indicating that these hybrid lines are responsive in this environment. The line from the origin of the biplot to the genotype suggests the difference in yield of genotypes from the grand mean. Genotypes with long vectors can exhibit either good or poor performance. The ability of any test environment can be visualized with the aid of the discriminating power and representativeness view of the environment (29). The length of the environment vectors is proportional to the standard deviation within the respective environments on the biplot and also displays the discriminating ability of the environment. The GGE biplot utilises the environment vector to measure discriminativeness, where the length of the environment vector indicates the standard deviation within the environment, thereby indicating a higher discriminating ability. The environment with no discriminating ability gives no information of useless lines and the environment, not representative, is useless and misleading. Thus, late environments E2 and E3 with lower vector length, were less discriminating than timely sowing environments in the case of grain yield per plant. This is primarily due to the general decrease in yield in most genotypes of late-sown crops resulting from severe temperature stress. Representativeness is the measure of the environment, similar to the AEC ranking of genotypes. The desirability of the environment is not evident due to the limited use of specific environments. However, all three environmental vectors inscribe somewhat equal angles with the average environmental coordinate, which symbolises the similar representativeness of irrigated and terminal heat-stressed environments.

The 'which-won-where' pattern analysis of G18, G11 and G9 were the vertex cultivars in E1, E2 and E3 environments, respectively, that expressed the better yielding ability. G18 (CMS96A × Res-37) is the winning hybrid in an irrigated, timely sowing environment, while hybrid G9 (CMS88A × Res-37) is the winning hybrid in a heat-stressed environment. In addition, the polygon view showed elite wheat line G7 (CMS87A × Res-37) near the origin of the biplot, which means this line ranks the same in all three test environments and hybrids: G1 (CMS82A × Res-37), G10 (CMS89A × Res-37), G17 (CMS95A × Res-37), G19 (CMS97A × Res-37), G21 (CMS2041A × Res-37) are present in a sector with no test environment symbolizes these hybrids are poor adapted to all three environments. The promising performance of the vertex genotypes in the desired wheat environment (30). This delineation of mega-environments is a primary strength of GGE biplot analysis and mirrors findings in other large-scale cereal METs. For example, studies in the wheat belts of North America and the Indian subcontinent have successfully used GGE biplots to identify distinct production zones that require specifically adapted cultivars. Our findings provide a similar roadmap for breeding programs in our target region, suggesting that pursuing a single, universally adapted genotype may be less effective than developing a portfolio of genotypes tailored to specific sub-regions.

In summary, the discussion above demonstrates that hybrid G15 (CMS94A × Res-37) is suitable for general adaptation and has been identified for cultivation in various temperature regimes. Hybrids G10 (CMS89A × Res-37), G9 (CMS88A × Res-37) and G21 (CMS 2041 × Res-37) exhibited above-average stability for yield and yield components and therefore adapted explicitly to high-temperature regimes. The results suggest that the genotypes used in the study exhibit different combinations of genes that govern their responses to sowing dates and tolerance to heat stress (31-33). The present stability analysis study of hybrids from breeding programs across three testing environments revealed the significant role of genotype-by-environment interaction in influencing grain yield under different temperature regimes. They can be considered as potential genotypes for cultivation under terminal heat stress after evaluating them under multilocation trials. Hence, the above-mentioned hybrids could be used to accelerate wheat improvement programs for different cropping systems. To identify a better genotype for grain yield, further studies on temperature tolerance mechanisms, including physiological and molecular parameters, are needed. The identified tolerant genotypes can be utilized in future crop improvement programs.

Conclusion

The present stability analysis study of hybrids from breeding programs across three testing environments revealed the significant role of genotype-by-environment interaction in influencing grain yield under different temperature regimes. Hybrids G10 (CMS89A × Res-37), G9 (CMS88A × Res-37) and G21 (CMS 2041 × Res-37) exhibited above-average stability for yield and yield components and therefore adapted explicitly to high -temperature regimes. They can be considered potential genotypes for cultivation under terminal heat stress after evaluation in multilocation trials. Hence, the above-mentioned hybrids could be used to accelerate wheat improvement programs for different cropping systems. To identify a better genotype for grain yield, further studies on temperature tolerance mechanisms, including physiological and molecular parameters, are needed. The identified tolerant genotypes can be utilized in future crop improvement programs.

Acknowledgements

The authors are thankful for the support of the Genetics Division, IARI, New Delhi and IIWBR, Karnal, for providing seed material.

Authors' contributions

VK designed the experiments, analyzed the data and prepared the first draft. RS designed the experiments. MEH analyzed the data and prepared the first draft. SP and SK provided inputs and finalized the draft. All authors reviewed and finalized the manuscript. All authors have read and agreed to the published version of the manuscript.

Compliance with ethical standards

Conflict of interest: The Authors do not have any conflicts of interest to declare.

Ethical issues: None

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