Plant Archives Vol. 26, No. 2, 2026 pp. 3179-3189 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org

DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2026.v26.no.2.441

AMMI AND GGE BIPLOT ANALYSIS OF GENOTYPE × ENVIRONMENT INTERACTION FOR GRAIN YIELD STABILITY OF MAIZE (*Zea mays* L.) HYBRIDS UNDER CONTRASTING MOISTURE REGIMES

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(Date of Receiving-21-08-2026; Date of Revision-20-10-2026; Date of Acceptance-25-10-2026)

ABSTRACT

Drought around flowering is the main abiotic constraint to maize yield in rainfed South Asia. Twenty experimental maize (*Zea mays* L.) hybrids and four commercial checks were evaluated to quantify genotype × environment (G × E) interaction for grain yield and to identify hybrids combining high yield, stability and drought tolerance. Entries were grown in an alpha-lattice design with two replications in six environments formed by well-watered, moderate-stress and severe-stress regimes over *rabi* 2024–25 and *kharif* 2025 at Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya, Uttar Pradesh, India. Environments, genotypes and G × E accounted for 63.16, 30.70 and 6.14% of the treatment sum of squares and the first two interaction principal component axes captured 68.42 and 15.03% of the G × E sum of squares. GGE biplot PC1 and PC2 together explained 95.82% of genotype plus G × E variation. H14 (9.183 t ha^{-1}), C4 (9.083 t ha^{-1}) and H08 (8.983 t ha^{-1}) were the highest yielding entries and lay closest to the ideal genotype and H08 was the most stable of the three. Under severe stress, H18 (14.26%), C2 (14.71%), H14 (15.96%) and C4 (16.63%) showed the smallest yield reductions, whereas H19 lost 37.70%. AMMI-based stability statistics favoured average-yielding hybrids because the main interaction axis reflected drought tolerance. The severe-stress environments E6 and E3 were the most discriminating and the moderate-stress environment E5 the most representative. H14 and H08 were identified for multi-location and on-farm testing.

Key words : Drought stress, Mega-environment, Multi-environment trials, Crossover interaction, Stress tolerance index, WAAS.

Introduction

Maize (*Zea mays* L.) is grown across a wider range of environments than any other cereal, and in the tropics most of the crop is still produced by smallholders under rainfed conditions (Erenstein *et al*., 2022; Prasanna *et al*., 2021). Water deficit is the most widespread abiotic stress limiting maize yield (Sheoran *et al*., 2022). The crop is most sensitive around flowering, when water deficit delays silk emergence, widens the anthesis-silking interval (ASI) and under severe stress, causes ear abortion and barrenness (Bolaños and Edmeades, 1996). Hybrids must therefore be selected for performance under both optimal and stressed conditions (Prasanna *et al*., 2021).

Multi-environment trials (METs) used to identify such hybrids are complicated by genotype × environment (G × E) interaction, and when the interaction is of the crossover type the best hybrid in one environment is not the best in another (Yan and Tinker, 2006). Joint regression

(Finlay and Wilkinson, 1963; Eberhart and Russell, 1966) and variance statistics (Wricke, 1962 and Shukla, 1972) assume a linear response to the environment mean and capture only part of the interaction (Becker and Léon, 1988). The additive main effects and multiplicative interaction (AMMI) model separates the main effects from a multiplicative interaction term (Zobel *et al*., 1988), whereas the GGE biplot retains the genotype main effect together with G × E (Yan *et al*., 2000). The two methods treat the genotype main effect differently (Gauch, 2006; Yan *et al*., 2007), and recent maize METs have combined them to select drought-tolerant hybrids (Li *et al*., 2023; Sitonik *et al*., 2026). The weighted average of absolute scores (WAAS) further uses all significant interaction axes and allows joint selection for yield and stability (Olivoto *et al*., 2019).

Indian AMMI and GGE studies of maize hybrids have compared test locations (Raj *et al*., 2023; Singh *et al*., 2024), but most were conducted under a single, usually favourable, moisture regime. Few have analysed well-watered, moderate-stress and severe-stress regimes jointly at one site and the relationship between interaction-based stability and drought tolerance is seldom examined directly. The present study evaluated 20 experimental hybrids and four commercial checks in six environments formed by three moisture regimes over two seasons in the Eastern Plain Zone of Uttar Pradesh. The objectives were (i) to partition grain yield variation and describe the structure of G × E with the AMMI model, (ii) to compare AMMI-based, regression-based and variance-based stability parameters, (iii) to evaluate hybrids and test environments with GGE biplots, and (iv) to identify drought-tolerant hybrids with stress tolerance indices.

Materials and Methods

Experimental site, material and design

The experiments were conducted at the Agrometeorological Research Farm of Acharya Narendra Deva University of Agriculture and Technology (ANDUAT), Kumarganj, Ayodhya, Uttar Pradesh, India (26°47′ N, 82°12′ E; 113 m above mean sea level), during rabi 2024–25 (Season I, sown on 20 November 2024) and kharif 2025 (Season II, sown on 25 June 2025). The subtropical site receives about 1,001 mm of rainfall annually, mostly between June and September. The soil (0–15 cm) was a silt loam (sand 25.0%, silt 49.5%, clay 25.5%) with pH 8.2, electrical conductivity 0.24 dS m^{-1} and organic carbon 0.32%, and contained 136.5, 14.5 and 248.5 kg ha^{-1} of available N, P and K, respectively (Jackson, 1973; Walkley and Black, 1934; Subbiah and Asija, 1956; Olsen *et al*., 1954).

The material comprised 20 experimental hybrids (H01 to H20) and four commercial check hybrids (C1 to C4) grown by farmers in eastern Uttar Pradesh. Each season carried three moisture regimes, well-watered (WW), moderate stress (MS) and severe stress (SS), and each season × regime combination was treated as an environment: E1, E2 and E3 (Season I; WW, MS and SS) and E4, E5 and E6 (Season II; WW, MS and SS). Within each environment the entries were laid out in an alpha-lattice design (Patterson and Williams, 1976) with two replications of six incomplete blocks of four entries. Plots were two rows 4 m long at 75 × 20 cm spacing (6.0 m²; about 66,666 plants ha^{-1}). The three regimes were grown as adjacent blocks separated by a buffer strip. The WW regime was irrigated at all critical stages, whereas in the MS and SS regimes irrigation was withheld over a window spanning anthesis, silking and early kernel development (Bänziger *et al*., 2000), the MS regime being relieved by irrigation at a higher soil water content than the SS regime. In kharif, rainfall was excluded during the stress window with a temporary rain-out shelter, which was removed after rescue irrigation. All other operations followed the recommended package of practices of ANDUAT.

Grain yield (t ha^{-1}) was computed from plot fresh ear weight, shelling percentage and grain moisture and adjusted to a standard moisture content. Secondary traits were recorded following CIMMYT protocols (Bänziger *et al*., 2000), but only grain yield is analysed here.

Statistical analysis

Residual normality and homogeneity of error variances were checked with the Shapiro-Wilk (Shapiro and Wilk, 1965) and Bartlett (Bartlett, 1937) tests. Each environment was analysed as a resolvable incomplete block design and the combined analysis followed the model

$$Y_{ijkl} = \mu + g_i + e_j + (ge)_{ij} + r_{k(j)} + b_{l(jk)} + \varepsilon_{ijkl}$$

where g_i, e_j and $(ge)_{ij}$ are the genotype, environment and interaction effects, $r_{k(j)}$ is replication within environment, $b_{l(jk)}$ is block within replication and environment and ε_{ijkl} is the error. Environments were tested against replications within environments, and genotypes and G × E against the pooled error (Gomez and Gomez, 1984); standard errors, critical differences and coefficients of variation followed Panse and Sukhatme (1985).

The AMMI model (Gauch and Zobel, 1997) was fitted to the genotype × environment table of means as

$$Y_{ij} = \mu + g_i + e_j + \Sigma_{k=1\ldots n} \lambda_k \alpha_{ik} \gamma_{jk} + \rho_{ij} + \varepsilon_{ij}$$

where, λ_k is the singular value of the *k*th interaction principal component axis (IPCA), α_{ik} and γ_{jk} are the genotype and environment eigenvectors, ρ_{ij} is the residual interaction and ε_{ij} is the error. Axis sums of squares ($r\lambda_k^2$) were tested against the pooled error with degrees of freedom following Gollob (1968). The AMMI stability value was calculated as $ASV_i = \sqrt{[(SS_{IPCA1}/SS_{IPCA2})(IPCA1_i)^2 + (IPCA2_i)^2]}$ (Purchase *et al*., 2000) and the genotype selection index as GSI = rank of mean yield + rank of ASV (Farshadfar, 2008). The weighted average of absolute scores, $WAAS_i = \Sigma_k|IPCA_{ik} \times EP_k|/\Sigma_k EP_k$, used all five axes, EP_k being the percentage of the G × E sum of squares explained by axis *k* (Olivoto *et al*., 2019). WAAS was computed from the fixed-effect AMMI decomposition of the means, and mean yield and WAAS were rescaled to 0–100 and combined with equal weights into the WAASY index (higher is better).

The joint regression model $Y_{ij} = \mu_i + b_i I_j + \delta_{ij}$ (Eberhart and Russell, 1966) was fitted, where b_i is the regression coefficient on the environmental index I_j and δ_{ij} is the deviation from regression with variance S^2_{di}; $b_i = 1$ was tested by a *t* test and $S^2_{di} = 0$ by an *F* test. Wricke's ecovalence (W_i; Wricke, 1962) and Shukla's stability variance (σ^2_i; Shukla, 1972) were also computed, smaller values indicating greater static stability (Becker and Léon, 1988).

GGE biplots were constructed from the environment-centred, unscaled means table (Yan and Kang, 2003) as

$$Y_{ij} - \mu - \beta_j = \lambda_1\xi_{i1}\eta_{j1} + \lambda_2\xi_{i2}\eta_{j2} + \varepsilon_{ij}$$

where, β_j is the main effect of environment *j*, λ_1 and λ_2 are the singular values of PC1 and PC2, and ξ_{ik} and η_{jk} are the genotype and environment eigenvectors. Genotype-focused singular value partitioning (SVP = 1) was used for the which-won-where, mean versus stability and ranking views, and environment-focused partitioning (SVP = 2) for the discriminativeness versus representativeness view (Yan, 2002; Yan and Tinker, 2006; Yan *et al*., 2011).

Yield under potential (Y_p), moderate-stress (Y_m) and severe-stress (Y_s) conditions was the mean of E1 and E4, E2 and, E5 and E3 and E6, respectively. Yield reduction was YR (%) = $100 \times (1 - Y_s/Y_p)$. The drought susceptibility index was DSI = $(1 - Y_s/Y_p)/SI$, with stress intensity SI = $1 - \bar{Y}_2/\bar{Y}_p$ (Fischer and Maurer, 1978); the stress tolerance index STI = $Y_pY_s/\bar{Y}_p^2$ and geometric mean productivity GMP = $\sqrt{(Y_pY_s)}$ (Fernandez, 1992); tolerance TOL = $Y_p - Y_s$ (Rosielle and Hamblin, 1981) and yield stability index YSI = Y_s/Y_p (Bouslama and Schapaugh, 1984). Mean productivity was not tabulated because it was almost perfectly correlated with GMP ($r = 0.999$).

Treating genotypes and environments as random, variance components were estimated as $\sigma^2_g = (MS_G - MS_{GE})/re$ and $\sigma^2_{ge} = (MS_{GE} - MS_e)/r$, and broad-sense heritability on an entry-mean basis as $H^2 = \sigma^2_g/(\sigma^2_g + \sigma^2_{ge}/e + \sigma^2_e/re)$ (Holland *et al*., 2003). Analyses were carried out in R version 4.3.3 using agricolae version 1.3-7 (analysis of variance and AMMI) and metan version 1.18.0 (WAAS and WAASY; Olivoto and Lúcio, 2020), and GGE biplots were drawn with GGEBiplotGUI version 1.0. Significance was assessed at $p \leq 0.05$.

Results

Analysis of variance and partitioning of variation

Error mean squares were homogeneous across environments (0.0099 with 13 df in each), and genotypes differed significantly ($p \leq 0.01$) in every environment, with genotype mean squares rising from 0.30–0.31 under WW to 1.09 (E3) and 1.48 (E6) under SS. In the combined analysis, environments, genotypes and G × E were all highly significant (Table 1). Environments accounted for 63.16%, genotypes for 30.70% and G × E for 6.14% of the treatment sum of squares. The G × E mean square was nevertheless about 22 times the pooled error. IPCA1 and IPCA2 explained 68.42 and 15.03% of the G × E sum of squares (83.45% together). IPCA3 to IPCA5 were also significant against the small pooled error but jointly explained only 16.55%, so the AMMI2 model was retained for graphical interpretation and all five axes were used for WAAS.

Mean performance and rank changes

Environment mean yield ranged from 6.687 t ha^{-1} in E6 to 9.321 t ha^{-1} in E4, with a grand mean of 8.038 t ha^{-1} (Table 2). Relative to the WW environment of the same season, moderate stress reduced the mean by 9.61% (Season I) and 14.66% (Season II) and severe stress by 21.43 and 28.25%. The range among hybrids widened from 1.580 t ha^{-1} in E1 to 3.653 t ha^{-1} in E6. H14 gave the highest mean yield (9.183 t ha^{-1}), followed by C4 (9.083 t ha^{-1}), H08 (8.983 t ha^{-1}) and H18 (8.883 t ha^{-1}), whereas H11 (6.983 t ha^{-1}) and H19 (7.083 t ha^{-1}) were the poorest. Only H14 exceeded the best check, by 0.100 t ha^{-1}, a margin slightly larger than the critical difference (0.081 t ha^{-1}) and six experimental hybrids (H14, H08, H18, H04, H12 and H20) out-yielded the check mean (8.283 t ha^{-1}). The winning hybrid changed with environment: H08 in E1, C4 in E2, H14 in E3, E4 and E5, and H18 in E6. Rank changes were small among the leading hybrids, but larger among average hybrids; H09,

Table 1 : Combined analysis of variance and AMMI analysis for grain yield of 24 maize hybrids across six environments.

Source of variation	df	SS	MS	*F* value	% of total SS	% of G × E SS
(a) Combined analysis of variance (alpha-lattice, block-adjusted)						
Environments (E)	5	257.2533	51.4507	237.53**	68.70	
Replications within E	6	1.2997	0.2166	21.96**	0.35	
Genotypes (G)	23	88.3687	3.8421	389.51**	23.60	
G × E	115	16.3318	0.1420	14.40**	4.36	
Blocks within replications × E	60	10.4102	0.1735	17.59**	2.78	
Pooled error	78	0.7694	0.0099		0.21	
(b) AMMI analysis of the genotype × environment means (plot basis)						
Environments (E)	5	257.2533	51.4507	237.53**	63.16	
Genotypes (G)	23	125.0350	5.4363	551.13**	30.70	
G × E	115	25.0130	0.2175	22.05**	6.14	100.00
IPCA1	27	17.1140	0.6339	64.26**		68.42
IPCA2	25	3.7603	0.1504	15.25**		15.03
IPCA3	23	2.0930	0.0910	9.23**		8.37
IPCA4	21	1.2189	0.0580	5.88**		4.87
IPCA5	19	0.8257	0.0435	4.41**		3.30
Residual (IPCA3 to IPCA5)	63	4.1387	0.0657	6.66**		16.55
Pooled error	78	0.7694	0.0099			

(a) Percentages are of the total SS. (b) Percentages for E, G and G × E are of the treatment (E + G + G × E) SS and those for IPCAs are of the G × E SS; sums of squares are on a plot basis (two replications) and are not block-adjusted. Environments were tested against replications within environments and all other terms against the pooled error (MS = 0.009864). IPCA degrees of freedom follow Gollob (1968). ** $p \leq 0.01$. IPCA, interaction principal component axis.

for example, ranked tenth in E1, but 18th to 22nd elsewhere. Spearman rank correlations between environments ranged from 0.819 to 0.950.

AMMI analysis

In the AMMI1 biplot (Fig. 1a), environments separated along IPCA1 by moisture regime rather than by season. The WW environments had positive scores (E1, 0.512; E4, 0.442), the SS environments negative scores (E3, –0.397; E6, –0.616), and the MS environments lay near zero. Hybrids with large negative IPCA1 scores, H18 (–0.989), C2 (–0.871), H14 (–0.721) and H20 (–0.640), gained relative to the average hybrid as stress intensified, whereas H19 (1.099), H09 (0.929), H15 (0.881) and H03 (0.826) lost ground. IPCA1 was negatively correlated with mean yield (r = –0.922, $p \leq$ 0.01). In the AMMI2 biplot (Fig. 1b), IPCA2 separated the Season I environments (negative scores) from E4 and E6 (positive scores), with E5 near zero and the separation increased with stress. C1, H10, H16, H01 and H02 lay closest to the origin and contributed least to the interaction.

Stability parameters

AMMI-based stability parameters ranked the hybrids almost independently of yield (Table 3), the rank correlation between mean yield and ASV being –0.070 (not significant). C1 had the smallest ASV (0.074), followed by H16, H10, H01 and H02, which also had the smallest WAAS; of these, only H16 and H02 yielded above the grand mean. The three highest yielding hybrids had intermediate to large ASV (ranks 11 for H08, 15 for C4 and 18 for H14) and H18 had the second largest. GSI favoured H16 (11), C1 (13) and H08 (14), whereas WAASY placed H08 first (76.4), followed by H16 (75.9), C4 (74.3), C1 (72.7) and H14 (71.0).

Regression coefficients ranged from 0.593 (H18) to 1.441 (H19), were negatively correlated with mean yield (r = –0.926, $p \leq 0.01$) and almost perfectly correlated with IPCA1 (r = 0.999). H14, C4, H08, H18, C2, H12, H20 and H06 had b_i significantly below 1, H03, H05, H09, H11 and H15 significantly above 1, and C1 (0.997) and H16 (0.965) were closest to unity. Deviations from regression were significant for most hybrids but non-

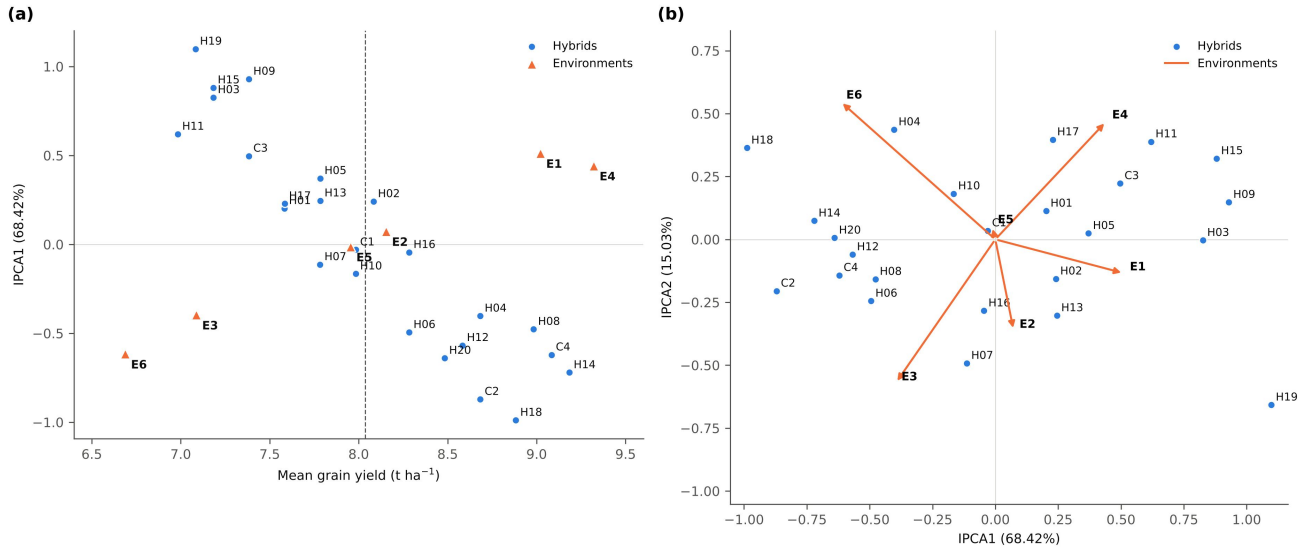


Fig. 1 : AMMI biplots for grain yield of 24 maize hybrids in six environments: (a) AMMI1 biplot of mean yield against IPCA1 scores; (b) AMMI2 biplot of IPCA1 against IPCA2 scores.

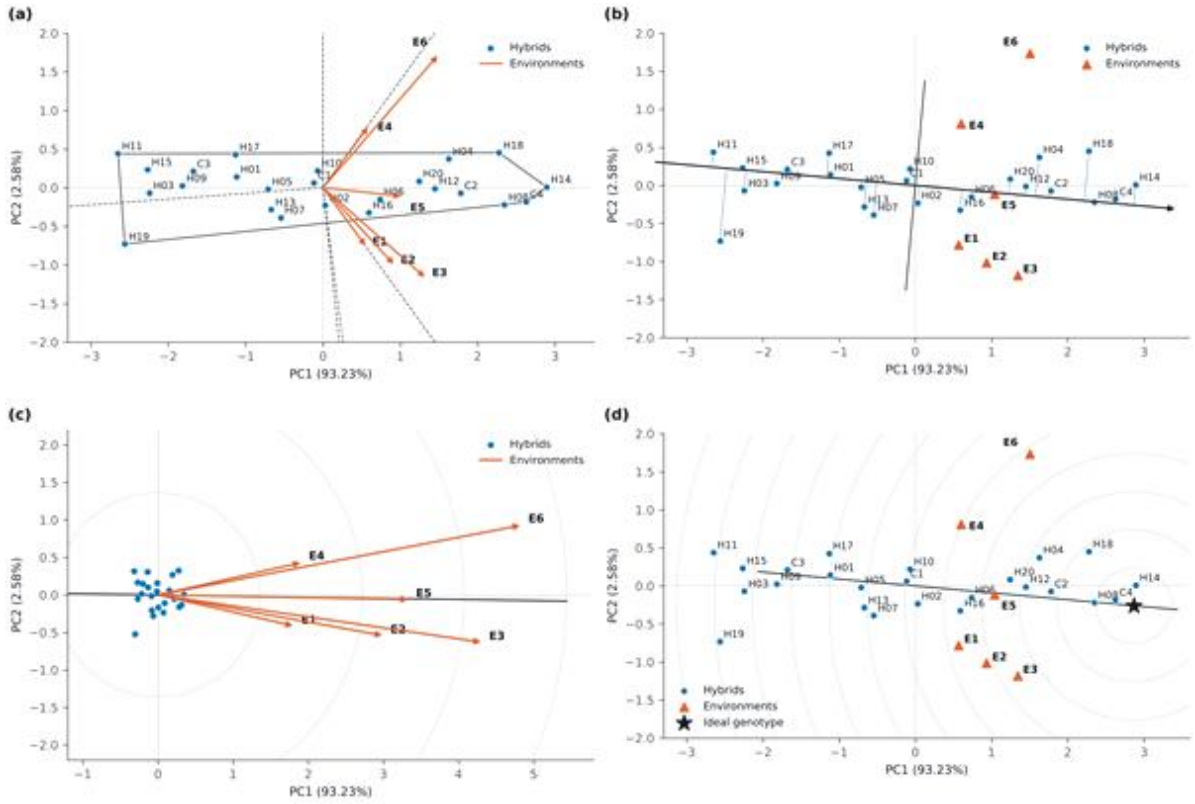


Fig. 2 : GGE biplot views (environment-centred) for grain yield of 24 maize hybrids in six environments: (a) which-won-where (SVP = 1); (b) mean versus stability (SVP = 1); (c) discriminativeness versus representativeness of test environments (SVP = 2); (d) ranking of hybrids relative to the ideal genotype (SVP = 1).

significant for C4, H12 and C1 and marginal for H08. Ecovalence and Shukla's variance gave identical rankings, with C1, H10, H01, H16 and H02 the most stable and H19, H18, H09, H15 and C2 the least; only σ^2_i is therefore shown in Table 3.

Drought tolerance indices

Mean yield was 9.171, 8.054 and 6.888 t ha^{-1} under WW, MS and SS conditions, giving stress intensities of 0.122 and 0.249 (Table 4). Yield reduction ranged from 6.20% (H20) to 19.89% (H09) under moderate stress and from 14.26% (H18) to 37.70% (H19) under severe stress. STI and GMP were closely correlated with yield under both WW (r = 0.954–0.958) and SS conditions (r = 0.994–0.996); H14 had the highest STI (0.987), followed

Table 2 : Mean grain yield (t ha^{-1}) of 24 maize hybrids in six environments.

Hybrid	E1 (S1, WW)	E2 (S1, MS)	E3 (S1, SS)	E4 (S2, WW)	E5 (S2, MS)	E6 (S2, SS)	Overall mean	Rank
H01	8.501	7.584	6.596	9.145	7.616	6.058	7.583	17
H02	9.018	8.423	7.082	9.470	8.074	6.434	8.083	11
H03	8.648	7.084	5.999	8.799	7.318	5.252	7.183	21
H04	9.262	8.850	7.438	9.896	8.864	7.790	8.683	5
H05	8.921	7.769	6.831	9.375	7.636	6.168	7.783	14
H06	9.200	8.254	7.742	9.185	8.192	7.127	8.283	9
H07	8.665	8.209	7.088	8.795	7.731	6.210	7.783	14
H08	9.911	9.108	8.242	9.839	8.878	7.922	8.983	3
H09	9.119	7.303	6.016	9.005	7.217	5.640	7.383	19
H10	8.954	8.077	6.863	9.116	8.002	6.888	7.983	12
H11	8.331	7.073	5.574	8.732	6.629	5.562	6.983	24
H12	9.385	8.577	7.947	9.575	8.436	7.580	8.583	7
H13	8.959	8.129	6.917	9.078	7.434	6.183	7.783	14
H14	9.670	9.126	8.499	10.204	9.398	8.204	9.183	1
H15	8.504	7.330	5.621	8.970	7.234	5.440	7.183	21
H16	9.284	8.391	7.511	9.363	8.396	6.755	8.283	9
H17	8.663	7.417	6.505	9.300	7.311	6.306	7.583	17
H18	9.397	8.704	8.194	9.925	8.706	8.373	8.883	4
H19	8.697	7.635	6.007	8.521	6.920	4.720	7.083	23
H20	9.033	8.866	7.583	9.418	8.441	7.560	8.483	8
C1	8.883	8.050	7.132	9.400	7.793	6.642	7.983	12
C2	9.289	8.774	8.306	9.588	8.348	7.795	8.683	5
C3	8.419	7.798	5.925	8.974	7.331	5.853	7.383	19
C4	9.788	9.170	8.482	10.028	8.993	8.039	9.083	2
Environment mean	9.021	8.154	7.088	9.321	7.954	6.687	8.038	
Environment index	0.983	0.117	“0.950	1.283	“0.083	“1.350		
SE(m) ±	0.070	0.070	0.070	0.070	0.070	0.070	0.029	
CD (p = 0.05)	0.215	0.215	0.215	0.215	0.215	0.215	0.081	
CV (%)	1.101	1.218	1.401	1.066	1.249	1.485		

S1, Season I (*rabi* 2024–25); S2, Season II (*kharif* 2025); all environments at ANDUAT, Kumarganj, Ayodhya; WW, well-watered; MS, moderate stress; SS, severe stress. C1 to C4 are commercial checks. Tied means share the same rank. SE(m)± and CD for individual environments were derived from the error mean square of each environment (0.0099, 13 df); those for overall means from the pooled error (0.009864, 78 df). Environment index is the environment mean minus the grand mean.

by C4 (0.973), H18 (0.952) and H08 (0.949). DSI, TOL and YSI were more closely correlated with stress yield ($|r|$ = 0.964–0.982) than with WW yield ($|r|$ = 0.787–0.834). H18 had the lowest DSI (0.573) and TOL (1.378 t ha{ ¹) and the highest YSI (0.857), followed by C2, whereas H19, H15, H09, H03 and H11 lost more than 34% under severe stress (DSI > 1.39). Yield reduction under severe stress was almost perfectly correlated with b_i (r = 0.996) and IPCA1 (r = 0.993). The order of hybrids was similar in the two seasons (rank correlation 0.927), although severe-stress losses ranged from 10.58 to 34.03% in Season I and from 15.64 to 44.61% in Season II.

GGE biplot analysis

PC1 and PC2 of the GGE biplot explained 93.23 and 2.58% of genotype plus G × E variation (95.82% together), and all environment vectors formed acute angles, indicating similar hybrid rankings. In the which-won-where view (Fig. 2a), the polygon was formed by H14, H18, H11, H19, H08 and C4, and all six environments fell within the sector of H14, so no separate mega-environments were indicated. Within that sector the Season I environments (1.9–4.5° apart) and E4 and E6 (1.8°) formed separate clusters, with H18 at the adjacent vertex on the Season II side and H08 and C4 on the Season I

Table 3 : Stability parameters of 24 maize hybrids for grain yield.

Hybrid	Mean (t ha^{-1})	IPCA1	ASV	R	WAAS	R	WAASY	R	b_i	S^2_{di}	σ^2_i	R	GSI
H01	7.583	0.2025	0.4466	4	0.1156	4	55.7	14	1.101	0.0166**	0.0516	3	21
H02	8.083	0.2411	0.5375	5	0.1431	6	64.3	9	1.104	0.0207**	0.0601	5	16
H03	7.183	0.8257	1.7616	19	0.3644	19	21.8	20	1.348*	0.0403**	0.3519	19	40
H04	8.683	–0.4030	0.9638	10	0.2582	13	66.5	6	0.843	0.0963**	0.2243	15	15
H05	7.783	0.3709	0.7917	9	0.1781	8	54.0	15	1.168*	0.0101*	0.0820	6	23
H06	8.283	–0.4953	1.0847	13	0.2576	12	57.5	12	0.772*	0.0195**	0.1542	12	22
H07	7.783	–0.1132	0.5483	6	0.1276	5	59.0	10	0.934	0.0630**	0.1190	8	20
H08	8.983	–0.4768	1.0294	11	0.2274	10	76.4	1	0.778**	0.0075*	0.1269	9	14
H09	7.383	0.9293	1.9881	22	0.4272	22	20.2	22	1.389*	0.0560**	0.4505	22	41
H10	7.983	–0.1660	0.3977	3	0.1087	3	65.4	7	0.926	0.0196**	0.0458	2	15
H11	6.983	0.6199	1.3783	17	0.3257	17	21.2	21	1.281*	0.0489**	0.2691	17	41
H12	8.583	–0.5681	1.2135	14	0.2513	11	64.9	8	0.752**	0.0018	0.1454	11	21
H13	7.783	0.2449	0.6039	7	0.1584	7	55.9	13	1.095	0.0404**	0.0904	7	21
H14	9.183	–0.7207	1.5392	18	0.3268	18	71.0	5	0.697*	0.0328**	0.2706	18	19
H15	7.183	0.8807	1.9061	21	0.4128	21	17.0	23	1.389**	0.0217**	0.3897	21	42
H16	8.283	–0.0454	0.3001	2	0.0721	2	75.9	2	0.965	0.0293**	0.0528	4	11
H17	7.583	0.2287	0.6286	8	0.1782	9	49.4	18	1.123	0.0586**	0.1361	10	25
H18	8.883	–0.9885	2.1399	23	0.4611	23	50.9	17	0.593*	0.0605**	0.4912	23	27
H19	7.083	1.0985	2.4339	24	0.5386	24	2.3	24	1.441	0.1494**	0.7143	24	47
H20	8.483	–0.6399	1.3650	16	0.2972	16	58.1	11	0.726*	0.0360**	0.2374	16	24
C1	7.983	–0.0308	0.0743	1	0.0354	1	72.7	4	0.997	0.0072	0.0113	1	13
C2	8.683	□0.8708	1.8690	20	0.4069	20	51.7	16	0.626**	0.0301**	0.3790	20	25
C3	7.383	0.4967	1.0826	12	0.2702	14	35.7	19	1.225	0.0469**	0.1986	14	31
C4	9.083	“0.6208	1.3319	15	0.2714	15	74.3	3	0.728**	“0.0017	0.1683	13	17

R, rank; for WAASY, rank from highest (1). ASV, AMMI stability value; WAAS, weighted average of absolute scores from all five IPCAs (fixed-effect AMMI); WAASY, WAAS and yield combined with 50:50 weights (higher is better); b_i, regression coefficient (* and ** indicate significant difference from 1 at $p \leq 0.05$ and 0.01); S^2_{di}, deviation from regression (* and ** indicate significant difference from 0); σ^2_i, Shukla's stability variance (Wricke's ecovalence gave an identical ranking and is not shown); GSI, genotype selection index (rank of mean + rank of ASV). Ranks for ASV, WAAS and σ^2_i run from smallest (1) to largest. IPCA1, hybrid score on the first interaction axis (IPCA2 scores are shown in Fig. 1b); ranks of mean yield are given in Table 2.

side.

In the mean versus stability view (Fig. 2b), H14, C4, H08 and H18 had the highest means, but their perpendicular distances from the average environment coordinate (AEC) differed: H08 lay almost on the AEC (0.007), C4 close to it (0.054), H14 at a moderate distance (0.270) and H18 farthest (0.655). H19 was the most unstable hybrid (0.958). In the discriminativeness versus representativeness view (Fig. 2c), vector length increased with stress in both seasons, from 1.882 (E1) and 1.985 (E4) to 4.381 (E3) and 4.947 (E6). E5 made the smallest angle with the AEC (0.2°) and E1 and E4 the largest (12.0 and 13.6°) and E3 lay closest to the ideal test environment. In the ranking view (Fig. 2d), C4 (0.254) and H14 (0.270) were closest to the ideal genotype, followed by H08 (0.521), H18 (0.925) and C2 (1.105), whereas H11, H19 and H15 were farthest.

Variance components and heritability

Genotypic variance within environments increased with stress, from 0.147 (E1) to 0.538 (E3) in Season I and from 0.152 (E4) to 0.735 (E6) in Season II, and the genotypic coefficient of variation rose from about 4% to 10–13% (Table 5). Heritability remained high in every environment (0.967–0.993). Across environments, the genotypic variance (0.3083) was 4.7 times the G × E variance (0.0661) and broad-sense heritability on an entry-mean basis was 0.963, with genotypic and phenotypic coefficients of variation of 6.91 and 7.04%.

Table 4 : Grain yield and drought tolerance indices of 24 maize hybrids under three moisture regimes.

Hybrid	Y_p (WW)	Y_m (MS)	Y_s (SS)	YR_{MS} (%)	YR_{SS} (%)	DSI	STI	GMP	TOL	YSI
H01	8.823	7.600	6.327	13.86	28.29	1.136	0.664	7.471	2.496	0.717
H02	9.244	8.248	6.758	10.77	26.89	1.080	0.743	7.904	2.486	0.731
H03	8.723	7.201	5.625	17.45	35.51	1.426	0.583	7.005	3.098	0.645
H04	9.579	8.857	7.614	7.54	20.51	0.824	0.867	8.540	1.965	0.795
H05	9.148	7.703	6.500	15.80	28.95	1.163	0.707	7.711	2.648	0.710
H06	9.192	8.223	7.434	10.55	19.12	0.768	0.813	8.267	1.758	0.809
H07	8.730	7.970	6.649	8.71	23.84	0.957	0.690	7.619	2.081	0.762
H08	9.875	8.993	8.082	8.93	18.16	0.729	0.949	8.934	1.793	0.818
H09	9.062	7.260	5.828	19.89	35.69	1.433	0.628	7.267	3.234	0.643
H10	9.035	8.040	6.876	11.02	23.90	0.960	0.739	7.882	2.159	0.761
H11	8.531	6.851	5.568	19.70	34.74	1.395	0.565	6.892	2.963	0.653
H12	9.480	8.506	7.764	10.27	18.11	0.727	0.875	8.579	1.716	0.819
H13	9.018	7.781	6.550	13.72	27.37	1.099	0.702	7.686	2.468	0.726
H14	9.937	9.262	8.352	6.79	15.96	0.641	0.987	9.110	1.585	0.840
H15	8.737	7.282	5.530	16.65	36.70	1.474	0.575	6.951	3.207	0.633
H16	9.323	8.393	7.133	9.97	23.49	0.944	0.791	8.155	2.190	0.765
H17	8.982	7.364	6.405	18.01	28.68	1.152	0.684	7.585	2.576	0.713
H18	9.661	8.705	8.284	9.90	14.26	0.573	0.952	8.946	1.378	0.857
H19	8.609	7.277	5.364	15.47	37.70	1.514	0.549	6.795	3.245	0.623
H20	9.226	8.654	7.572	6.20	17.93	0.720	0.831	8.358	1.654	0.821
C1	9.142	7.921	6.887	13.35	24.66	0.991	0.749	7.935	2.255	0.753
C2	9.438	8.561	8.050	9.30	14.71	0.591	0.903	8.717	1.388	0.853
C3	8.697	7.565	5.889	13.02	32.28	1.297	0.609	7.156	2.808	0.677
C4	9.908	9.082	8.261	8.34	16.63	0.668	0.973	9.047	1.648	0.834
Mean	9.171	8.054	6.888	12.30	25.17	1.011	0.755	7.938	2.283	0.748

Y_p, mean of E1 and E4; Y_m, mean of E2 and E5; Y_s, mean of E3 and E6. YR, yield reduction relative to Y_p. Indices are based on Y_p and Y_s; stress intensity SI = 0.249. DSI, drought susceptibility index (lower is more tolerant); STI, stress tolerance index; GMP, geometric mean productivity; TOL, tolerance (t ha^{-1}; lower is more tolerant); YSI, yield stability index.

Table 5 : Characteristics of the six test environments.

Env.	Mean (t ha^{-1})	YR vs WW (%)	MS_G (23 df)	σ^2_g	H^2	GCV (%)	IPCA1	IPCA2	Vector length	Angle with AEC (°)
E1 (I, WW)	9.021	0.00	0.3043**	0.1472	0.967	4.25	0.512	“0.135	1.882	12.0
E2 (I, MS)	8.154	9.61	0.6454**	0.3177	0.985	6.91	0.073	“0.363	3.071	9.4
E3 (I, SS)	7.088	21.43	1.0857**	0.5379	0.991	10.35	“0.397	“0.572	4.381	7.5
E4 (II, WW)	9.321	0.00	0.3145**	0.1523	0.969	4.19	0.442	0.469	1.985	13.6
E5 (II, MS)	7.954	14.66	0.7226**	0.3564	0.986	7.50	“0.014	0.053	3.363	0.2
E6 (II, SS)	6.687	28.25	1.4796**	0.7349	0.993	12.82	“0.616	0.548	4.947	11.7

I and II, Season I (rabi 2024–25) and Season II (kharif 2025); WW, well-watered; MS, moderate stress; SS, severe stress. YR vs WW, reduction of the environment mean relative to the WW environment of the same season. MS_G, genotype mean square from the individual alpha-lattice analysis (error MS = 0.0099, 13 df); ** $p \le 0.01$. σ^2_g, genotypic variance; H^2, broad-sense heritability on an entry-mean basis; GCV, genotypic coefficient of variation. IPCA1 and IPCA2 are AMMI environment scores; vector length and angle with the average environment coordinate (AEC) are from the environment-focused (SVP = 2) GGE biplot.

Discussion

Magnitude and structure of G × E

The partitioning of variation (environment > genotype > G × E) agreed with recent maize METs in south-west China (Ma *et al*., 2024) and Tanzania (Sitonik *et al*., 2026), although the genotype share (30.70%) was much higher than the 4 and 9.52% reported there. The entries spanned a wide range of drought tolerance, which stress magnified, and a single location tested over two seasons contained less environmental diversity than multi-location networks. Although, G × E formed only 6.14% of the treatment sum of squares, it was concentrated on one biologically interpretable axis. IPCA1 ordered the environments from WW to SS in both seasons and ordered the hybrids almost exactly as b_i did. Because the leading axis was collinear with the environment means, the multiplicative term reduced largely to heterogeneity of regression slopes, the case in which joint regression is nested within AMMI (Zobel *et al*., 1988) and the interaction was mainly a difference in sensitivity to water supply. IPCA2 separated the seasons, most probably reflecting rabi–kharif contrasts in temperature, humidity and vapour pressure deficit at flowering, and explained why H18 won only in Season II and H08 and C4 only in Season I. The interaction was largely of the non-crossover type among the leading hybrids, which merely exchanged positions, but of the crossover type among average hybrids, because yield potential dominated the ranking under ample water and tolerance under stress (Yan and Tinker, 2006).

Divergent verdicts of AMMI and GGE

AMMI-based and variance-based statistics favoured average-yielding hybrids (C1, H16, H10, H01 and H02), whereas GGE placed C4, H14 and H08 closest to the ideal genotype. This was not a contradiction. AMMI stability statistics were computed after the genotype main effect had been removed and measured how closely a hybrid followed the average response (Gauch, 2006), whereas the GGE biplot retained the main effect and measured stability relative to an axis of increasing mean (Yan and Kang, 2003). Where yield and interaction were strongly correlated, as here through IPCA1, the two approaches diverged; Li *et al*. (2023) reported similar discrepancies in drought-tolerant maize and recommended joint use. ASV and ecovalence therefore penalised H14, C4 and H18 for the very property that made them valuable, namely losing less yield under stress than the average hybrid. Such static stability offered little to growers, whereas breeders sought dynamic stability, that is, following the environmental trend without unpredictable deviations (Becker and Léon, 1988). A regression coefficient below unity with small deviations, as in C4, H12 and H08, described a hybrid that was above average everywhere and relatively better under stress.

The composite indices partly corrected this bias. GSI and WAASY moved H08 and C4 into the leading group, yet H14 ranked only fifth on WAASY, because indices combining an AMMI stability statistic with yield remained sensitive to the weights chosen (Olivoto *et al*., 2019) and in this trial, IPCA1 measured tolerance. The which-won-where pattern also required cautious reading. With only 2.58% of the variation on PC2 and the cell-mean winners in E1, E2 and E6 differing from H14 by margins near the critical difference, the biplot indicated a single mega-environment, and two seasons at one site were not sufficient to establish a repeatable crossover pattern (Yan and Tinker, 2006).

Drought tolerance and its physiological basis

Average losses of about 12% under moderate and 25% under severe stress, together with the more than twofold widening of the range among hybrids, were consistent with reduced kernel set as the main mechanism of loss under stress at flowering, through delayed silking, a wider ASI and ear abortion (Bolaños and Edmeades, 1996; Sheoran *et al*., 2022). Whether H18, C2, H14 and C4 lost least yield through better silk emergence and kernel set remained to be confirmed with the yield-component data. Stomatal regulation, osmotic adjustment, deeper rooting and stay-green could also have contributed (Sheoran *et al*., 2022; Lynch, 2022; Chibane *et al*., 2021).

The two groups of indices behaved as their construction predicted. STI and GMP rewarded high yield under both regimes, whereas DSI, TOL and YSI rewarded small proportional loss and could favour low-yielding hybrids with little to lose (Fernandez, 1992). They agreed more than usual because the highest yielding hybrids were also the most tolerant, as the negative association between b_i and mean yield showed; yield potential and tolerance were therefore not opposed in this panel and could be improved together when testing included stress environments (Prasanna *et al*., 2021). H18 combined the smallest DSI and TOL with the third highest STI, H14 and C4 combined the highest STI with low DSI, and H08 had high potential, but a larger relative loss than H18, C2, H14, C4, H20 and H12. Because yield reduction, DSI, b_i and IPCA1 were almost perfectly correlated, they were four expressions of the same property, and counting them as independent evidence would have overstated the information in the data.

Evaluation of test environments and limitations

The WW environments discriminated poorly because tolerance differences were not expressed under ample water. The SS environments were the most discriminating but less representative than E5 and discriminating but unrepresentative environments were most useful for culling (Yan *et al.*, 2011). Genotypic variance rose under stress while error variance did not, so heritability stayed high in every environment, unlike most field drought studies in which uneven stress lowered heritability (Bänziger *et al.*, 2000); this favoured selection under stress, although the uniformity of stress within blocks warranted verification. A scheme combining one moderate-stress and one severe-stress environment would have ranked the hybrids nearly as well as all six environments at lower cost (cf. Prasanna *et al.*, 2021; Singh *et al.*, 2024). The study was limited to one location, two seasons, flowering-stage drought, grain yield and 24 on-station entries, so confirmation across agro-climatic zones of Uttar Pradesh, under terminal and combined heat–drought stress and with secondary-trait phenotyping (Araus *et al.*, 2022), was needed.

Conclusion

Grain yield of the 24 hybrids was governed mainly by the moisture environment, but G × E was structured along an axis that contrasted well-watered with stressed conditions, and the hybrids interacting most strongly with it were those that held yield best under drought. AMMI-based and variance-based stability measures therefore favoured average-yielding hybrids, whereas the GGE ideal-genotype view together with STI and DSI identified hybrids that were both high yielding and tolerant, and these criteria were better suited to drought-prone target areas. H14, with the highest mean yield, the top STI and low DSI, was the leading candidate for wide adaptation; H08, the most stable high-yielding hybrid, suited areas with occasional drought; and H18, with the smallest loss under severe stress, suited drought-prone areas of eastern Uttar Pradesh. H12 and H20 were secondary candidates, whereas H03, H09, H11, H15 and H19 were candidates for discarding. Moderate-stress and severe-stress environments were more informative than well-watered ones. Multi-location and on-farm testing, evaluation under combined heat and drought, and physiological phenotyping are needed before these hybrids are released.

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