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Genotype and Environmental Interactions in Maize (*Zea mays* L.) Across Regions of India: Implications for Hybrid Testing Locations in South Asia

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Abstract: Maize in South Asia is primarily rainfed and is particularly vulnerable to the changing climate. Defining a breeding environment (product profile/market segment) is the first key step of any breeding program. Further, identifying discriminative and representative locations for hybrid evaluation ensures efficiency and cost optimization. Therefore, this study was an extensive evaluation of elite maize hybrids across 12 locations in India to determine the G×E interactions in order to identify representative sites for CIMMYT product profiles for gaining resource efficiency while achieving enhanced genetic gains. Twenty-one promising hybrids that had been identified to be either drought-tolerant, excess moisture tolerant or heat tolerant through a stage-gate process, were planted as an Alpha lattice during the rainy season of 2017, spanning 12 locations in India. GGE biplot analysis was used to determine the top-performing hybrids and more importantly to discern the most representative environments. Hybrids VH151139 and VH131376 were found to be highly promising (and stable across locations) hybrids for grain yield in the main cropping season. Ideal test location/s for selecting superior maize hybrids were identified and ranked based on their grain-yielding and discriminating potential. The grouping of the locations based on the environmental vector biplot, identified location Meerut (E3) in the first group to represent areas prone to excess moisture. Bheemarayanagudi (E5) was in the second group representing drought-prone areas; and locations Nadiad (E6), Kalol (E9), and Wadadhe (E10) were in the third group where crops face drought and heat stress in the same season. Consequently, these locations should be consistently utilized for the selection of stable hybrids. The findings from this study have implications for similar and wider stress-prone maize growing agroecologies covering South and South-East Asia. Expanding the testing across similar regional locations will enhance the reach of CIMMYT's Asia breeding program which presently targets approximately 6.3 million hectares.

Keywords: Climate resilient; drought; GGE Biplot; heat; rainfed; waterlogging.

Introduction

Indian maize area has been growing at a compound annual growth rate (CAGR) of 2.02% from 6.61 million hectares in 2000-01 to 9.86 million hectares in 2020-21 with productivity increase at a CAGR of 2.85% from 1.82 tons per hectare in 2000-01 to 3.19 tons per hectare in 2020-21 (FAOSTAT 2021). However, a large portion of maize in India is still grown as a rainfed crop, which is particularly vulnerable to the changing climate and erratic rainfall patterns in the country. These conditions have made it necessary for breeding programs to develop maize hybrids that are tolerant to combinations of abiotic stress *viz.* excess moisture and drought stress; drought stress and dry heat stress. There has been a negative deviation in annual and southwest rainfall in India from the long-term average (IMD 2021) which has further increased the need for abiotic stress-tolerant maize hybrids.

Yields are greatly reduced during years with drought stress compared to years with normal rainfall. In the past, breeders mainly focused on breeding for higher yields, tolerance to biotic stresses and drought escape. However, in recent years, with a deeper understanding of the mechanisms of drought and the availability of phenotyping equipment (Hall et al. 1982; Bolaños and Edmeades 1996; Bänziger et al. 2000; Badu-Apraku et al. 2012; Cairns et al. 2013) it has become possible to identify hybrids that are tolerant to mid-season (reproductive stage) and terminal (grain-filling stage) drought. With this understanding, breeders have shifted their focus to breeding maize for higher yields with full maturity that incorporates mid-season and terminal stress tolerance, rather than developing early maturing maize hybrids that escape drought. Breeding for drought tolerance also helps in understanding the genetics and physiological mechanisms of the stress in order to breed maize hybrids that withstand the adverse effects of drought when it occurs and minimize the yield losses. Considering the current climate scenario, drought-tolerant hybrids are crucial for increasing maize productivity under rainfed farming systems. The presence of genotype (G) × environment (E) interaction makes it difficult to identify superior cultivars in multilocation trials (Yates and Cochran 1938; Fakorede 1986; Cairns et al. 2013; Badu-Apraku et al. 2008; Badu-Apraku et al. 2012) as some cultivars may perform well in some environments but poorly in others. Therefore, it is important to assess maize hybrids to identify high-yielding and stable hybrids and also to identify ideal maize testing sites that will not only be representative of Indian maize agroecologies but also have relevance for maize growing regions of South Asia. The identification of ideal testing sites can reduce the cost of testing, thereby enhancing the selection efficiency of high-yielding and stable full-maturing hybrids for commercialization.

Several statistical methods have been used for the analysis and interpretation of multi-environment trial data (Yates and Cochran 1938; Gauch Jr. and Zobel 1997; Yan et al. 2000; Yan et al. 2007; Fan et al. 2007; Setimela et al. 2007; Crossa and Cornelius 1997). Among these, the two most frequently used are the Additive Main Effects and Multiplicative Interaction (AMMI) model (Gauch 1988; Zobel et al. 1988; Gauch Jr. and Zobel 1997) and the Genotype Main Effect plus G × E interaction (GGE) biplot methodology proposed by (Yan et al. 2000). Both methods have been compared and contrasted with respect to their suitability for G × E analysis in several reviews (Yan et al. 2007; Gauch Jr. 2006; Gauch Jr. et al. 2008; Yan et al. 2010; Yang et al. 2009; Badu-Apraku et al. 2012). A review by Badu-Apraku et al. (2012) which reported that AMMI and GGE biplots provides similar results in terms of stability and performance of the cultivars but concluded that the GGE biplot was more versatile and flexible and provided a better understanding of G × E interaction than the AMMI method. The GGE biplot is considered effective in identifying the best-performing genotype(s) in a given environment (specific adaptation) and the most suitable environment(s) for each genotype, and for comparing pairs of genotypes in individual environments (Yan and Kang 2002; Yan and Tinker 2006; Yan et al. 2007). These suitable environments possess the highest ability to discriminate among genotypes and are most representative of all test environments (Yan and Kang 2002; Yan et al. 2007; Badu-Apraku et al. 2008; Yan and Tinker 2006). In recent years, CIMMYT in collaboration with public and private partners within India has been involved in extensive testing of maize hybrids. The objectives for this study are to identify the best high yielding stable hybrids suited for rainfed conditions along with identification of testing locations with optimized discrimination for selecting superior hybrids with greater resource efficiency. This analysis aims to map CIMMYT Asia's maize evaluation locations to the broadly defined maize agroecologies which should help in moving towards defining product profiles for the CIMMYT Asia maize improvement program. Grouping of an additional locations (including locations in other countries of the region), as they become available, will systematically expand the relevance of CIMMYT's maize breeding efforts in Asia which targets 6.3 million stress-prone hectares.

Results

Variance component and entry-mean heritability

The results for combined genetic variance across locations for hybrids were found to be significant for all the traits under study for genotype variance, genotype × location variance, and environmental variance except for anthesis-silking interval where genotype variance was non-significant (Table 1).

Hybrid performance across locations and at individual locations

Mean performance for grain yield across twelve locations showed that two CIMMYT hybrids *viz*., VH151139 and VH131376 were on par with the best commercial check P3502 (**Error! Reference source not found.**). All the hybrids had comparable maturity with days to anthesis ranging from 51 days to 55 days. Hybrid VH151139 was high yielding (6.62 t ha^{-1}), had low anthesis-silking interval (2 days), and was found to have drought tolerance compared to other test hybrids. Entry-mean heritability ranged from 0.2 to 0.9 for different traits under study. The lowest entry-mean heritability (0.2) was recorded for ears per plant and the highest (0.9) was obtained for days to anthesis, plant height, and ear height.

Grain yield among the hybrids varied in individual locations (Supplementary Table 1). The lowest yield of 1.4-2.2 t ha^{-1} was obtained at Mahbubnagar (E12), and the highest yield of 7.8-11.1 t ha^{-1} was recorded at Mandya (E4). Hybrid VH151139 was the highest yielding at four locations (E1, E3, E10, and E11) and was among the top five high-yielding hybrids in four locations (E5, E6, E7, and E12). Likewise, hybrid VH131376 was top-performing for grain yield in six locations viz., E1, E3, E4, E5, E6, and E9 and had low anthesis-silking interval (1.2 days). The locations could be ranked in terms of their grain-yielding potential in descending order as follows: E4 > E5 > E11 > E10 > E7 > E6 > E3 > E9 > E1 > E8 > E2 > E12.

Trait association

Across locations, grain yield was significantly positively correlated to eh (rg = 0.56; rp = 0.5) and epp (rg = 1; rp = 0.63), implying that entries with a higher number of ears gave higher yield (**Error! Reference source not found.**). The present study found that grain yield and anthesis-silking interval were significantly negatively correlated (rg = -0.94; rp = -0.51), implying that whenever drought stress occurs just before or during the flowering period, a delay in silking was observed, which resulted in an increase in the length of anthesis-silking interval and a decrease in grain yield.

Environmental association

Environmental correlations were worked between locations for grain yield (**Error! Reference source not found.**). E1 was significantly positively correlated with E2 (0.45), E3 (0.50), E6 (0.51), and E11 (0.68); E3 with E5 (0.41) and E11 (0.42); E5 with E7 (0.41); E6 with E9 (0.60), E10 (0.64), and E11 (0.51); E10 with E7 (0.44) and E9 (0.49). The relationships between the locations were evident from the GGE biplot analysis as well and has been discussed in detail in the subsequent section.

GGE biplot analysis for yield identification of stable hybrids

The significant G × E interaction for grain yield (Table 3) necessitated the use of the GGE biplot to decompose the G + G × E interaction to determine the yield potential and stability of the hybrids and to identify the ideal test locations. In the GGE biplot, the PC1 (Axis 1) explained 39.7% of total variation, whereas PC2 (Axis 2) explained 16.26% of the variation for grain yield. Thus, the two axes together accounted for 55.96% of the total variation for grain yield (**Error! Reference source not found.**). The grouping of the locations based on environmental vector biplot identified as E5 in one group, E6, E9, and E10 as second group and E4 as third group while other locations were less discriminative and hence not conclusively grouped. Discriminating test environments accurately resolves genotype differences, thereby providing necessary information to a breeder to select top performing stable hybrids across locations. E8 was the least discriminating location, as evidenced by the shorter environment vector. Hybrids should be evaluated in the most representative and highly discriminating environments to get valid results.

The vertex hybrids, (as a general rule, the vertex cultivar is the highest-yielding genotype in environments with which it shares a sector) VH151139, P3502, VH131199, VH141552, VH141229, VH13554, and VH141651 (**Error! Reference source not found.**). Among these, VH151139 was the highest-yielding hybrid at locations E1, E3, E5, and E11, indicating its superior performance at these sites (Supplementary Table 1). However, hybrids VH141552, VH141229, VH141651, and VH13554 did not have any locations within their respective sectors, suggesting they were low-yielding entries.

The mean versus stability view biplot (**Error! Reference source not found.**) was used to evaluate the stability of the 24 hybrids across the 12 locations. This analysis accounted for 55.96% of the total variation in grain yield. The biplot's average environment coordinate (AEC) abscissa, also known as the average environment axis, passes through the biplot origin and the average environment at the center of the small circle. The vertical line separated entries with below-average grain yield from those with above-average grain yield. The mean yield of the hybrids was approximated by the projections of their markers on the average-tester axis. The highest-yielding hybrids were identified as P3502, VH151139, NK6240, and VH131376. Hybrid P3502 exhibited both high yield and stability due to its short projections onto the AEC ordinate. Other hybrids, such as VH15607 and VH13306, were stable but did not achieve high yields. Among all test hybrids, VH131376 and VH151139 emerged as high-yielding and stable performers next to the commercial check P3502. Hybrids VH15607, anthesis-silking interval VH13306, and VH13729 were stable but performed on par with the commercial checks. GGE biplot analysis gives good visual pictures on which one can easily identify promising high yielding and stable hybrids. The ideal hybrid should be amongst the top yielding and have stable performance across locations. The promising hybrids identified by this study were VH131376 and VH151139.

Discriminating Power and Representative Environment

The discriminating power vs. representativeness view of the GGE biplot revealed significant differences among test environments. Locations with short vectors, such as E8, E2, E12, E7, and E11-E1, were classified as low-expressing environments, while moderate-expressing environments included E11 and E1 (**Error! Reference source not found.**). Conversely, locations E3, E5, E9, E10, E6, and E4 were identified as highly discriminating environments. Three broad testing zones were inferred: (1) E3 and E5, (2) E6, E9, and E10, and (3) E4. These locations exhibited varying stress conditions, including excess moisture stress, drought, and heat stress. Locations E3, E5, and E10 were the most effective in discriminating among hybrids, indicating their suitability for hybrid evaluation and selection.

Table 1. Variance components, entry-mean heritability of grain yield and other traits for 21 test hybrids and commercial checks across 12 locations during the rainy season of 2017.

Sources of Variation	Grain yield	Days to Anthesis	Days to Silking	Anthesis silking interval	Plant Height	Ear height	Ear position	Ears per plant
	t ha^{-1}	days	days	days	cm	cm	%	#
Genotype Variance	0.22**	1.00**	0.81**	0.00	100.99**	66.01**	0.00**	0.00
Gen × Env Variance	0.31**	1.06**	1.37**	0.37**	36.56**	32.54**	0.00**	0.00
Environment Variance	5.53**	11.87**	8.51**	3.50**	1090.34**	323.85**	0.00**	0.00*
Residual Variance	0.50	1.38	1.66	0.20	116.67	59.51	0.00	0.00
Grand Mean	5.90	53.03	55.83	1.74	214.82	95.90	0.45	0.94
LSD (0.05)	0.63	1.18	1.31	0.00	10.04	8.35	0.03	0.00
CV (%)	11.97	2.21	2.31	25.90	5.03	8.04	6.04	5.57
Heritability	0.81	0.86	0.77	0.09	0.91	0.91	0.89	0.08

* Significance at the 0.05 probability level; ** Significance at the 0.01 probability level

Table 2. Mean performance of 21 test entries along with three commercial checks across 12 different locations of India during the rainy season of 2017.

Sl. No	Hybrid	Grain yield	Days to Anthesis	Days to Silking	Anthesis-silking interval	Plant Height	Ear height	Ear position	Ears per plant
		t ha^{-1}	days	days	days	cm	cm	%	Number
1	VH131306	5.85	53.2	56.2	2.1	218	97	0.45	0.92
2	VH141552	5.25	51.2	54.3	2.1	210	90	0.44	0.98
3	VH13296	5.73	53.9	56.5	1.2	222	100	0.45	0.91
4	VH13306	5.90	54.3	57.1	2.0	225	109	0.48	0.93
5	VH13729	5.93	53.3	56.0	1.5	206	98	0.48	0.91
6	VH13740	5.62	52.0	55.0	1.8	215	92	0.43	0.94
7	VH1640	5.78	51.9	55.0	2.0	206	85	0.42	0.90
8	VH151139	6.62	52.8	55.5	2.0	208	98	0.47	0.92
9	VH15607	6.00	53.8	56.6	1.5	218	98	0.45	0.92
10	VH1652	5.86	53.0	55.7	1.8	199	94	0.47	0.97
11	VH15884	5.54	52.0	55.1	2.3	205	95	0.47	0.91
12	VH1660	5.86	52.6	55.6	1.7	232	110	0.48	0.94
13	VH141618	5.47	51.6	54.9	1.9	204	93	0.46	0.95
14	VH133209	5.84	54.8	57.3	1.5	223	102	0.45	0.92
15	VH151280	5.65	54.6	57.1	2.1	219	100	0.46	0.93
16	VH141229	5.34	52.4	55.2	1.6	203	84	0.42	0.97
17	VH141651	5.57	53.3	56.0	1.9	215	92	0.43	0.98
18	VH13554	5.52	53.9	56.7	1.9	206	81	0.39	0.94
19	VH16161	6.15	52.7	55.4	1.4	211	98	0.47	0.92
20	VH131199	5.90	53.6	55.8	1.3	229	90	0.40	0.93
21	VH131376	6.47	52.5	55.1	1.1	213	87	0.41	0.94
22	P3502	6.91	53.5	56.3	1.6	234	111	0.47	0.95
23	DKC8101	6.50	52.9	55.9	1.9	221	98	0.45	0.95
24	NK6240	6.40	52.6	55.5	1.7	215	98	0.46	0.98
	Max	6.91	54.8	57.3	2.3	234	111	0.48	0.98
	Min	5.25	51.2	54.3	1.1	199	81	0.39	0.90
	Mean	5.90	53.0	55.8	1.7	215	96	0.45	0.94
	Heritability	0.81	0.86	0.77	0.09	0.91	0.91	0.89	0.08
	LSD (0.05)	0.63	1.18	1.31	0.00	10.04	8.35	0.03	0.00
	CV (%)	11.97	2.21	2.31	25.90	5.03	8.04	6.04	5.57

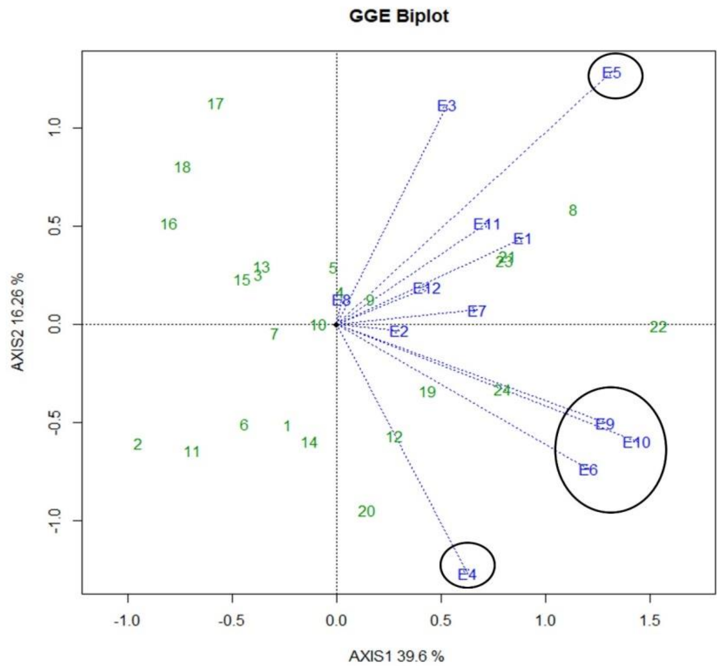

Fig 1. The environment vector biplot showing environmental differences in discriminating the 24 hybrids for grain yield at 12 test locations during the rainy season of 2017.

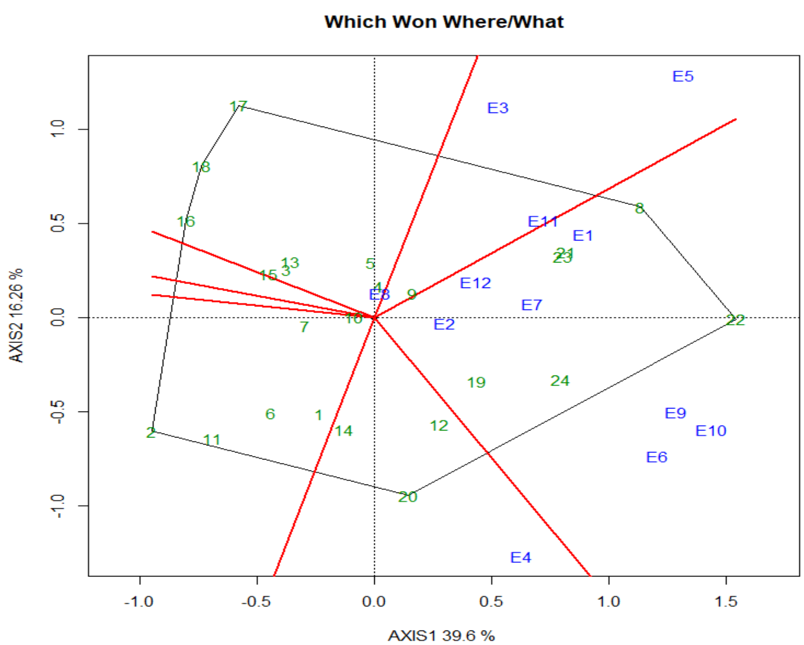

Fig 2. An environment focused biplot showing "winning hybrid" for grain yield at 12 locations during the rainy season of 2017.

Table 3. Genetic and phenotypic correlation for traits under consideration across locations.

Trait		GYF	AD	SD	ASI	PH	EH	EPO
AD	Genotypic	0.19						
	Phenotypic	0.15						
SD	Genotypic	0.15	0.97**					
	Phenotypic	0.10	0.98**					
ASI	Genotypic	-0.94**	-0.83**	-0.77**				
	Phenotypic	-0.51*	-0.41*	-0.28				
PH	Genotypic	0.38	0.48*	0.47*	-0.40			
	Phenotypic	0.39	0.42*	0.40*	-0.28			
EH	Genotypic	0.56**	0.41*	0.55**	0.21	0.69**		
	Phenotypic	0.50*	0.36	0.41	-0.10	0.68**		
EPO	Genotypic	0.43*	0.19	0.33	0.32	0.11	0.80**	
	Phenotypic	0.34	0.14	0.21	0.09	0.11	0.78**	
EPP	Genotypic	1.00**	-0.13	-0.21	-0.48*	1.00**	0.64**	0.66**
	Phenotypic	0.63**	-0.15	-0.14	0.02	0.40*	0.41*	0.23

Correlation scale

-1.0 -0.5 0.0 0.5 1.0

* Significance at the 0.05 probability level; ** Significance at the 0.01 probability level, GYF-Grain yield; AD-Anthesis day; SD-silking days; ASI-Anthesis silking interval, PH-Plant height; EH-Ear height; EPO-Ear position

Table 4. Phenotypic correlation among test locations for grain yield.

Environments	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11
E2	0.45*										
E3	0.50*	0.19									
E4	0.12	0.17	-0.25								
E5	0.34	0.21	0.41*	0.23							
E6	0.51*	0.39	0.14	0.40	0.19						
E7	0.40	0.03	0.20	0.15	0.41*	0.33					
E8	-0.09	-0.04	0.09	-0.18	0.10	0.09	0.27				
E9	0.23	0.35	0.20	0.23	0.37	0.60**	0.39	-0.02			
E10	0.40	0.12	0.13	0.39	0.31	0.64**	0.44*	0.01	0.49*		
E11	0.68*	0.35	0.42*	-0.17	0.31	0.51*	0.31	0.07	0.37	0.39	
E12	0.27	0.01	0.16	-0.07	0.19	0.01	0.09	-0.20	0.13	0.34	0.34

Correlation scale

-1.0 -0.5 0.0 0.5 1.0

* Significance at the 0.05 probability level; ** Significance at the 0.01 probability level

E1-Agra; E2-Himmatnagar; E3-Meerut; E4-Mandya; E5-Bheemarayanagudi; E6-Nadiad; E7-Ranebennur; E8-Akola; E9-Kalol; E10-Wadadhe; E11-Chandrapur; E12-Mahbubnagar

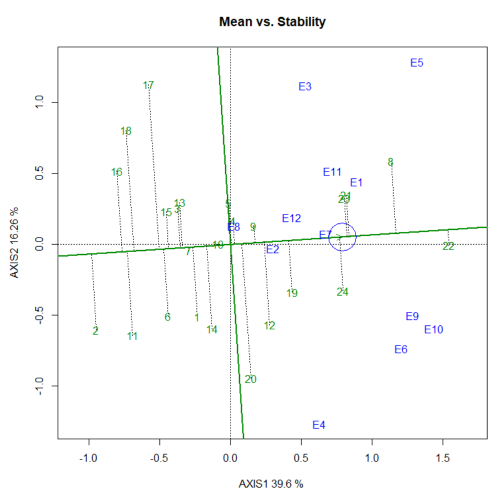

Fig 3. The mean versus stability view of the hybrids main effects plus genotype × environment interaction (GGE) biplot for grain yield of 24 hybrids evaluated across 12 locations during the rainy season of 2017.

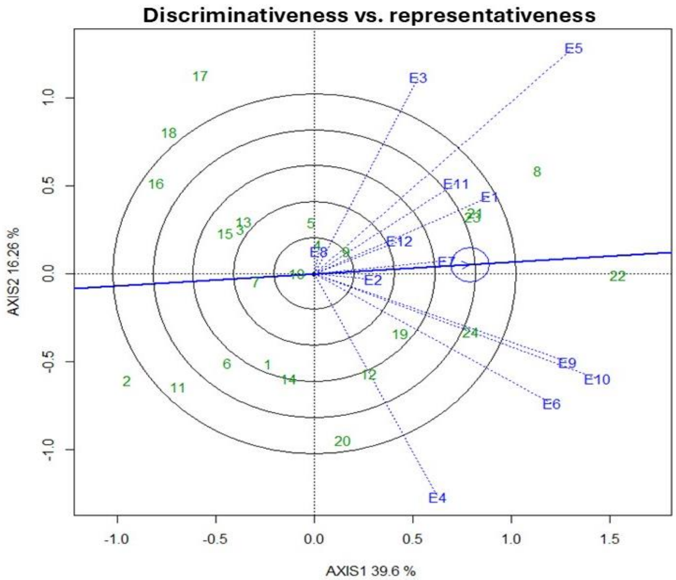

Fig 4. The discriminating power and representativeness view of the genotype main effects plus genotypes × environment interaction (GGE) biplot for grain yield data of 24 hybrids evaluated across 12 locations during the rainy season of 2017.

Table 5. List of maize hybrids used in the study and their pedigree.

Sl. No	Hybrid	Pedigree	Hybrid type
G1	VH131306	((CA00388/KTX3752F2-7-1-1-2-B*9)/CML444)-Bp98-1-BB-1-B*4-#/CML451-B*8	DT
G2	VH141552	(CL02450/OFP67//CL02450)-9-B*5/(Composite4//AMDROUT1(DT-Tester)c1F2	DT
G3	VH13296	(CML465/CML165-B//CML465)-BB-15-B2-BB/CL02450-B*6	WL
G4	VH13306	(CML465/CML165-B//CML465)-BB-36-B*4/CL02450-B*6	WL
G5	VH13729	CML613A/CML581	DT
G6	VH13740	(CML466/CML165-B//CML466)-BB-26-B*4/CML581	DT
G7	VH1640	(DTPWC9-F67-2-2-1-3-2-1-2-B/Bio9681-WLS-6-3-2-1-2-B*4)-BB-4-B1-B-#/CML451-B*8	HT
G8	VH151139	(CA34505xCA00302)-B-2-1-B-1-BB(T)-B5-#17-3-B-2-BBB/CML581	DT
G9	VH15607	(VL1110240/VL108722)-B-1-1-B-2/CML451-B*7	DT
G10	VH1652	AMDROUT1(DT-Tester)c1F2-16-B-4/CML581	DT
G11	VH15884	AMDROUT1c3F2/CML581	DT
G12	VH1660	AMDROUT2c2-12-B-3/CL02836-B*4	DT
G13	VH141618	(Compiste3/Composite4)/((CML161xCML451)-B-18-1-BBB/CML161-B)-B-13-BB(NonQ)-BB	DT
G14	VH133209	CA00360/PIO3011F2-3-5-6-1-B*11-#/CL02450-B*6	WL
G15	VH151280	(CLQRCYQ44-B*8/VH112651(InbSel)-2-BB-1-B-2)/CL02450-B*5	WL
G16	VH141229	(CML161X165-30-1-1-BBB/CLQ-RCYQ28xP390Am/CMLc4F218-B-1-B)-B-6-2-B*7/CML451-B*8	DT
G17	VH141651	(CML472-BBB/Composite4)/CML451-B*7	HT
G18	VH13554	G26C32HS#69-1-1-2-2-B*9/CML451-B*8	DT
G19	VH16161	Composite11-BBB-1-2-B-#/(CML444/VL111354)-42-B-1-B*4	HT
G20	VH131199	Pop45c10F1-321-1-1-BBB-#/CML451-B*8	DT
G21	VH131376	Composite15-BBB-1-B-1-B-#/CML451-B*8	DT
G22	P3502	Commercial check from Corteva	
G23	DKC8101	Commercial check from Bayer	
G24	NK6240	Commercial check from Syngenta	

Note: DT Drought tolerant, HT Heat tolerant, and WL waterlogging tolerant

Discussion

Climate change in recent years has posed significant challenges to crop breeding for resilience. Fluctuations in rainfall, temperature, and relative humidity are expected to become more frequent, necessitating adaptive breeding strategies. In response to these projections, CIMMYT has initiated targeted breeding efforts to align hybrid development with specific market profiles and environmental conditions. Differentiating excess moisture stress from low moisture stress is critical in this approach, requiring precise breeding strategies tailored to each stress condition. In the present study, the significant genotype × environment interaction variance for grain yield indicates that hybrids exhibit varied responses across different test locations.

This finding underscores the necessity of extensive multi-environment testing to ensure that promising hybrids are not prematurely discarded due to inconsistent performance across locations (Badu-Apraku et al. 2012; Stojaković et al. 2015; Badu-Apraku et al. 2016). The findings of this study align with previous research, demonstrating a significant positive correlation between grain yield and both ear height and ears per plant. The strong association between ears per plant and grain yield suggests that genotypes with a higher number of ears tend to achieve greater yields, reinforcing earlier studies that emphasize the role of prolificacy in enhancing yield potential (Bolaños and Edmeades 1996; Badu-Apraku et al. 2012). Conversely, the significant negative correlation between grain yield and anthesis-silking interval highlights the adverse impact of an extended anthesis-silking interval under drought stress conditions. A prolonged anthesis-silking interval indicates delayed silking, which disrupts pollination and kernel set, ultimately reducing grain yield. This observation is well supported by previous studies reporting that drought stress occurring just before or during flowering prolongs anthesis-silking interval and diminishes yield in tropical maize (Hall et al. 1982; Bolaños and Edmeades 1996; Campos et al. 2004). Furthermore, the effectiveness of direct selection for grain yield under drought stress is often limited by high environmental variance relative to genetic variance, resulting in reduced heritability. In such conditions, selecting for secondary traits like anthesis-silking interval, which exhibit strong genetic correlations with yield and higher entry-mean heritability, can improve selection efficiency (Bolaños et al. 1993). These findings further underscore the significance of anthesis-silking interval as a reliable selection criterion for enhancing drought tolerance in maize, providing a practical approach to improving yield stability in stress-prone environments.

GGE biplot analysis is a powerful tool for visualizing genotype performance across multiple environments. The identification of vertex hybrids follows the principle that the highest-yielding genotype within a sector typically dominates the respective environment (Yan et al. 2000). In this study, VH151139 demonstrated exceptional performance in multiple locations, suggesting its adaptability and yield potential. The absence of locations in the sectors of VH141552, VH141229, VH141651, and VH13554 aligns with previous findings indicating that low-yielding hybrids often fail to occupy specific environmental sectors (Yan et al., 2000).

The mean versus stability view biplot allowed for an integrated assessment of hybrid performance, considering both mean yield and stability (Yan et al. 2007). Hybrid P3502 emerged as the most stable high-yielding hybrid, reinforcing the importance of stability in breeding programs. The observation that some hybrids e.g., VH15607, VH13306 were stable but not high yielding is consistent with previous research emphasizing the trade-off between stability and absolute yield (Yan and Kang 2002). The discriminating power vs. representativeness view provided insights into the efficiency of test environments. The identification of locations with strong discriminative ability, such as E3, E5, and E10, is critical for optimizing hybrid evaluation (Yan et al. 2010). The classification of environments into different stress categories—waterlogging and drought (E3), drought (E5), and heat-drought stress (E6, E9, E10)—aligns with CIMMYT's product profiles for South Asia (CIMMYT internal estimates). Targeted selection in these representative environments enhances breeding efficiency and genetic gain, as highlighted in previous studies (Yan et al. 2010).

Location E3, situated in North India, represents an environment where maize experiences both excess moisture stress early in the season and drought stress during flowering and grain filling within the same cropping cycle. In contrast, E5, located in South India, is characterized by persistent drought stress throughout the growing season. Similarly, locations E6, E10, and E11, spanning Central and West India, face concurrent drought and heat stress during flowering and grain filling. Environmental correlation analysis (Table 7) further confirms a significant positive association between E6, E10, and E11, reinforcing their similarity in stress conditions. E4 presents a unique environment with a high discriminative power but lacks correlation with any other tested location, necessitating further data collection before drawing definitive conclusions. Given the importance of cost efficiency in crop breeding programs, prioritizing hybrid testing in locations with high discriminative ability while omitting those with low differentiation potential would optimize resource utilization. Among the three major testing locations identified, E3 aligns with CIMMYT's emerging South Asia Waterlogging and Drought Stress Profile (SAWLDT), E5 corresponds to the South Asia Drought Profile (SADT), and E6, E9, and E10 fit within the South Asia Heat and Drought Stress Profile (SAHDT). These profiles are increasingly being utilized by CIMMYT as breeding targets. Expanding hybrid evaluations across these locations will further refine agroecological understanding and enhance hybrid selection strategies.

The CIMMYT Asia Breeding Program currently focuses on approximately 6.3 million hectares in South Asia and an additional 1.9 million hectares in Southeast Asia. Given the similarity in agroecological conditions across the region, expanding hybrid testing beyond India—particularly in Nepal, Bangladesh, Pakistan, and Sri Lanka—will be instrumental in mapping the entire South Asian stress landscape. As the program aims for greater precision in defining stress regimes, integrating multi-stress selection (e.g., waterlogging + drought, heat + drought) will be critical for achieving higher genetic gains and ensuring maize productivity in variable tropical environments.

Furthermore, the significance of cost-effective hybrid testing cannot be overlooked. The use of highly discriminative environments while omitting less informative locations aligns with breeding strategies aimed at resource optimization (Yan and Kang, 2002). As maize breeding programs strive for higher resolution in stress profiling, expanding hybrid evaluation to additional locations across South Asia, including Nepal, Bangladesh, Pakistan, and Sri Lanka, would provide a more comprehensive understanding of agroecological variations (personal communication with national maize partners and seed companies). Future efforts should focus on stress combinations such as waterlogging-drought and heat-drought to achieve greater genetic gains in maize improvement.

Materials and Methods

Planting material

Twenty one elite promising CIMMYT bred hybrids that had been identified to be either drought tolerant, excess moisture tolerant or heat tolerant through a stage-gate process (**Error! Reference source not found.**), along with three popular commercial checks NK6240, DKC8101, and P3502 were used for the experiment.

Field evaluation and experimental design

These selected test hybrids were evaluated in the 2017 rainy season across twelve locations of major maize growing states i.e., Karnataka, Maharashtra, Gujarat, Telangana, Uttar Pradesh, and Bihar of India (Supplementary Table 2) Rainfall during the crop period varied from 398 mm at Dharwad, Karnataka (15.48^0 N, 74.98^0 E) to 1233.74 mm at Nadiad, Gujarat (22.69^0 N, 72.86^0 E). These test entries were selected through a stage-gate testing process conducted between 2012 and 2016 at target locations in the rainy season and under managed drought screening during dry seasons at CIMMYT Hyderabad location (17.49^0 N, 78.25^0 E). Area specific crop management practices were followed at each testing location. The trials were conducted using an Alpha lattice design, each plot consisted of four rows of 4m long with two replications, with inter-row spacing of 0.6m and intra-row spacing of 0.2m. Two seeds were planted per hill, and later thinned to one plant per hill. Plots were kept weed free by interculture and manual weeding.

Data collection

Data was recorded for each plot on days to anthesis (AD) and days to silking (SD). Anthesis-silking interval (ASI) was determined as the difference between SD and AD. Other data recorded were plant height (PH) and ear height (EH) measured in centimeters from which ear position, was derived as a ratio of ear height to plant height. number of ears per plant (EPP) was calculated based on plant count and harvested ear count. Harvested ears from each plot were weighed and a randomly selected representative samples of ears were shelled and weighed for grain yield. Grain moisture was recorded; grain weight was adjusted to 12.5% moisture to get the final grain weight (GY) in tons per hectare (t ha^{-1}).

Statistical analysis

Analysis of variance was performed for individual locations and later combined across locations for grain yield, days to anthesis, days to silking, anthesis-silking interval, ears per plant, Plant height using META-R (Multi-Environment Trial Analysis with R) (Alvarado et al. 2015) Genotypic and phenotypic correlation was calculated with the help of META-R software. The GGE biplots were constructed by using GEA-R (Genotype by Environment Analysis with R)(Pacheco et al. 2016) from the first two principal components (PC1 and PC2) that were derived by subjecting environment-centered grain yield means to singular-value decomposition. The options used for data analysis were no transformation (Transform = 0), no standardization (Scale = 0), and environment centering (Centering = 2). The biplot was based on environment-focused singular-value partitioning (SVP = 2) and therefore appropriate for visualizing the relationships among locations. When relationships among genotypes were desired, the biplots were based on genotype focused singular-value partitioning (SVP = 1). The following GGE biplot model was used (Yan and Kang, 2002):

$Y_{ij} - \bar{Y}_j = \lambda_1 \xi_{i1} \eta_{j1} + \lambda_2 \xi_{i2} \eta_{j2} + \varepsilon_{ij}$ ……..(1)

where Y_{ij} is the mean yield of genotype i in environment j; $\bar{Y}_j$ is the mean yield across all genotypes in environment j; λ_1 and λ_2 are the singular values for PC1 and PC2, respectively; ξ_{i1} and ξ_{i2} are the PC1 and PC2 scores, respectively, for genotype i; η_{j1} and η_{j2} are the PC1 and PC2 scores, respectively, for environment j; and ε_{ij} is the residual of the model associated with genotype i in environment j.

Conclusion

Hybrid VH131376 is a promising cultivar that can achieve yields on par with the best commercial check, P3502, while also having the lowest Anthesis Silking Interval (ASI). The study delineates three distinct maize evaluation environments that were highly discriminative for selection of hybrids: 1) Location E3; 2) Location E5; and 3) Locations E6, E9 and E10. This means that these testing locations are particularly useful for identifying hybrids that would perform well in the three respective CIMMYT Asia product profiles and should be used frequently for selection of stable hybrids. However, further testing across

South Asian locations with additional hybrids will expand the coverage and reach of CIMMYT's Asia breeding program that currently targets about 6.3 m ha. The South Asia Drought and Excess Moisture (SAWLDT) profile needs more test locations from Nepal and Bangladesh; the South Asia Drought (SADT) profile needs more test locations from Pakistan and Sri Lanka; and South Asia Heat and Drought (SAHDT) profile needs more dry heat locations from Pakistan and the Tarai belt of Nepal. It is important to continue to study these locations over the years to monitor changes in environmental conditions that could affect the performance of different cultivars.

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Author contributions

Conceptualization: PN and BSV; methodology: PN, SAT and BSV; formal analysis: PN and SAT; investigation – PN, SAT, SMM, and PBN; resources: BSV; data curation: PN, SAT, SMM and PBN; writing - original draft: PN and BSV; writing – review & editing: PN, JS, and BSV, supervision: PN, CHL, RMK, PK, SKI, NKS, DGK and BSV; project administration: BSV; funding acquisition: BSV

References

Alvarado G, López M, Vargas M, Pacheco Á, Rodríguez F, Burgueño J, Crossa J (2015) META-R (Multi Environment Trail Analysis with R for Windows) Version 6.04. CIMMYT Research Data & Software Repository Network, Mexico

Badu-Apraku B, Fakorede MAB, Oyekunle M, Akinwale RO (2016) Genetic gains in grain yield under nitrogen stress following three decades of breeding for drought tolerance and *Striga* resistance in early maturing maize. The Journal of Agricultural Science 154 (4):647-661. doi:10.1017/S0021859615000593

Badu-Apraku B, Oyekunle M, Obeng-Antwi K, Osuman AS, Ado SG, Coulibay N, Yallou CG, Abdulai M, Boakyewaa GA, Didjeira A (2012) Performance of extra-early maize cultivars based on GGE biplot and AMMI analysis. The Journal of Agricultural Science 150 (4):473-483. doi:10.1017/S0021859611000761

Badu-Apraku B, Lum FA, Fakorede MAB, Menkir A, Chabi Y, The C, Abdulai M, Jacob S, Agbaje S (2008) Performance of Early Maize Cultivars Derived from Recurrent Selection for Grain Yield and *Striga* Resistance. Crop Science 48 (1):99-112. doi:10.2135/cropsci2007.01.0060

Bänziger M, Edmeades GO, Beck DL, Bellon MR 'Breeding for drought and nitrogen stress tolerance in maize: From theory to practice'. In, Mexico, 2000. CIMMYT,

Bolaños J, Edmeades GO (1996) The importance of the anthesis-silking interval in breeding for drought tolerance in tropical maize. Field Crops Research 48 (1):65-80. doi:10.1016/0378-4290(96)00036-6

Bolaños J, Edmeades GO, Martinez L (1993) Eight cycles of selection for drought tolerance in lowland tropical maize. III. Responses in drought-adaptive physiological and morphological traits. Field Crops Research 31 (3):269-286. doi:10.1016/0378-4290(93)90066-V

Cairns EJ, Crossa J, Zaidi HP, Grudloyma P, Sanchez C, Araus LJ, Thaitad S, Makumbi D, Magorokosho C, Bänziger M, Menkir A, Hearne S, Atlin NG (2013) Identification of Drought, Heat, and Combined Drought and Heat Tolerant Donors in Maize. Crop Science 53 (4):1335-1346. doi:10.2135/cropsci2012.09.0545

Campos H, Cooper M, Habben JE, Edmeades GO, Schussler JR (2004) Improving drought tolerance in maize: a view from industry. Field Crops Research 90 (1):19-34. doi:10.1016/j.fcr.2004.07.003

Crossa J, Cornelius LP (1997) Sites Regression and Shifted Multiplicative Model Clustering of Cultivar Trial Sites under Heterogeneity of Error Variances. Crop Science 37 (2):406-415. doi:10.2135/cropsci1997.0011183X003700020017x

Fakorede MAB (1986) Selection of sites for preliminary maize yield trials in the rainforest zone of South-Western Nigeria. Euphytica 35 (2):441-447. doi:10.1007/BF00021852

Fan XM, Kang SM, Chen H, Zhang Y, Tan J, Xu C (2007) Yield Stability of Maize Hybrids Evaluated in Multi-Environment Trials in Yunnan, China. Agronomy Journal 99 (1):220-228. doi:10.2134/agronj2006.0144

FAOSTAT (2021) Crops and livestock products. FAO https://www.fao.org/faostat/en/#data/QCL. Accessed 4 Nov 2022

Gauch GH (1988) Model Selection and Validation for Yield Trials with Interaction. Biometrics 44 (3):705. doi:10.2307/2531585

Gauch Jr. HG (2006) Statistical Analysis of Yield Trials by AMMI and GGE. Crop Science 46 (4):1488-1500. doi:10.2135/cropsci2005.07-0193

Gauch Jr. HG, Piepho HP, Annicchiarico P (2008) Statistical Analysis of Yield Trials by AMMI and GGE: Further Considerations.

Crop Science 48 (3):866-889. doi:10.2135/cropsci2007.09.0513
Gauch Jr. HG, Zobel RW (1997) Identifying Mega-Environments and Targeting Genotypes. Crop Science 37 (2):311-326. doi:10.2135/cropsci1997.0011183X003700020002x
Hall AJ, Vilella F, Trapani N, Chimenti C (1982) The effects of water stress and genotype on the dynamics of pollen-shedding and silking in maize. Field Crops Research 5:349-363. doi:10.1016/0378-4290(82)90036-3
IMD (2021) India Meteorological Department (Ministry of Earth Science). IMD. https://mausamjournal.imd.gov.in/. Accessed 4 Nov 2022
Pacheco Á, Vargas M, Alvarado G, Rodríguez F, Crossa J, Juan B (2016) GEA-R (Genotype x Environment Analysis with R for Windows) Version 4.1. V16 edn. CIMMYT Research Data & Software Repository Network. doi:hdl:11529/10203
Setimela PS, Vivek B, Bänziger M, Crossa J, Maideni F (2007) Evaluation of early to medium maturing open pollinated maize varieties in SADC region using GGE biplot based on the SREG model. Field Crops Research 103 (3):161-169. doi:10.1016/j.fcr.2007.05.010
Stojaković M, Mitrović B, Zorić M, Ivanović M, Stanisavljević D, Nastasić A, Dodig D (2015) Grouping pattern of maize test locations and its impact on hybrid zoning. Euphytica 204 (2):419-431. doi:10.1007/s10681-015-1358-7
Yan W, Glover KD, Kang MS (2010) Comment on "Biplot Analysis of Genotype × Environment Interaction: Proceed with Caution," by R.-C. Yang, J. Crossa, P.L. Cornelius, and J. Burgueño in Crop Science 2009 49:1564–1576. Crop Science 50 (4):1121-1123. doi:10.2135/cropsci2010.01.0001le
Yan W, Hunt LA, Sheng Q, Szlavnics Z (2000) Cultivar Evaluation and Mega-Environment Investigation Based on the GGE Biplot. Crop Science 40 (3):597-605. doi:10.2135/cropsci2000.403597x
Yan W, Kang MS (2002) GGE Biplot Analysis: A Graphical Tool for Breeders, Geneticists, and Agronomists. CRC Press, Boca Raton. doi:10.1201/9781420040371
Yan W, Kang SM, Ma B, Woods S, Cornelius LP (2007) GGE Biplot vs. AMMI Analysis of Genotype-by-Environment Data. Crop Science 47 (2):643-653. doi:10.2135/cropsci2006.06.0374
Yan W, Tinker NA (2006) Biplot analysis of multi-environment trial data: Principles and applications. Canadian Journal of Plant Science 86 (3):623-645. doi:10.4141/p05-169
Yang RC, Crossa J, Cornelius LP, Burgueño J (2009) Biplot Analysis of Genotype × Environment Interaction: Proceed with Caution. Crop Science 49 (5):1564-1576. doi:10.2135/cropsci2008.11.0665
Yates F, Cochran WG (1938) The analysis of groups of experiments. The Journal of Agricultural Science 28 (4):556-580. doi:10.1017/S0021859600050978
Zobel RW, Wright MJ, Gauch Jr. HG (1988) Statistical Analysis of a Yield Trial. Agronomy Journal 80 (3):388-393. doi:10.2134/agronj1988.00021962008000030002x