Stability of grain yield of pre-commercial maize (*Zea mays* L.) hybrids in rainfed ecosystems of South Asia

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Abstract

A study was conducted to assess the yield stability of 45 single cross maize (*Zea mays* L.) hybrids across five locations in North India, namely Samastipur, Muzaffarpur, Meerut, Kannauj, and Varanasi. Of the 45 hybrids tested, 21 displayed a higher-than-average yield (3.76 t/ha) across all environments. The analysis of variance showed that environment contributed to 88.4% of the total variation, followed by genotype × environment (7.9%) and genotype (3.7%). The first two significant interaction principal component axes accounted for about 81.54% of the total variation for grain yield. Hybrid 39 had the highest yield under diverse environments. Meerut and Muzaffarpur were identified as being more representative for grain yield compared to Kannauj, Samastipur, and Varanasi. Meerut was found to be the most discriminating environment. Hybrid 27, with an AMMI (Additive main effects and multiplicative interaction) stability value (ASV) of 0.00, was widely adapted. Hybrids specifically adapted to Samastipur (2), Muzaffarpur (2), Meerut (1), Kannauj (2), and Varanasi (2) were identified. With the least yield stability index (YSI), Hybrid 40, is recommended for cultivation during the monsoon in Northern India. Meerut and Muzaffarpur sites are recommended for evaluating early stages of maize test crosses.

Abbreviations

AMMI: Additive main effects and multiplicative interaction
ANOVA: Analysis of variance
ASV: AMMI stability value
CIMMYT: International Maize and Wheat Improvement Center
GEI: Genotype × environment interaction
GGE: Genotype and genotype × environment interaction
IPCA: Interaction principal component axis
PCA: Principal component analysis
SAWLDT: South Asia waterlogging and drought tolerant
SI: Stability index
YSI: Yield stability index

Introduction

Maize is a unique cereal crop owing to its diverse uses, suitability for the production of numerous value-added products, diverse adaptation ability, and unique morphological features. Due to intensive breeding, maize has become the highest yielding and leading cereal crop worldwide. The single cross hybrid approach by Shull (1908; 1909), made possible by the derivation of high yielding inbred lines from improved populations, has made a significant contribution to increasing maize production and productivity. Additionally, the high heterotic effect in the progenies of diverse parental lines has become a guideline for improvement in many crops. Single cross maize hybrids are being cultivated widely across continents. Maize productivity is more than 10 t/ha in the USA, average productivity worldwide is more than 5.0 t/ha whereas, in India, average productivity is around 3.0 t/ha (FAOSTAT 2023). Maize productivity is also lower in many countries where maize is primarily cultivated during the monsoon/rainy season. Thus, along with high genetic yield potential, adaptability, and stability in the performance of single cross hybrids of maize are a priority (Jha *et al.*, 2013; Kumar and Singh 2015). The monsoon season is full of uncertainty and may be accompanied by higher or lower than average rainfall which leads to excess or low soil moisture stress respectively, ranging anywhere from a few days to an extended period during the cropping season. In addition, severe biotic stress in maize is routine during this season (Zaidi *et al.*, 2020) and environmental parameters vary greatly between the Northern and Southern areas of India. Based on genetic response across diverse growing conditions, breeding strategies for the development of hybrids with specific or general adaptation should be developed. Although the development of hybrids has undoubtedly elevated the yield potential of maize, the performance of new hybrids are increasingly challenged by erratic weather patterns across different environments. Therefore, to breed for climate resilience and to increase the acceptance of hybrid maize across environments, multilocation testing of hybrids is needed to determine the adaptability of a hybrid to a particular environment and also to ascertain the stability of the hybrid across environments.

In recent years, the International Maize and Wheat Improvement Center (CIMMYT) has been focusing on developing hybrid maize for regions in South Asia affected by both early season waterlogging and midseason drought tolerance (Product Profile SAWLDT). This region of South Asia, encompassing India, Nepal, Bangladesh, Pakistan, and Bhutan, accounts for approximately 2.8 million hectares of maize cultivation (CIMMYT internal estimates). Use of multi-location testing at sites that can differentiate hybrid performance is critical for success. For a variety to be commercially cultivated, both yield and stability must be considered simultaneously (Cairns *et al.*, 2013). Yield is a complex quantitative trait determined by the sensitivity of genotypes to different environmental conditions which will result in genotype × environment interaction (GEI). Varieties grown in a large heterogeneous area for evaluating the yield response, rank differently across different evaluation sites. It is increasingly important to subdivide large, heterogenous maize growing regions into smaller, relatively homogenous areas with similar performance (mega-environments). Hybrids exhibit consistent performance (ranking) across locations within the same mega-environment which facilitates optimization of testing locations significantly reducing costs. To estimate the level of interaction of genotypes with environments and to eliminate the unexplainable and extraneous variability several statistical techniques that describe GEI have been developed. Joint regression analysis, multivariate analysis like additive main effects and multiplicative interaction (AMMI) and genotype and genotype by environment interaction (GGE) biplot analysis, are a few statistical tools used to determine the stability and adaptability of the genotypes across environments over the years. Since the genotype response to environmental variation is multivariate (Lin *et al.*, 1986) most of the statistical stability methods including regression analysis and stability variance analysis are unable to provide an accurate and complete variety response pattern for GEI (Hohls 1995). However, the AMMI interaction analysis, also referred to as double centered principal component analysis, combines analysis of variance (ANOVA) for the genotype and environment main effects along with principal components analysis of GEI (Zobel *et al.*, 1988; Gauch *et al.*, 1997) leading to reliable yield estimation in multilocation trials. Thus, the AMMI model helps in multivariate analysis for GEI investigation (Mohammadi *et al.*, 2010) by considering the interaction sum of squares and separating the main as well as the interaction effects (Farshadfar and Sutka 2006). Biplot analysis is a graphical representation of GEI and is the best way for (i) identifying the interaction patterns between genotypes and environments for genotype discrimination, (ii) identifying varieties that are appropriate for a specific environment and stable across the environments, and (iii) grouping of the test environments into different mega- environments (Gauch and Zobel 1998). The AMMI analysis has been used in grouping mega-test environments and determining the stability and adaptability of the genotypes in many crops including maize (Wolde *et al.*, 2019). In this study AMMI analysis was used to assess the main effects of environment and genotype × environment interactions on maize hybrids. This facilitated informed decision-making on: i) the selection of suitable maize hybrids for specific cultivation areas and ii) characterization of environments and their interactions with genotypes

Materials and methods

Maize genotypes

The experimental material comprised of 45 single-cross hybrids developed using elite stress-tolerant inbred lines for drought and waterlogging tolerances (Supplementary Table 1). Among these, 40 were pre-commercial hybrids from CIMMYT, evaluated alongside two internal checks and three widely cultivated commercial checks under excess moisture condition during the rainy season across five locations in North India.

Experimental trials and treatments

The five test environments were Samastipur, Muzaffarpur, Meerut, Kannauj, and Varanasi which were located between 25.23 to 28.90° N latitude and 77.66 to 85.90° E latitude (Table 1). The genotypes were tested in alpha lattice design with two replications at each lo-

Table 1 - Testing locations topography and rainfall pattern for evaluation of maize hybrids during main season

Location	Planting date	Longitude	Latitude	Annual Rainfall
Samastipur	25 July, 2020	25.87°N	85.90°E	1236 mm
Muzaffarpur	6 July, 2020	26.24°N	85.29°E	1271 mm
Meerut	30 June, 2020	28.90°N	77.66°E	886 mm
Kannauj	23 July, 2020	27.05°N	79.90°E	916 mm
Varanasi	24 July, 2020	25.23°N	83.00°E	982 mm

cation. The genotypes were sown in two rows of 4m row-length spaced 60 cm apart. Plant to plant spacing was kept at 20 cm. Sowing of trials at different locations was done from 30 June 2020 to 25 July 2020. Site specific agronomical practices were adopted to ensure optimum growth and development of each hybrid entry. At the time of harvesting fresh cob yield/plot along with moisture content was noted and finally, grain yield was calculated at 12.5% moisture. A total of nine plot yield data points were missing due to damage - four from Samastipur, two each from Kannauj and Varanasi, and one from Muzaffarpur.

Statistical Data analysis

The AMMI model was used to analyze the GEI (Gauch, 1992). All the statistical analysis related to the AMMI model as well as the construction of biplots were performed using Meta R (Alvarado *et al.*, 2015) and GEA-R software (Pacheco *et al.*, 2016). AMMI stability value (ASV) was used to assess the grain yield stability of genotypes across environments as suggested by Purchase *et al.*, 2000. Lower ASV indicates more stability of the genotype. Hence ASV was used to rank genotypes based on yield stability and was calculated as per the

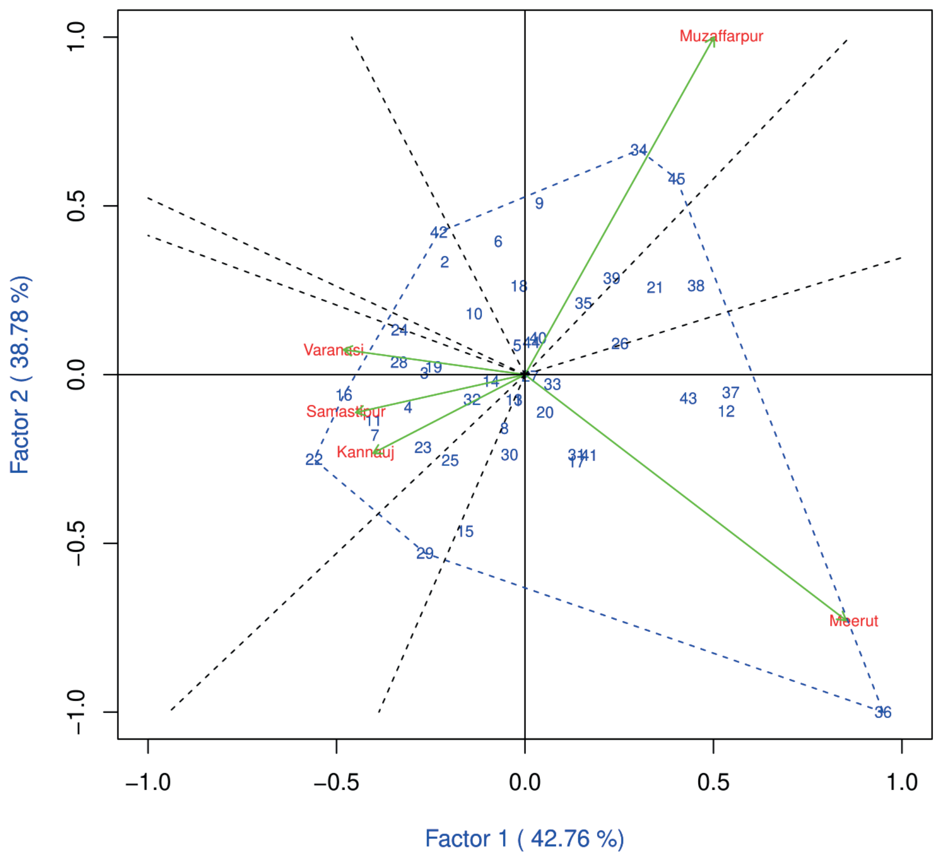

Fig. 1 - Depiction of AMMI 1 biplot for maize grain yield during testing season across environment

Table 2 - Location-wise grain yield (t/ha) and rank of 45 maize hybrids

Sl.	Hybrid Name	Kannauj	Rank	Meerut	Rank	Muzaffarpur	Rank	Samastipur	Rank	Varanasi	Rank
1	VH18233	1.96	14	7.17	13	5.59	22	2.50	10	1.89	32
2	VH1946	1.95	16	6.36	39	5.66	18	2.26	40	2.03	16
3	VH18253	1.79	36	6.32	41	5.19	37	2.33	29	1.85	34
4	VH152761	1.75	43	6.24	43	5.13	39	2.26	37	1.89	31
5	VH19486	**2.03**	5	6.97	22	5.86	10	2.35	27	2.04	14
6	VH1876	1.71	44	6.47	36	5.88	9	2.43	15	1.93	24
7	VH131603	1.92	24	6.41	38	4.96	41	2.24	42	1.96	23
8	VH18751	1.94	20	7.29	12	5.66	19	**2.59**	4	2.11	11
9	VH171144	1.76	42	6.48	35	6.09	6	2.31	31	2.00	19
10	VH133099	1.87	30	6.65	31	5.77	16	**2.64**	3	1.91	28
11	VH152562	1.96	12	6.34	40	5.05	40	2.42	16	1.78	39
12	KH15485	1.79	37	**7.68**	4	5.70	17	2.36	23	1.63	45
13	VH18776	1.95	19	6.91	26	5.37	29	2.20	44	1.92	25
14	VH182708	2.02	6	6.95	25	5.57	23	2.36	24	2.06	13
15	VH18614	**2.12**	1	7.08	17	4.89	43	2.24	41	1.92	27
16	VH18792	1.77	41	6.08	45	4.95	42	2.26	39	1.84	36
17	VH18808	1.88	28	7.17	14	5.34	31	2.32	30	1.70	42
18	VH182711	1.89	27	6.59	32	5.80	15	2.28	36	1.89	30
19	VH18796	1.96	13	6.52	33	5.31	32	2.35	26	1.77	41
20	VH18759	1.87	29	6.87	27	5.38	28	2.31	33	1.70	43
21	VH18810	1.89	26	6.97	23	5.86	11	2.07	45	1.69	44
22	VH15405	**2.09**	3	6.43	37	4.89	44	2.35	25	2.11	12
23	VH151646	1.85	33	6.85	28	5.24	35	2.40	18	**2.19**	3
24	VH15773	1.84	34	6.24	44	5.40	26	2.29	34	2.04	15
25	VH182713	1.93	23	6.95	24	5.28	33	2.51	9	1.89	29
26	VH171309	1.78	40	**7.63**	5	6.00	7	**2.68**	1	2.11	9
27	VH18766	1.99	7	7.04	19	5.63	20	2.45	13	1.81	38
28	VH18592	1.68	45	6.31	42	5.19	38	2.53	7	1.85	35
29	VH18594	1.90	25	7.00	20	4.78	45	2.48	12	1.92	26
30	VH182715	1.97	11	6.99	21	5.25	34	2.21	43	2.02	17
31	VH2060	1.97	10	7.58	6	5.51	24	2.55	6	1.97	20
32	VH2057	1.94	21	6.85	29	5.48	25	2.26	38	**2.19**	4
33	VH18572	1.95	18	7.32	10	5.62	21	2.39	19	**2.22**	2
34	VH18108	1.95	17	7.30	11	**6.73**	1	2.37	20	**2.46**	1
35	VH1935	1.85	32	7.12	15	5.96	8	2.52	8	1.96	21
36	VH182716	1.95	15	**9.33**	1	5.22	36	2.37	21	1.82	37
37	VH19392	**2.04**	4	**8.06**	2	**6.12**	5	2.34	28	2.15	6
38	VH2059	1.86	31	7.48	8	**6.30**	3	2.48	11	2.00	18
39	VH2058	**2.11**	2	7.39	9	**6.25**	4	2.36	22	2.11	8
40	VH19416	1.97	9	7.11	16	5.82	14	2.41	17	**2.16**	5
41	CAH1817Check	1.78	39	7.53	7	5.39	27	**2.59**	5	1.96	22
42	CAH153Check	1.79	38	6.51	34	5.85	13	**2.64**	2	2.11	10
43	NK6240Check	1.94	22	**7.91**	3	5.85	12	2.44	14	2.12	7
44	PAC745Check	1.82	35	6.76	30	5.34	30	2.31	32	1.78	40
45	P3502Check	1.99	8	7.07	18	**6.55**	2	2.28	35	1.85	33
	Mean	1.91		6.98		5.57		2.38		1.96	
	Maximum	2.12		9.33		6.73		2.68		2.46	
	Minimum	1.68		6.08		4.78		2.07		1.63	
	H2	0.26		0.56		0.47		0.27		0.39	
	LSD (0.05)	0.37		1.15		1.03		0.46		0.44	
	CV%	26.19		14.79		17.90		25.19		24.40	

*Bold entries are top five entries in each location respectively

Table 3 - AMMI ANOVA for grain yield in maize during maize season

Source of variation	df	Sum of square (SS)	Mean of square (MS)	Per cent contribution	Cumulative per cent contribution
Environment (E)	4	1988.99	497.25**	88.40	88.40
Genotype (G)	44	83.77	1.90**	3.72	92.12
G × E	176	177.22	1.01*	7.88	100
IPCA 1	47	77.32	1.65**	42.76	42.76
IPCA 2	45	70.11	1.56**	38.78	81.54
IPCA 3	43	24.53	0.57	13.57	95.11
IPCA 4	41	8.85	0.22	4.89	100
Residuals	216	161.42	0.75		

* 0.05 level significance and ** 0.01 level significance

formula given below:

$$ASV=\sqrt{\left(\frac{IPCA1\ sum\ of\ square}{IPCA2\ sum\ of\ square}\ \mathrm{X}\ \ IPCA1\ \mathrm{score}\right)^2+\left(IPCA2\ \mathrm{score}\right)^2}$$

For a hybrid to gain widespread acceptance, it must demonstrate both high and stable yield performance. In order to identify higher yielding stable hybrids, Yield stability index (YSI) was calculated as per the formula suggested by (Chalwe *et al.*, 2017).

$$\mathrm{YSI= RASV + RY}$$

Where, RASV= ASV rank of the genotype for grain yield; RY= rank of the genotype based on mean grain yield across locations.

Hybrid with the lowest YSI was considered to be superior and stable for grain yield. Both ASV and YSI were computed using Microsoft Excel.

Results and Discussion

Yield performance of hybrids

The mean grain yield of the hybrids when evaluated

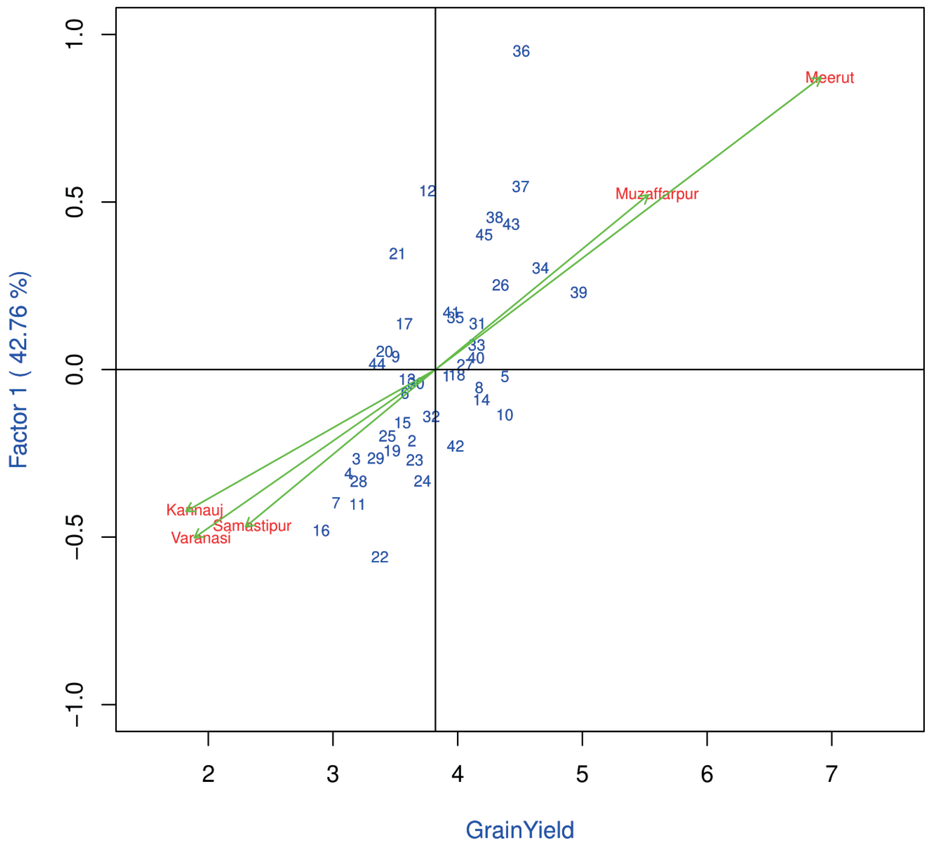

Fig. 2 - Depiction of AMMI 2 biplot for maize grain yield during testing season across environment

Table 4 - Mean grain yield, grain yield rank, ASV, ASV rank and yield stability index (YSI) for the 45 maize hybrids

Sl.	Hybrid Name	Mean grain yield (t/ha)	Grain yield rank (A)	ASV	ASV rank (B)	YSI (A+B)
1	**VH18233**	3.9	13.5	0.10	4	17.5
2	VH1946	3.6	33.5	0.37	26	59.5
3	VH18253	3.5	40	0.33	20.5	60.5
4	VH152761	3.4	43.5	0.34	23	66.5
5	**VH19486**	3.9	13.5	0.10	4	17.5
6	VH1876	3.7	20.3	0.41	29	49.3
7	VH131603	3.4	43.5	0.48	34	77.5
8	**VH18751**	4.0	9	0.23	14	23
9	VH171144	3.7	20.3	0.50	35	55.3
10	VH133099	3.8	18.5	0.23	14	32.5
11	VH152562	3.5	40	0.45	31	71
12	KH15485	3.8	18.5	0.56	38	56.5
13	VH18776	3.6	33.5	0.10	4	37.5
14	VH182708	3.8	18.5	0.11	7.5	26
15	VH18614	3.6	33.5	0.55	36	69.5
16	VH18792	3.3	45	0.56	38	83
17	VH18808	3.7	20.3	0.32	19	39.3
18	VH182711	3.7	20.3	0.30	17	37.3
19	VH18796	3.6	33.5	0.22	12	45.5
20	VH18759	3.6	33.5	0.15	9.5	43
21	VH18810	3.6	33.5	0.45	31	64.5
22	VH15405	3.6	33.5	0.72	42	75.5
23	VH151646	3.7	20.3	0.39	28	48.3
24	VH15773	3.5	40	0.34	23	63
25	VH182713	3.7	20.3	0.37	26	46.3
26	**VH171309**	4.1	4.5	0.34	23	27.5
27	**VH18766**	3.8	18.5	0.00	1	19.5
28	VH18592	3.5	40	0.33	20.5	60.5
29	VH18594	3.6	33.5	0.60	40	73.5
30	VH182715	3.7	20.3	0.20	11	31.3
31	**VH2060**	4.0	9	0.23	14	23
32	**VH2057**	3.7	20.3	0.15	9.5	29.8
33	**VH18572**	3.9	13.5	0.11	7.5	21
34	VH18108	4.2	1.5	0.77	44	45.5
35	VH1935	3.9	13.5	0.30	17	30.5
36	VH182716	4.1	4.5	1.49	45	49.5
37	VH19392	4.2	1.5	0.56	38	39.5
38	VH2059	4.0	9	0.63	41	50
39	VH2058	4.1	4.5	0.37	26	30.5
40	**VH19416**	4.0	9	0.10	4	13
41	CAH1817Check	3.8	18.5	0.30	17	35.5
42	CAH153Check	3.8	18.5	0.46	33	51.5
43	NK6240Check	4.1	4.5	0.45	31	35.5
44	PAC745Check	3.5	40	0.10	4	44
45	P3502Check	4.0	9	0.74	43	52

*Bold entries are top five entries in each location respectively under different locations varied from 1.63 t/ha (Hybrid 12) in Varanasi to 9.33 t/ha (Hybrid 36) in Meerut. The rank of the hybrid varieties with respect to grain yield in different environments is presented in Table 2 which indicates that Hybrid 15 (2.12 t/ha) was the best performer in Kannauj while at Meerut and Muzaffarpur locations, Hybrid 36 (9.33 t/ha) and 34 (6.73 t/ha) respectively, were the best performers. Hybrid 26 with a mean yield of 2.68 t/ha and Hybrid 34 with a mean yield of 2.46 t/ha were superior under Samastipur and Varanasi conditions, respectively. Hybrid 34 was the best performing hybrid under two locations *i.e.* Muzaffarpur and Varanasi. Analysis of location mean over all the hybrids indicated that Meerut with a mean yield of 6.98 t/ha was the most conducive environment for grain yield while Kannauj with a minimum grain yield of 1.91 t/ha was an unfavourable environment for the expression of the trait. 21 hybrids of the 45 evaluated displayed grain yield higher than the mean yield (3.76 t/ha) of all the hybrids across environment (Table 4). Across the locations, two hybrids namely, Hybrids 34 and 37, exhibited the highest mean grain yield of 4.2 t/ha while the lowest yield of 3.3 t/ha was shown by Hybrid 16. The grain yield difference in hybrids is attributed to genotypic effects, environmental effects, and G×E interaction effects leading to a change in the rank of the hybrids when tested across the diverse cultivation sites. When there is no change in the ranks of genotypes over environments, there is a non-crossover type of interaction effects, and genotypes with superior means can be recommended for all the environments (Baye *et al.*, 2011).

Analysis of Variance of AMMI Model

Analysis of variance for yield (Table 3) of 45 hybrids at five locations partitioned overall genetic variability into additive main effects due to the environment (E), genotype (G), and non-additive G × E interaction (GEI). All the effects showed significant statistical differences among the hybrids for mean grain yield indicating the influence of both main and interaction effects in controlling trait variability. The AMMI ANOVA indicated that the highest contribution of 88.40 per cent to the total variability was attributed to the environment effect. This was followed by the GEI effect which contributed 7.88 per cent to the yield variability while the contribution of genotype to the total variation was only 3.72 per cent. Further decomposition of GEI using AMMI analysis showed that the first two interaction principal component axes (IPCA) were significant and revealed about 81.54 percent (42.76% and 38.78% by IPCA1 and IPCA2, respectively) of the total variation for grain yield. The third and fourth principal component axes were non-significant and accounted for 13.57% and 4.89% of the phenotypic variation for grain yield, respectively. Here, we noted variation in the ranks of the hybrids across the environments indicating the influence of the G × E interaction effect along with the presence of crossover types of interaction. Further partitioning of the variances indicated that the environment component had the highest share of the total variation in yield across environments. While the contribution of GEI (7.88 per cent) and genotype (3.72 per cent) was considerably lower than the contribution due to environment (88.40 per cent). Similar results for grain yield were also reported by Zerihun (2011) in barley. The predominance of environmental effect in controlling grain yield across locations indicates that the experiment was carried out under variable climatic conditions which had a significant impact on the yield of genotypes. This makes genotype assessment and mega location analysis imperative (Fox and Rosielle 1982; Gauch and Zobel 1997). Also, the presence of a larger environmental influence compared to genotype and G×E influence is indicative of the low heritability of the trait (Brar *et al.*, 2010). Large and significant environmental and GEI effects observed in the investigation also indicated large differences among the diverse environments for grain yield and these results are in line with the findings of Adu (2013) and Anley (2013). The contribution of the GEI effect to the total variation was almost twice the contribution of the genotype effect, indicative of the probable existence of different mega environments (Ndhlela *et al.*, 2014).

The biplots allow easy visualization of differences in G × E interaction effects (Gabrial, 1971). AMMI biplots are of two types *i.e.*, AMMI 1 and AMMI 2. In the case of the AMMI 1 biplot (Figure 1), genotype and environment mean (main effects) are plotted on the X-axis against the IPCA 1 score of both genotype and environment on the Y-axis (Vargas Hernandez and Crossa, 2000). The vertical line is the grand mean for grain yield and the horizontal line (x-ordinate) represents the IPCA 1 value of zero. IPCA 1 scores are an indication of genotype stability. The lower the IPCA 1 score, the greater the stability of the genotype. Genotypes falling near the center of the biplot and having an IPCA 1 score of near zero are believed to be broadly adapted to diverse climatic conditions. While genotypes with larger IPCA 1 scores, either negative or positive, are said to be specifically adapted to certain environments (Mafouasson *et al.*, 2018). Based on the AMMI 1 biplot analysis between IPCA1 and grain yield, a total of nine hybrids namely, 1, 5, 9, 13, 18, 27, 30, 40, and 44 were located almost on the horizontal line and displayed an IPCA1 score near to zero. These genotypes showed minimum interaction with the environments with respect to grain yield and hence may be considered the most adaptable to all the environments. Seven hybrids namely, 1, 12, 23, 24, 32, 41 and 42 falling almost on the vertical line had grain yield equivalent to the grand mean of the grain yield of all the genotypes in all the environments. Hybrid 16 with an IPCA1 score of -0.5 was located on the extreme left of the biplot and therefore was specifically adapted and displayed the lowest grain yield. On the other hand, Hybrid 39 with an IPCA1 score of 0.2 was situated to the extreme right of the biplot and hence was broadly adapted and displayed the highest yield. Eighteen hybrids *i.e.*, 37, 38, 43, 45, 34, 39, 26, 35, 31, 33, 40, 27, 18, 5, 8, 14, 10 and 36 fall on the right side of the vertical line were characterized with a yield higher than the mean yield of all the hybrids while twenty hybrids namely, 16, 7, 11, 22, 28, 4, 3, 29, 19, 25, 15, 2, 6, 30, 13, 44, 20, 9, 17 and 21 were situated on the left side of the vertical line and therefore, were expected to have lower grain yield. The degree of interaction of the genotypes in different environments is indicated by their distances from the origin. Hybrids 36 and 37 were highly interacting and unstable, hence can be recommended for specific locations. Among the five environments, Meerut and Muzaffarpur locations were favourable environments for grain yield as they occupied the right-hand side of the biplot and the rest three environments namely, Kannauj, Samastipur and Varanasi were situated on the left-hand side of the biplot and were relatively unfavourable for grain yield.

The AMMI1 biplot depicted that 18 hybrids of the 45 evaluated positioned on the right side of the vertical line were high yielders and, also, grouped Meerut and Kannauj as the most suitable and most unsuitable environments for grain yield, respectively. The suitability of these environments to support higher grain yield can also be validated from the analysis of location mean over all the hybrids which also showed that Meerut and Muzaffarpur with mean grain yield of 6.98 t/ha and 5.57 t/ha, respectively, were the most favourable for grain yield. While Samastipur and Varanasi with a grain yield of 2.38 t/ha and 1.96 t/ha showed intermediate suitability for grain yield. Kannauj on the other hand with a grain yield of 1.91 t/ha was the most unsuitable environment with respect to grain yield. The polygon view of the AMMI 2 biplot indicates promising genotype(s) in each environment and group of environments (Yan, and Tinker 2006). The polygon is divided into seven sectors and the 5 environments were falling into three of them indicating the presence of three mega environments. The first group included Varanasi, Kannauj and Samastipur; the second and third groups had Muzaffarpur and Meerut respectively.

The AMMI 2 biplot or interaction biplot (Figure 2) analysis gives an overview of the responsiveness of both the genotypes as well as the environments. As the distance of the genotype or environment from the origin increases its responsiveness is also enhanced. The present investigation revealed that two locations *viz.*, Meerut followed by Muzaffarpur were the most discriminating environments among the five on account of their longest distance from the origin of the biplot. These were followed by Varanasi, Samastipur and Kannauj. The biplot revealed that hybrids 18, 10, 35, 40, 44, 5, 26, 3, 19, 14, 32, 13, 8, 30, 20, 33, 41, 27, 17 and 31 were located in the vicinity of the origin while rest of the hybrids were away from the origin and hence, they were, respectively, more stable, and more responsive for grain yield. Hybrids 16 and 11 were placed closer to Samastipur on AMMI 2 biplots. Hybrids 34, 45, 36, 29, 22, 16 and 42 were present at the outer boundary of the polygon. Polygon analysis identified specific adaptation of hybrids 34 and 45 were placed closer to Muzaffarpur; Hybrid 36 was closer to Meerut; hybrids 7 and 23 were closer to Kannauj and hybrids 24 and 28 were placed closer to Varanasi on AMMI biplot 2 indicating specific adaptation to these environments and therefore these hybrids can be recommended for cultivation in the respective environments. Hybrids 27, 5, 40, 44, 33, 13, 1 and 14 exhibited nearly zero IPCA1 and IPCA2 scores implying that these hybrids were less interactive with environments. Locations *viz.*, Kannauj, Varanasi and Samastipur formed an acute angle of varying degrees, while these three locations were in an obtuse angle with Muzaffarpur and Meerut. The two locations Muzaffarpur and Meerut were at the right angle to each other. Hybrid 27 (3.8t/ha) and 44 (3.5 t/ha) were located on the vertical line revealing uniform performance across all the environments. The AMMI 2 biplot indicated the responsiveness of both genotypes and environments, with Meerut and Muzaffarpur being the most discriminating environments. In the AMMI 2 biplot, lines were drawn to connect the test environments to the biplot origin. These lines were known as the environment vector. When the test environment has a very short vector (Kannauj), it means that all genotypes in this environment performed similarly and therefore it provided little or no information about the genotype differences. Environments with long vectors (Meerut) are more discriminating of the genotype and representative of the test environments and consequently are ideal for selecting superior genotypes. In the biplot, the environments were represented as vectors and the angle between the genotype and environment vector would help to interpret the nature of the interaction between them. The cosine angle between two environments is also used to find out the relationship between them. The acute angle is interpreted as the positive interaction and positive correlation between genotype-environment and environment-environment, respectively. The right angle represented neutral and the obtuse angle represented negative interaction and correlation. Locations Kannauj, Varanasi and Samastipur were positively correlated to each other as they formed an acute angle of varying degrees, while these three locations formed obtuse angles with Muzaffarpur and Meerut and therefore, were negatively correlated with them. The two locations Muzaffarpur and Meerut were at the right angle to each other thereby showing a neutral relationship. If the test environments display a positive correlation with each other, it indicates that a genotype will perform similarly in both environments and under such circumstances an indirect selection for grain yield can be applied across these test environments and therefore the number of test environments can be reduced without affecting the validity of the data (Ndhlela *et al.*, 2014). Genotypes close to a particular environment on AMMI 2 biplot showed specific adaptation to that environment. Therefore, hybrids 16, 11; 34, 45; 36; 7, 23 and 24, 28 were specifically adapted to Samastipur, Muzaffarpur, Meerut, Kannauj and Varanasi, respectively. Hybrids that occupied the outer boundary of the polygon namely Hybrid: 34, 45, 36, 29, 22, 16 and 42 were said to be more interactive with a particular environment and therefore, exhibited specific adaptation.

Trait association

ASV was utilized to estimate the stability of hybrids for grain yield (Table 4). ASV of the hybrids varied from 0 to 1.49. Hybrid 27 showed the lowest ASV score (0.00) and was thought to possess broad adaptation while Hybrid 36 (1.49) had the highest ASV and therefore, was specifically adapted. Other hybrids 1, 5, 13, 40, 44, 14, 33, 20, and 32 also displayed lower ASV scores, and were identified to be stable for grain yield under diverse climatic conditions. High ASV scores (>0.55) were displayed by hybrids 15, 12, 16, 37, 29, 38, 22, 45, 34, 36 and these hybrids were expected to show specific adaptation. Similar studies were also reported by Nayak *et al.* (2008) and Akter *et al.* (2015). The yield stability index (YSI) of the evaluated hybrids varied from 13 (Hybrid 40) to 83 (Hybrid 16). Hybrid 40 showed the lowest YSI and therefore had a high (3.89 t/ha) and stable yield across the studied environments. It was followed by Hybrid 1, 5, 27, 33, 8, 31, 14, 26, 32 which displayed YSI values (>17.5). These hybrids, therefore, were characterized by better adaptability and higher grain yield. ASV helps in ranking the different genotypes on the basis of their yield stability (Purchase *et al.*, 2000). The genotype with the lowest YSI is considered to be the most stable with a high grain yield (Bose *et al.*, 2014).

Therefore, GEI must be taken into consideration while selecting a genotype. For this purpose, the stability of genotypes must be analysed to identify genotypes showing broader adaptability to diverse climatic conditions (Yaghotipoor and Farshadfar 2007). In contrast to the results of the present study, (Sharifi *et al.*, 2017) indicated that environment, genotype, and GEI effects accounted for 29%, 30% and 41% of the total sum of squares of rice grain yield, respectively. Genotypes with IPCA 1 values near zero are said to have broader adaptability, and genotypes with higher IPCA 1 values are more suitable for localities with IPCA 1 values of the same sign. Due to the significance of the first two IPCAs in the present investigation, ASV seems to be useful and adequate for determining the stable genotypes, and it also facilitates the interpretation of GEI and the identification of superior genotypes

Conclusions

Multi-environmental evaluation of 45 maize hybrids showed significant difference in locations in determining grain yield. Meerut location was noted to be the most representative and discriminating environment for grain yield, while Kannauj was the least representative one. Analysis of the data identified three mega environments. The first mega environment constituted of Varanasi, Kannauj and Samastipur; while the second and third mega environments were Muzaffarpur and Meerut, respectively. From AMMI 1 analysis, 18 hybrids had grain yield higher than the average yield. AMMI 2 biplot analysis revealed that the hybrids 27, 5, 40, 44, 33, 13, 1, and 14 had nearly zero values on both IPCA 1 and IPCA 2 scores implying hybrids were less interactive with the environments. Also, on account of their proximity to different test environments *viz.*, Samastipur, Muzaffarpur, Meerut, Kannauj and Varanasi, hybrids 16, 11; 34, 45; 36; 7, 23 and 24, 28, respectively, were identified specifically adapted to these environments. Based on YSI, Hybrid 40 was identified to be the most stable.

It is important to use a representative location to efficiently identify high-performing hybrids while conserving resources. A good representative site would ensure that results are extrapolatable to a wider area, thus optimizing breeding resources for hybrid evaluation and identification. Although this present study is limited to India, larger parts of South Asia are known to be prone to excess moisture stress [personal communication with respective national partners]. Presently all areas with excess moisture are perceived to be similar and hybrids selected in existing excess moisture stress locations are recommended for all such regions. However, it is very clear from this study that locations within the same market segment and requiring the same product profile, have genotype-environment interaction. A fine resolution of intra-segment testing sites, as described in this study, is critical for enhancing genetic gains. To move ahead and bring a more harmonized classification of mega-environments in the region and have a region-inclusive picture of this product profile, sites from Nepal, Bangladesh, Pakistan, and Bhutan could be included in future studies.

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Conflict of interest

The authors declare that there is no conflict of interest.

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SL N	Hybrid Name	Pedigree
1	VH18233	(((CML161xCML451)-B-18-1-BBB/CML161-B)-B-13-BB(NonQ)-B/Composite4//Composite4)-B-4-B(DM)-BBB/CL02450-B*6-#-BB
2	VH1946	((CA34505xCA00302)-B-2-1-B-1-BB-B1<20r>-HS4<20r>)-B1-16-B*6/(CML451-B*4//CML451-BBB/LaPostaSeqC7-F18-3-2-2-3-B*7///CML451-B*4//CML451-BBB/DRB-F2-60-1-1-1-BBB-3-B)-B*5
3	VH18253	((CL02450/OFP67//CL02450)-9-B*5/Composite3//Composite3)-B-2-1-BBB/CML451-B*8-#-B-B1
4	VH152761	(AMATLCOHS44-1-1-2E-4-5-1-B/P31C4S5B-6-##-B)-BBB-7-B*9/((CML150xCL-03618)-B-16-1-1-1-B*5/(CML150xCLG2501)-B-31-1-B-1-BBB)-B-4-BB(NonQ)-B*10
5	VH19486	(CA34505xCA00302)-B-2-1-B-1-BB(S)-B2-B*9-B1-#/(CML444-1-B*6/(CML444/VL111354)-42-B-1-BBB)-B-4-1-B1-B
6	VH1876	(CA34505xCA00302)-B-2-1-B-1-BB(T)-B3-#15-2-B-1-B*5-B1-#/(PobBTS-BBB-25/CML451)-BBB-7-BBB
7	VH131603	(CL02450/CML470)-B-60(Unsel)-BB-1-B*6/((CML161xCML451)-B-18-1-BBB/CML161-B)-B-13-BB(NonQ)-BBB-B1-##-B
8	VH18751	(CL02450Q/3[SSS]XX//CL02450Q)-B-16-2-1-1-B-#-BB/(VL111354/CML472)-7-B-1-B*4-#
9	VH171144	(CL02450Q/3[SSS]XX//CL02450Q)-B-16-2-1-1-B-#-BB/CML451-B*8-#-B-B1
10	VH133099	(CLQ-6601xCL-02843)-B-23-2-1-B-1-BBB-#-B/CL02450-B*6-#-BB
11	VH152562	(CLQ-RCYQ28xP390Am/CMLc4F218-B-1-B)-B-43-1-BB-2-B*8-1-BBB/G26C32HS#146-4-1-3-2-B*10
12	KH15485	(CML165/AMATLC0HS170-2-3-2-1-1-1-BBB)-B-4-1-B*12/(CML470/CML165-B//CML470)-BB-3-B1-B-B1-BBB
13	VH18776	(CML165xCL-02839)-B-22-1-1-BB-1-B*6-#-BBB/(CML451-B*4//CML451-BBB/DTPWC9-F24-2-3-1-3-2-1-2-B*4///CML451-B*5)-BBB-7-B-#-BB
14	VH182708	(CML165xCL-02843)-B-12-3-1-BB-1-B*8-#-BBB/(CA34505xCA00302)-B-2-1-B-1-BB(T)-B3-#15-2-B-1-B*5-B1-#
15	VH18614	(CML444/VL111354)-42-B-1-BBB-1-B*4/(CA34505xCA00302)-B-2-1-B-1-BB(T)-B3-#15-2-B-1-B*5-B1-#
16	VH18792	(CML465/CML165-B//CML465)-BB-15-B1-B*7/(CL02450Q/3[SSS]XX//CL02450Q)-B-16-2-1-1-B-#-BB
17	VH18808	(CML465/CML165-B//CML465)-BB-15-B1-B*7/AMDROUT2c2-3-B-3-#-B
18	VH182711	(CML466/CML165-B//CML466)-BB-11-B*7/(CA34505xCA00302)-B-2-1-B-1-BB(T)-B3-#15-2-B-1-B*5-B1-#
19	VH18796	(CML466/CML165-B//CML466)-BB-11-B*7/(CLQ-RCYQ31xCLQ-RCYQ35)-B-36-2-B*4
20	VH18759	(CML466/CML165-B//CML466)-BB-11-B*7/(VL111354/CML472)-7-B-1-B*4-#
21	VH18810	(CML466/CML165-B//CML466)-BB-26-B*8/AMDROUT2c2-3-B-3-#-B
22	VH15405	(CML468/CML444//VL105541)-5-B-4-B*5/CL02450-B*6-#-BB
23	VH151646	(CML474/S92145-2EV-7-3-B*5)-F2-58-1-B*15/POB45c9F210-17-1-2-B*17
24	VH15773	(VL1110438/CML451)-B-13-1-B-2-B-1-#-BB/((CML161xCML451)-B-18-1-BBB/CML161-B)-B-13-BB(NonQ)-BBB-B1-##-BBB
25	VH182713	AMDROUT1(DT-Tester)c1F2-16-B-4-#-B/(CA34505xCA00302)-B-2-1-B-1-BB(T)-B3-#15-2-B-1-B*5-B1-#
26	VH171309	AMDROUT2(Ac)c1-B-#-17-BBB/(CLQ-RCYQ28xP390Am/CMLc4F218-B-1-B)-B-43-1-BB-2-B*8-1-BBB
27	VH18766	AMDROUT2c2-3-B-3-#-B/(VL111354/CML472)-7-B-1-B*4-#
28	VH18592	CA14517/P145C4MH7-1-B-1-1-B-1-1-B*17-1-BBB/(CML451/PB80//CML451)-B-30-1-1-1-BB-B2-B
29	VH18594	CA14517/P145C4MH7-1-B-1-1-B-1-1-B*17-1-BBB/(CML451-B*4//CML451-BBB/ZEWBc1F2-216-2-2-B-2-B*4-1-B-1-BB///CML451-B*4//CML451-BBB/LaPostaSeqC7-F18-3-2-2-3-B*7)-1-1-B-1-B*4
30	VH182715	CML161X165-16-2-1-B*11/(CA34505xCA00302)-B-2-1-B-1-BB(T)-B3-#15-2-B-1-B*5-B1-#
31	VH2060	CML563-B/(CA34505xCA00302)-B-2-1-B-1-BB(S)-B2-B*10
32	VH2057	CML563-B/(CML465/CML165-B//CML465)-BB-15-B2-B-1-BB-1
33	VH18572	CML563-B/(CML465/CML165-B//CML465)-BB-36-B*7
34	VH18108	CML563-B/(CML466/CML165-B//CML466)-BB-11-B*7
35	VH1935	Composite14-BBB-1-B-1-B*6/CLQRCYQ44-B*4-1-#-BBB
36	VH182716	G25C32HS#126-2-1-1-1-B*8-4-BBB/(CA34505xCA00302)-B-2-1-B-1-BB(T)-B3-#15-2-B-1-B*5-B1-#
37	VH19392	WLCY2-7-1-2-1-5-B-2-3-1-2-2-B*5-#-BB/(CA34505xCA00302)-B-2-1-B-1-BB(S)-B2-B*10
38	VH2059	WLCY2-7-1-2-1-5-B-2-3-1-2-2-B*5-#-BB/(CML451/PB80//CML451)-B-30-1-1-1-BBB
39	VH2058	WLCY2-7-1-2-1-5-B-2-3-1-2-2-B*5-#-BB/(CML465/CML165-B//CML465)-BB-15-B2-B-1-BBB
40	VH19416	WLCY2-7-1-2-1-5-B-2-3-1-2-2-B*5-#-BB/(CML466/CML165-B//CML466)-BB-11-B*6-B1-#
41	CAH1817	Internal Check
42	CAH153	Internal Check
43	NK6240	Commercial Check
44	PAC745	Commercial Check
45	P3502	Commercial Check