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RESEARCH ARTICLE

A combination of analytical methods dissects genotype × environment interaction precisely and facilitates the selection of potential new field corn (*Zea mays* L.) hybrids

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Abstract

Environmental interactions influence grain yield. Multi-environment testing (MET) is vital to validate the performance of hybrids. To understand the grain yield and stability of hybrids across the major corn growing regions in India, 30 corn hybrids were assessed in five diverse environments in *Kharif* 2021. The grain yield data from all five environments showed highly significant ($p < 0.01$) variance due to genotype (G), environment (E), and genotype-environment interaction (GEI). Additive main effects and multiplicative interaction (AMMI) analysis illustrated the relationship between high-yielding hybrids and the test environments of different corn-growing ecologies. The results from the Jharkhand and Dharwad locations exhibited short vectors, which were very close to the point of origin, implying weak interactive forces. New Delhi, Mandsaur, and Bhubaneswar are distant from the origin and possess long vectors, suggesting strong interactive forces. From GGE analysis (genotypic main effect plus genotype-by-environment interaction), the first two initial principal component axis (IPCAs) accounted for 67% of the total variance by GEI with PC1 (39.68%) and PC2 (27.32%). The hybrid, AH-8127, possessed the least AMMI Stability Value (ASV) of 0.09, attributing the highest stability, followed by AH-4551 (0.13). High and stable performing hybrids, AH-8127, AH-4551, and AH-8089, have been identified through the Yield Stability Index (YSI), which are suitable for all environments.

Keywords: Field corn hybrids, MET, stability, AMMI, GGE biplot

Introduction

Corn (*Zea mays* L.), being an important cereal crop, is consumed as a staple food in many American, African, and Asian countries. In India, corn is used in many ways, including human consumption (20%), poultry feed (47%), animal feed (13%), industrial (starch) products (14%), beverages and seed (6%) (https://iimr.icar.gov.in/?page_id=51). Globally, hybrid cultivars predominate corn cultivation due to the fact that high-yielding hybrids are superior to open-pollinated varieties (Dijsbar and Gardner 1989). These hybrids are gifts from farmers and breeders to the modern era. The development of field corn hybrids with high genetic yield potential is made possible by its vigorous plant stature, large reproductive parts, and monoecious nature. In India, 1.5 crore farmers cultivate corn witnessed a significant jump in production from 25.9 million tonnes (Mt) (2016-17) to 31.65 Mt (2020-21) in a span of five years without a major change in the total cultivated area (9.63 million hectares (Mha) and 9.89 Mha in 2016-17 and 2020-21, respectively). Still, the corn productivity in India (3.19 t ha^{-1}) is way below the productivity of the USA (9.6 t ha^{-1}) (https://farmer.gov.in/m_cropstaticsmaize.aspx). When compared to other

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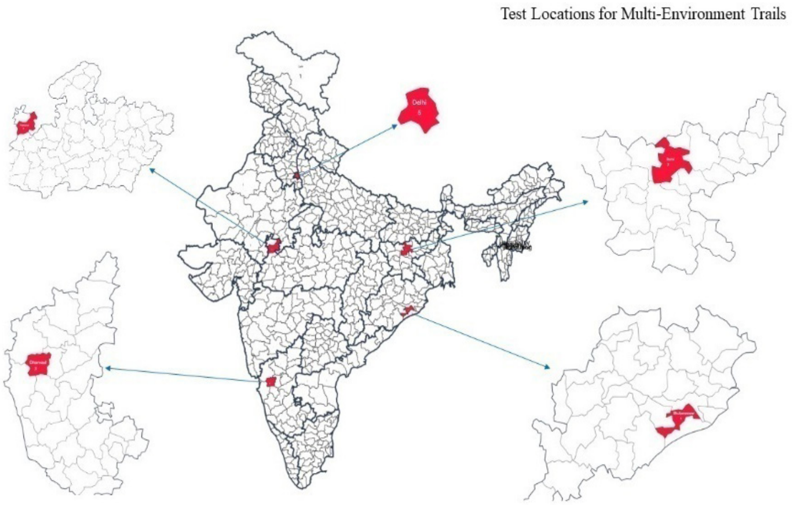

Fig. 1. Geographical details of the five locations where thirty field corn hybrids were tested during kharif, 2021

countries, the difference in yield is almost 130%. This is because conventional farmers continue to rely on composite types and hybrids that provide meager yields. There is an urgent need for strategizing to develop promising, potentially high-yielding hybrids catering to different end uses. There is a huge scope for public research institutions to fill this void and deliver low-cost hybrid seeds to farmers in India. The newly developed field corn hybrids must offer high productivity and other important agronomic features that manifest in a variety of environments. Hence, concerted efforts should be made to evaluate the performance of hybrids properly in various environments and facilitate the adoption of newly developed hybrids.

Most of the economically important traits, including grain yield are complex and influenced by a host of component traits and compounded by Genotype-Environment Interaction (GEI). As a result, it is very challenging to get a good estimate of the stability of the yield performance. Nonetheless, multi-environment trails of the candidate hybrids, covering different agro-climatic conditions, would provide a fair idea of the stability of performance.A genotype is said to be stable if its performance is proportionately higher and relatively unchanged across various environments. From the definition of stability, a stable genotype is one with minimal deviation in yield and reasonably high productivity across diverse environments (Becker and Leon 1988).

Multiple statistical tools, such as additive main effects and multiplicative interaction (AMMI) and genotypic main effect plus genotype-by-environment interaction (GGE), assess the stability and adaptability of hybrids across a variety of environments (Finlay and Wilkinson 1963; Eberhart and Russell 1966; Gauch 1992). AMMI analysis is preferable to alternative models because G and GE are clearly differentiated in AMMI. Biplot analysis is becoming popular in the field of agricultural sciences on account of its feature of multi-environment analysis (Yan et al. 2000). The GGE biplot graphically depicts the data obtained and aids in assessing and putting in proper perspective the comparative results. The biplot produced highly consistent graphical results for identifying high yields and genotype stability in field corn hybrid (Alwala et al. 2010; Kumar et al. 2024). GGE biplots exhibit both G and GE, which are the main variation sources that aid in cultivar evaluation (Yan and Kang 2002). Several previous researchers (Yan and Tinker 2006) stated the importance of testing novel hybrids in several environments to ensure their stability and described the GGE biplot methodology in a number of different ways to categorize mega environments, rank genotypes, and establish discriminativeness and representativeness. The present study aimed to understand the effects of environment, genotype, and their interactions on elite tropical field corn hybrids across environments using a combination of the results of different tools of stability analysis.

Materials and methods

Experimental material

The experimental material comprised a set of 28 elite experimental field corn hybrids and two check hybrids, Bio-9544 and P-3304. AICRP-Maize recommends the former check and the latter is widely cultivated by farmers across India. All the experimental hybrids were developed by ICAR-Indian Agricultural Research Institute (IARI), New Delhi as well as ICAR-IARI-Regional Research Centre (RRC), Dharwad, Karnataka. The details of the hybrids are listed in Supplementary Table S1.

Experimental design and environments

The experiment consisting of 30 field corn hybrids was laid out in Randomized Complete Block Design (RCBD) with two replications during *kharif*, 2021 in all five test environments. Each hybrid was sown in two rows, each of 4 m in length, with a spacing of 60 × 20 cm. The sowing was done in the second fortnight of July 2021 in all the environments. Based on the environment-specific soil requirement, the recommended dose of fertilizers (N, P_2O_5, K_2O) was applied and all the crop protection measures were taken timely as and when required and the irrigation was provided based on the climatic and soil moisture conditions of the test environments to raise a healthy crop. The experiment was conducted at five diverse locations, *viz.*, Bhubaneswar, Odisha, Barhi, Jharkhand, Dharwad, Karnataka, Mandsaur, Madhya Pradesh, and New Delhi. Among these, Bhubaneshwar and Barhi represented the eastern region, Mandsaur, the central; Dharwad, the southern part, and New Delhi represented the northern region of India (Fig. 1). The edaphic and climatic conditions of the trial environments were diverse (Supplementary Table S2).

Data recording

Ten random competitive plants, excluding the border plants, were selected and tagged from each plot for taking data on yield and yield component traits as per the standard procedures. Grains were shelled from the representative cobs for estimating the per cent grain moisture using a moisture meter (Milima's Grain Moisture Meter). The shelling percentage was calculated using the standard formula given by Jha et al. (2013).

Statistical analyses

ANOVA and genotype-environment interaction (GEI)

Analysis of Variance for yield (t ha^{-1}) was carried out both for individual environments as well as by combining five environments as per the procedure given by Gomez and Gomez (1984). As grain yield exhibited significant genotype-environment interaction (GEI), statistical analyses were carried out further.

AMMI GGE biplot analyses

AMMI biplots were erected based on the means vs the first Principal Component Axis (PCA1) followed by the second Principal Component Axis (PCA2), respectively. The following AMMI model given by (Zobel et al.1988) was used to understand the stability of the hybrids under evaluation. The hybrids were ranked based on AMMI's Stability Values (ASV) and Yield Stability Index (YSI), where ASV is a distance from the coordinate point in a 2D scatter diagram of Initial Principal Component Axis (IPCA) 1 scores against IPAC 2 scores. Yield data from all five environments were subjected to a GGE biplot and the following model suggested by (Yan and Kang 2002) was used to interpret the suitable hybrids for further selection.

Analysis of Variance (ANOVA) was performed through META-R (Alvarado et al. 2017) and 'agricolae' (De Mendiburu 2009) software packages. GEI and GGE biplots were erected using the METAN (Olivoto and Lúcio 2020) and 'gge' (Laffont et al. 2013) packages, available in R-Studiov 3.3.0.

Table 1. Analysis of Variance for grain yield of 30 field corn hybrids in five environments

Source	df	SS	MSS	%contribution of variance
Environment (E)	4	215.85	53.96**	25.72
Hybrid (G)	29	133.72	4.61**	15.94
GEI	116	273.98	2.36**	32.64
IPCA1	32	113.94	3.56	-
IPCA 2	30	91.65	3.05	-
IPCA 3	28	43.45	1.55	-
IPCA 4	26	24.95	0.96	-
Residuals	145	215.74	1.49	25.70
Total	415	1122.71	2.71	-

Equivalent distribution of variance of E, G, GEI and Residuals; ** Significant at $p < 0.01$

BLUP

The best linear unbiased prediction (BLUP) analysis was conducted to predict the genetic performance of corn hybrids in multi-environmental trials (MET). Both the fixed and random effects were considered for the analysis, where fixed effects represented the environmental factors, including location, season, and any other significant covariates, while the random effects accounted for genetic variation among the corn hybrids. The inclusion of random effects allowed for the estimation of the true genetic value of each hybrid while accounting for the variation caused by environmental factors.

Results and discussion

Analysis of variance and mean performances of the hybrids

ANOVA revealed highly significant mean squares due to hybrids (genotypes)in all the five tested environments, implying the existence of genetic differences among the hybrids with respect to yielding ability (Kandus et al. 2010). Pooled Analysis of Variance (ANOVA) for all the environments indicated the significant differences ($p \leq 0.01$) in the mean squares due to environments, hybrids, and environment × hybrid interaction (*i.e.*, G×E interaction) for yield. Pooled ANOVA over five environments are presented in (Table 1), which revealed the maximum contribution to variation by environment (E) (25.72%) residual (25.70%) followed by hybrid × environment (GEI) (32.64%) and hybrid (G) (15.94%).

The highest contribution of the environment might be due to the existence of all five tested environments in different states and lies in various agro-climatic zones. On the other hand, errors from uncontrolled variation within experimental fields also, unfortunately, cause inaccuracy

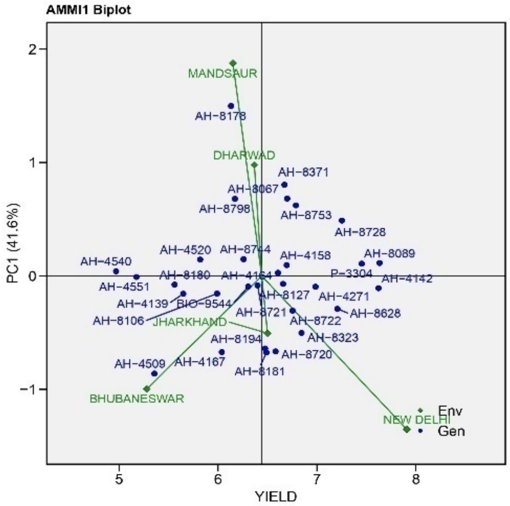

Fig. 2. AMMI biplot illustrating stability of grain mean yield across environments

or residual effects in grain yield estimates (Aktas and Ure 2020). The sole purpose of performing a pooled analysis of variance is to explain the primary cause of the variability and to measure the interactions between and within the sources of variation. The highly significant variation observed in different hybrids in the present study can be explained by the differences in the genetic makeup of the hybrids derived by crossing diverse parents and the highly varied environmental conditions in which hybrids were evaluated (Karuniawan et al. 2021; Kumar et al. 2023).

AMMI biplot

The potential yield of the hybrids, the association of the environments, and the stability of the performance were illustrated visually by using AMMI biplots (Fig. 2). The larger Interaction Principle Component Axis (IPCA) value indicates the higher adaptability of certain hybrids in a particular environment. Similarly, a low ASV value suggests higher stability in various environments (Mukri et al. 2018). Jharkhand and Dharwad environments are very close to the point of origin and exhibit short vectors, representing weak interactive forces. On the other hand, the other three environments, New Delhi, Mandsaur, and Bhubaneswar, are far away from the origin and possess long vectors, which represent the strong interactive forces. The lowest AMMI Stability Value (ASV) was observed for the hybrid, AH-8127 (ASV = 0.09) followed by AH-4551 (0.13), P-3304 (0.15), AH-8089 (0.16), AH-8180 (0.18) and AH-4540 (0.19) with a grand mean grain yield of 6.66, 5.17, 7.45, 7.63, 5.56, and 4.97 t ha^{-1}, respectively,

Indicated their high stability across the five environments (Table 2). On the contrary, the high ASV, in hybrids such as AH-8178 (ASV=1.87), AH-8371 (1.17), AH-4509 (1.10), AH-8728 (1.04) and AH-8798 (1.03)with a grand mean grain yield of6.13, 6.67, 5.36, 7.25 and 6.17 tha^{-1}, respectively, implied their lower grain yield stability (Table 2). The genotype, which showed high stability based on the parameters of ASV and IPCA, tends to show less yield. In that case, genotypes having high stability and exhibiting low yield shall not be selected further (Enyew et al. 2021). The use of AMMI (Additive Main Effect and Multiplicative Interaction) and analysis of variance allows for the assessment of the overall GEI effect of each genotype, as well as their individual contributions (Pour-Aboughadareh et al. 2022; Singh et al. 2024). As the stability value is not sufficient to judge the further performance of the individual genotype, the Yield Stability Index (YSI) seems to be the next best parameter. The YSI, a combination of ASV and mean of grain yield (tha^{-1}) was estimated to assess and categorize the hybrids. The Lower

Table 2. Illustrating the AMMI stability value, yield stability index, and their ranking orders of 30 field corn hybrids

	ASV	YSI	rASV	rYSI	Means
AH-8127	0.09	14	1	13	6.66
AH-4551	0.13	31	2	29	5.17
P-3304	0.15	6	3	3	7.45
AH-8089	0.16	5	4	1	7.63
AH-8180	0.18	32	5	27	5.56
AH-4540	0.19	36	6	30	4.97
AH-8744	0.31	27	7	20	6.26
AH-8628	0.41	13	8	5	7.21
AH-8106	0.46	33	9	24	5.99
AH-4520	0.54	35	10	25	5.82
AH-4139	0.54	37	11	26	5.65
AH-8721	0.59	30	12	18	6.40
BIO-9544	0.62	32	13	19	6.31
AH-8323	0.64	21	14	7	6.84
AH-4158	0.70	26	15	11	6.69
AH-4164	0.70	30	16	14	6.61
AH-4142	0.77	19	17	2	7.62
AH-8722	0.81	27	18	9	6.75
AH-8720	0.85	34	19	15	6.58
AH-4167	0.86	43	20	23	6.04
AH-8067	0.86	31	21	10	6.70
AH-8181	0.86	38	22	16	6.49
AH-8194	0.88	40	23	17	6.48
AH-4271	0.98	30	24	6	6.99
AH-8753	0.99	33	25	8	6.79
AH-8798	1.03	47	26	21	6.17
AH-8728	1.04	31	27	4	7.25
AH-4509	1.10	56	28	28	5.36
AH-8371	1.17	41	29	12	6.67
AH-8178	1.87	52	30	22	6.13

ASV = AMMI's Stability Value, YSI = Yield Stability Index, rASV = Ranking of ASV, rYSI = Ranking of YSI

YSI indicates a higher range of stability and productivity (Singamsetti et al. 2021). Based on the YSI**,** hybrids such asAH-8089 (YSI=5) followed by AH-4142(19), P-3304 (check) (6), AH-8728(31), AH-8628 (13)exhibited high stability as well as ranked as top hybrids. It also rightly identified AH-4540 (YSI=36) followed by AH-4551 (31) and AH-4509 (56) as poor hybrids due to their lower stability and productivity. To identify the best hybrid across the environments, YSI is the best selection statistic.

BLUP analysis

The best linear unbiased prediction (BLUP), as a statistical tool, addresses the challenges posed by the inherent variability in multi-environment trials by providing reliable estimates of hybrid performance and their adaptability across various environments by incorporating both genetic and environmental information. The results obtained through BLUP analysis also correspond to the AMMI analysis that indicated stable yielding hybrids tend to maintain their performance in the following season (Supplementary Fig. S1). BLUP enables researchers to accurately estimate the true genetic potential of field corn hybrids, minimizing the influence of environmental factors (Baretta et al. 2017).

GGE biplot analysis

The primary source of variation in the evaluation of the genotypes under multi-environment trials (MET) is genotype (G) and G×E interactions and identification of environment-specific hybrid may resolve the problems of GEI (Yan et al. 2000). To realize this (a) "which-won-where" pattern of MET to successfully visualizing the pattern of GEI dependent on the correlation between G and E; (b) stability versus mean performance over the environment for hybrid evaluation; and (c) representativeness and discriminating capacity for test environment were analyzed by the methods given by (Yan et al. 2000). The GGE biplots in the present study were erected with environment-centered data and scaled according to the procedure of (Yan et al. 2001). According to GGE analysis, the top two IPCAs (PC1 with 35% and PC2 with 31% towards total variance by GEI) accounted for 66% of the total variation.

Which-won-where pattern

GGE (Genotype and GEI) biplots were constructed using SREG (site regression model). It ignores random errors and merely explains the genotype's main effects along with GEI effects. The first step in creating a biplot was centering the data after sectionalizing the single value (SV)into GE scores for the two main components, PC1 and PC2, and then contrasting the PC1 scores with the PC2 scores. While a lower PC2 score denotes stability, a higher PC1 value implies high-yielding capacity. The graph of biplots aids in locating superior performing genotypes, which are adapted to a particular environment or multiple environments (Kalpana et al. 2017; Khan et al. 2021). GGE biplot significantly fits the 'which-won-where' pattern analysis for genotype and test environment evaluation (Yan et al. 2007). 'Which-won-where' GGE biplot graphs are split apart by an equality line into various sectors in which differing mega environments can be perceived. 'Which-won-where' polygon plots are created by connecting the far-away genotypes from the beginning of the biplot to the genotypes that are represented at the vertices of the plot. The genotypes represented at the vertex are winning genotypes in the specific sector-holding environments (Yan and Tinker 2006).

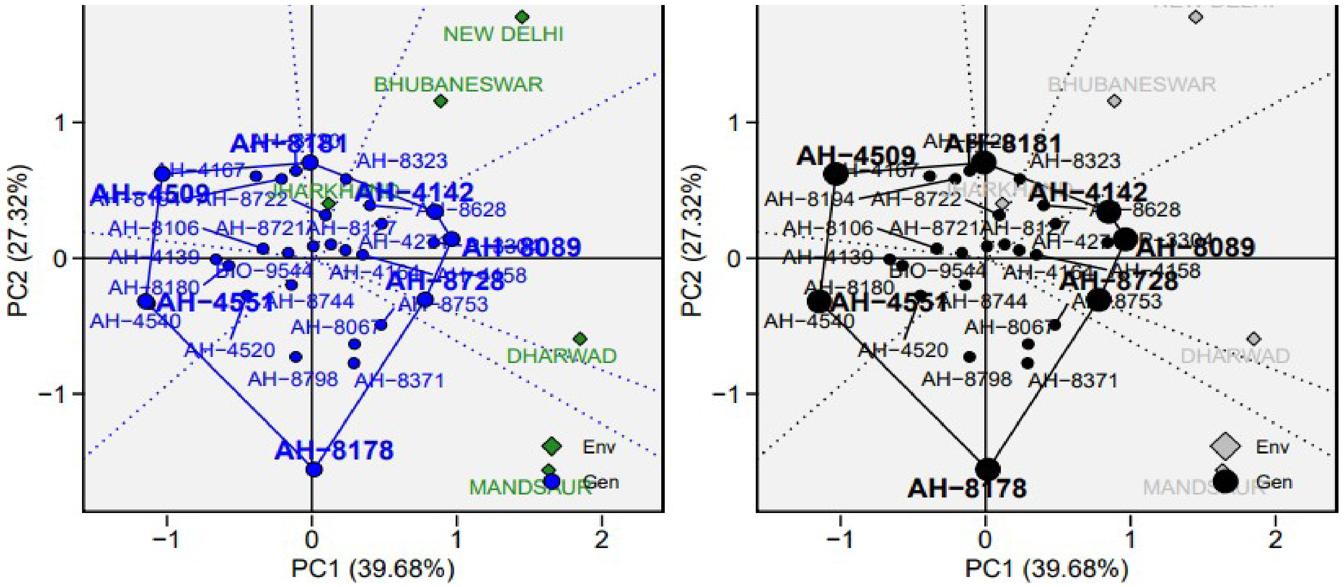

Fig. 3. The genotypes with the highest performance in each environment are shown in the Which-Won-Where polygon view of the GGE scatter biplot of the 30 field corn hybrids for grain yield

A total of six rays were formed and these rays divided the biplot into six sectors and the five environments (three and two) into two sectors (Fig. 3). The first ray cuts perpendicular to AH-4506 and AH-4142, the second ray to AH- 4142 and AH-8089, third ray to AH-8089 and AH-8728, fourth to AH-8728 and AH-8178, fifth to AH-8178 and AH-4551, and finally, sixth ray cuts AH- 4551 and AH-4509. All the hybrids at a vertex of each sector are high-yielding in the environments that fall in the particular sector. The three environments (Jharkhand, New Delhi and Bhubaneswar) fall in the sector representing between first and second rays. The hybrid for this vertex is AH-4142 implying it to be high yielding in these locations. Similarly, the remaining two environments *viz.*, Mandsaur and Dharwad, fall in the sector formed by third and fourth rays and the AH-8728 hybrid is at its vertex, indicating the high-yielding ability of this hybrid in these two environments. The displayed pattern by the biplots is arguably more robust than the individual raw data points (Yan 2002).

Mean vs. stability GGE biplot pattern

Through the 'which-won-where' pattern, merely winning elite performing hybrids in the environment were found. Further, it is necessary to do an analysis considering the mean performance and stability of all of the elite-performing hybrids before selection. With the assistance of average environment coordinates (AEC), the GGE biplot is able to visually display information on mean performance and stability. The 'Mean *vs.* Stability' view, often referred to as AEC and SVP (Single Value Portioning) helps to efficiently evaluate hybrids based on mean grain yield and stability in various environmental conditions (Fig. 4). The mean of the environmental scores' PC1 and PC2 were defined according to (Yan and Rajcan 2002). This biplot graph is made up of two straight lines: (i) the AEC ordinate (horizontal) and (ii) the AEC abscissa (vertical). The "mean-environment axis" is shown by the green line with the arrow passing through the origin (Fig. 4). A greater mean yield for the hybrids is indicated by the direction in which the arrow points is shown along the second axis; hybrids that are positioned closer to the point of origin tend to be more stable (Hongyu et al. 2014).

Based on the mean grain yield, the thirty hybrids were ranked and functionally classified on the basis of performance as AH-8089 (7.63 t ha^{-1}) > AH-4142 (7.62 t ha^{-1}) > P-3304 (7.45 t ha^{-1}) > AH-8728 (7.25 t ha^{-1}) > AH-8628(7.20 t ha^{-1}) > AH-4271 (6.98 t ha^{-1}) (See supplementary Table S3, and clearly depicted in Supplementary Fig. 2 for more information). A similar evaluation of the genotypes with the mean vs stability GGE biplot was reported by Neisse et al. (2018).

Ranking of hybrids

The ranking biplot of hybrids allows us to spot the best hybrid in comparison to the others. To rank the hybrids, two axes are drawn, one between the arrowhead and the origin (called the first axis) and the other perpendicular to the first axis at the origin (called the second axis). The arrowhead represents the ideal line (theoretically optimal but practically impossible line) (Fig. 5).

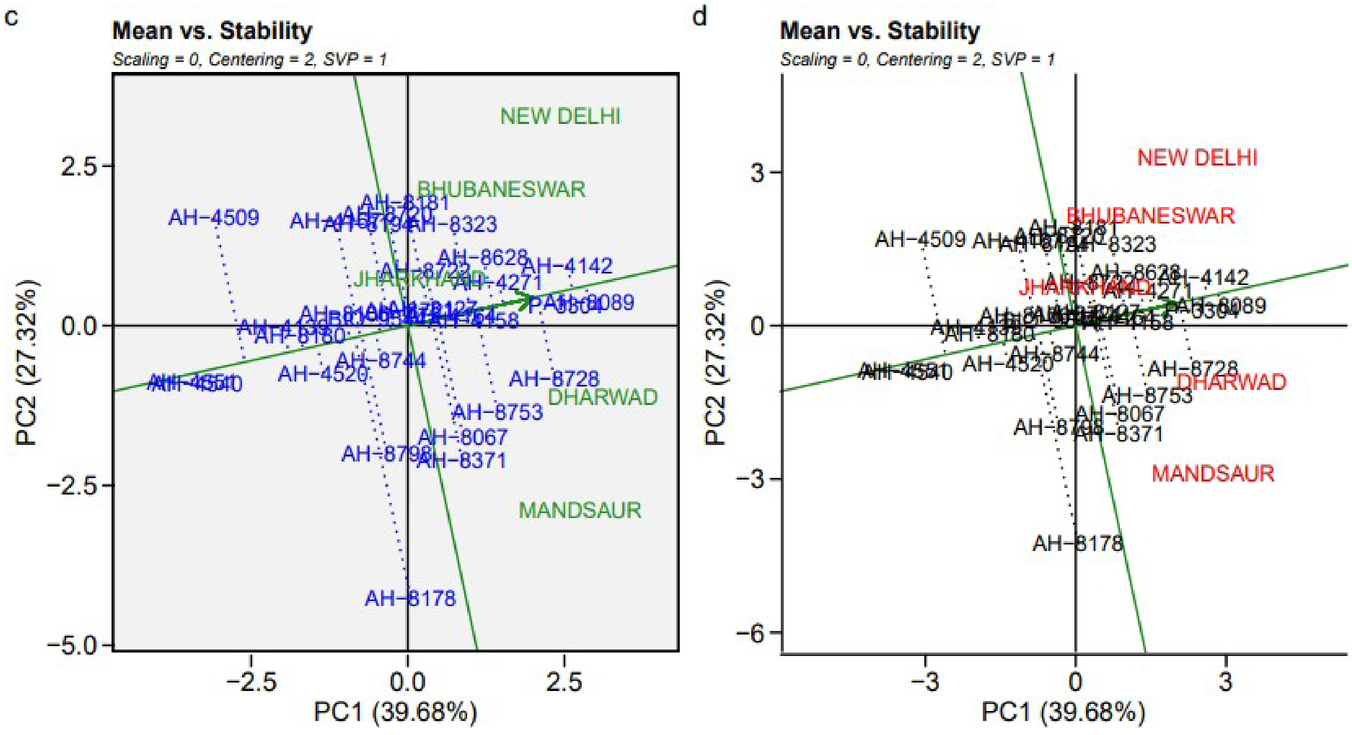

Fig. 4. Thirty field corn hybrids are depicted in vector form on a GGE-biplot graph with regard to the average environment coordinate (ACE)

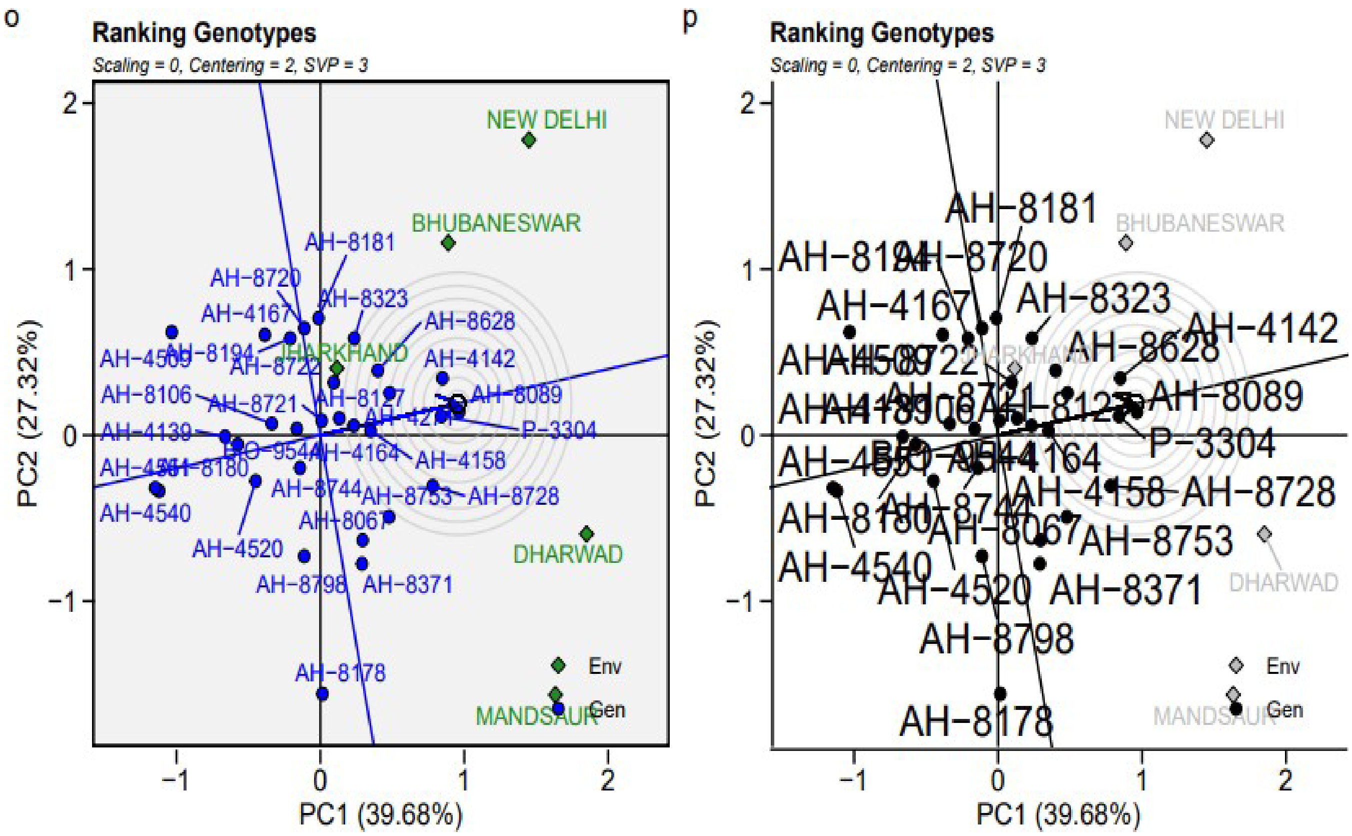

Fig. 5. Ranking of superior performing field corn hybrids in five tested environments

Table 3. Top performing hybrids based on mean yield among thirty field corn hybrids in each environment

S. No.	Bhubaneswar		Dharwad		Jharkhand		Mandsaur		New Delhi	
1	AH-8127	6.89	AH-8728	9.44	AH-8628	7.42	AH-8178	8.62	AH-4142	10.36
2	AH-8194	6.87	AH-8089	8.37	AH-8720	7.37	AH-4142	8.17	AH-4271	10.13
3	AH-8628	6.65	AH-8371	8.22	AH-8722	7.33	AH-8753	8.10	AH-4158	9.60
4	AH-8728	6.57	AH-8721	7.58	AH-8194	7.08	AH-8067	7.91	AH-8089	9.48
5	AH-8722	6.27	AH-8722	7.57	AH-4142	7.06	AH-8798	7.90	AH-4164	9.23
Check 1	BIO 9544	4.97	BIO 9544	7.34	BIO 9544	7.10	BIO 9544	4.82	BIO 9544	7.29
Check 2	P-3304	6.07	P-3304	8.14	P-3304	5.91	P-3304	7.12	P-3304	9.28
MEAN		5.28		6.37		6.50		6.15		7.91
MAX		2.38		2.80		5.58		2.11		4.16
MIN		7.34		9.76		7.78		9.50		11.11
SD		1.11		1.80		0.62		1.80		1.60

Then, we may further rank the hybrids based on whether or not they are included in the concentric rings along the arrowhead and how far away they are from the arrowhead in the ordinate. The hybrid AH-8127 is nearer to the ideal line and hence can be considered as a reference hybrid for the evaluation, while, AH-4551, AH-8089, AH-8180, AH-4540, and AH-8744 can be considered as better hybrids due to their closeness to the circle. These hybrids can be further evaluated for grain yield. The biplot ranking of the 30 hybrids was AH-8127> AH-4551> P-3304 >AH-8089 >AH-8180 >AH-4540. Similar to Yan (2002), the value of a hybrid may be judged by how near it is to the reference hybrid. The comparison of the mean grain yield ranking and stability biplot ranking is presented in Supplementary Table S4.

Discriminativeness vs. representativeness

The ideal environment for testing would pursue twin objectives of discriminativeness (the capacity of an environment to identify a certain genotype) and representativeness (the capability of one environment to represent all other tested environments) for genotypes. Environments showing short vectors imply that all genotypes function similarly and consequently reveal little information regarding genotypic differences. On the other hand, long-vector environments are more discriminatory among hybrids. Dharwad, New Delhi, and Mandsaur environments possessed long vectors, so these environments indicate high discriminativeness for the hybrids (Fig. 6). However, to select better hybrids, the ideal environment should have a long vector that makes a smaller angle with the AEC abscissa line (Oladosu et al. 2017). As the Dharwad environment possessed these ideal characteristics, it is considered the best environment. On the same logic, New Delhi and Mandsaur having long vectors and possessing greater angles can also be considered ideal environments. When compared to the AMMI biplot, the discriminativeness vs. representativeness perspective of the GGE biplot is more useful for evaluating the environment.

The same holds true for an environment that may effectively be able to select better hybrids. A Discriminative vs. Representative GGE biplot has been used to examine and assess the discriminating ability and favorability of the environments by Bishwas et al. (2021) and Kendal (2019).

Environment-specific hybrids based on mean yield

From the mean yield, five top-performing environments-specific hybrids are presented in Table 3 to understand the potential of those high-yielding hybrids comparatively with checks. The hybrid, AH-8127 (6.89 t ha^{-1}) showed a higher yield in the environment of Bhubaneswar followed by AH-8194 (6.87 t ha^{-1}), AH-8628 (6.65 t ha^{-1}), AH-8728 (6.56 t ha^{-1}) and AH-8722 (6.27 t ha^{-1}) in comparison to checks, P-3304 (6.07 t ha^{-1}) and Bio 9544 (4.97 t ha^{-1}). In Dharwad, AH-8728 (9.44 t ha^{-1}), AH-8089 (8.37 t ha^{-1}) and AH-8371 (8.22 t ha^{-1}) recorded higher grain yield in comparison to checks Bio-9544 (7.33 t ha^{-1}) and P-3304 (8.14 t ha^{-1}) (Table 3). Similarly, in Jharkhand, AH-8628 (7.42 t ha^{-1}), AH-8720 (7.37 t ha^{-1}), AH-8722 (7.33 t ha^{-1}), AH-8194 (7.08 t ha^{-1}) and AH-4142 (7.06 t ha^{-1}) were promising for grain yield compared to checks, Bio 9544 (7.10 t ha^{-1}) and P-3304 (5.90 t ha^{-1}).In New Delhi, AH-4142 (10.35 t ha^{-1}) followed by AH-4271 (10.12 t ha^{-1}), AH-4158 (9.59 t ha^{-1}), AH-8089 (9.47 t ha^{-1}), AH-4164 (9.23 t ha^{-1}) were high yielding than both the checks Bio-9544 (7.29 t ha^{-1}) and P-3304 (9.27 t ha^{-1}) respectively (Supplementary

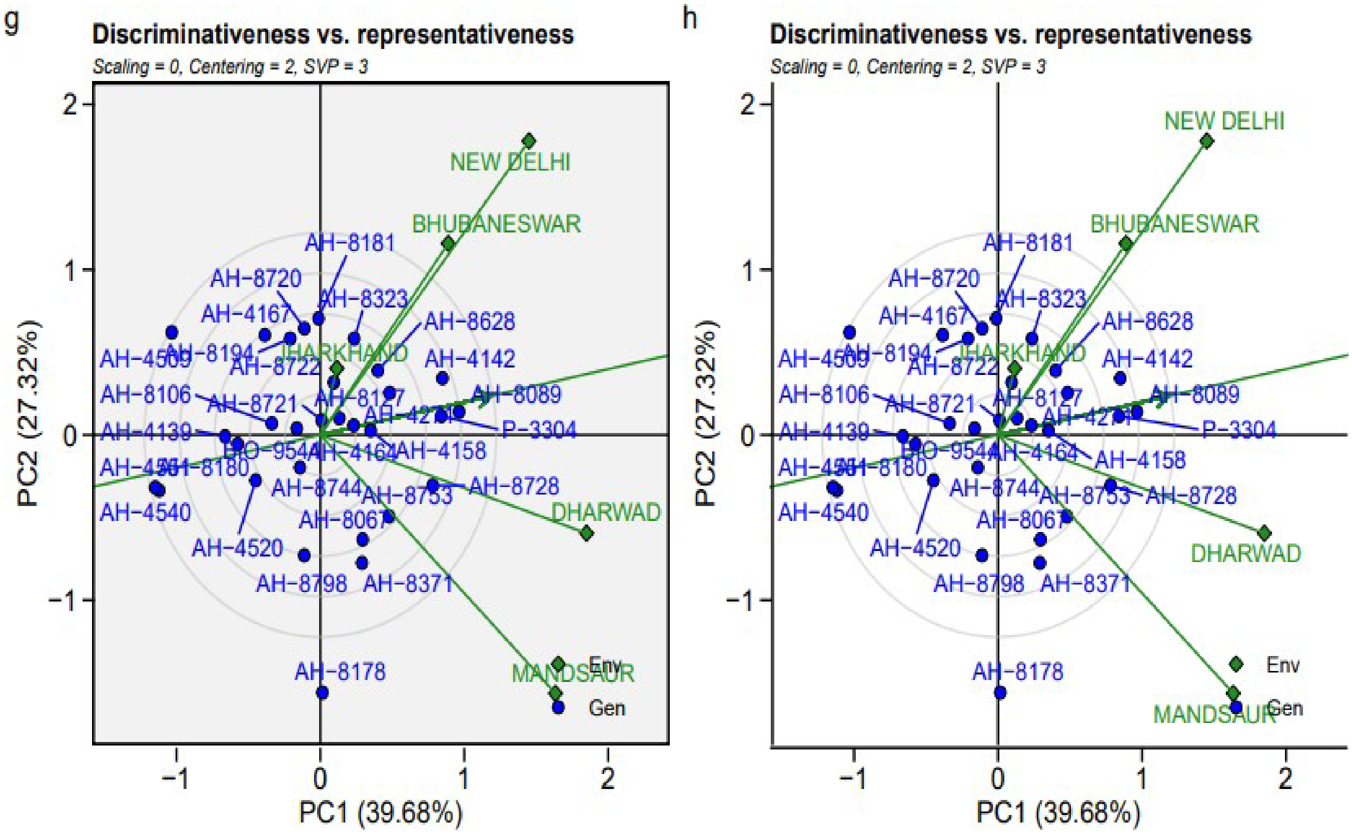

Fig. 6. Discriminativeness vs. representativeness of thirty field corn hybrids

Fig. S3). For many crops, acceptable yields have necessitated targeting narrowly adapted genotypes to several different, well-defined mega-environments. A cultivar/hybrid grown outside its mega-environment frequently suffers yield reductions. Furthermore, even if the breeding goal is a wide adaptation, the best strategy could be to identify several mega-environments and place a test environment in each to select for wide adaptation. Nevertheless, despite breeders' strong interests in interactions and specific adaptations, one can question whether they have routinely had adequate statistical tools to exploit interactions aggressively and to grasp the inevitable implications for identifying mega-environments (Gauch and Zobel 1997).

Hence, the combination of analytical methods plays a major role in the identification and selection of hybrids that exhibit superior performance in specific environments by analyzing and comparing data from multiple environments. The superiority of the hybrids can be further investigated by understanding their adaptability and stability across diverse environments through different statistical approaches. If a particular hybrid is found promising in a given analysis, it should be rechecked through multiple statistical analyses to understand the persistent superiority of the genotypes under selection.

In this study, the yield of thirty elite field corn hybrids was investigated in five diverse corn-growing regions. All five environments had significantly positive PC values. Based on the low YSI, hybrids such as AH-8089, followed by AH-4142, are considered to be more stable hybrids and hence suitable for all five environments. Hence, more than one statistical approach and a combination of analytical methods are required for the identification of the best genotype *vis-a-vis* target environments.

Supplimentary material

Supplimentary Tables S1 to S4 and Supplimentary Figures 1 to 3 are presented and can be accessed at www.isgpb.org

Author's contributions

Conceptualization of research (GM, JSB, RNG); Designing of the experiment (GM, JSB); Contribution of experimental materials (GM, JSB); Execution of field/lab experiments and data collection (RS, SK, DS, KKS, KS, CP); Analysis of data and interpretation (GM, KVG); Manuscript preparation (GM, JSB, RNG, and KVG).

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Supplementary Table S1. Brief description of the five tested environments

S. No	Environment	State	Agroclimatic Zone	Soil Order	Altitude (m.a.m.s.l.)	Rainfall (mm)	Sunshine hour (hr.)	R.H. (%)
1	Bhubaneswar	Odisha	East & East Coastal Plain Zone	Alfisol	58	1492	8.2	84
2	Barhi	Jharkhand	The South-Eastern Plateau Zone	Entisols	374	248	8.3	79
3	Dharwad	Karnataka	The Deccan Interior Region	Vertisols	750	838	6.0	82
4	Mandsur	Madhya Pradesh	The Maharastra Plateau Region	Vertisols	442	657	6.5	76
5	PUSA	New Delhi	The Aravali-Malwa Upland	Inceptisols	228	653	9.2	78

Supplementary Table S2. Details of thirty field corn hybrids grown in five tested environments

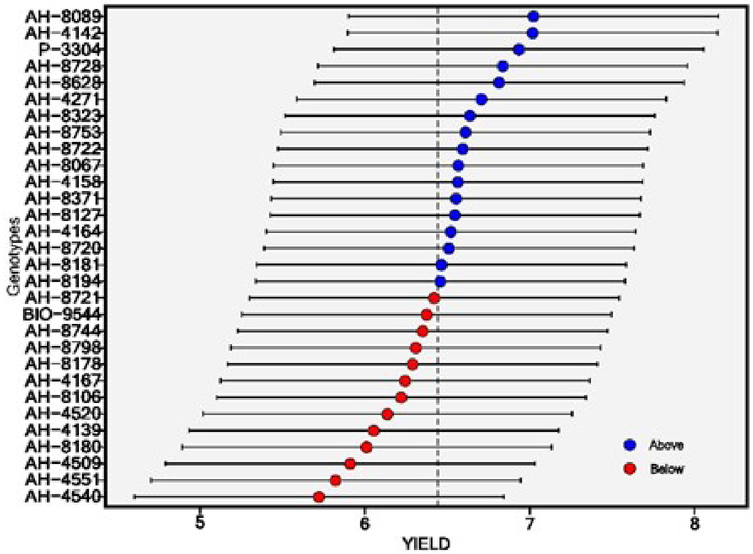
S. No	Hybrids	Pedigree	S.No	Hybrids	Pedigree
1	AH-4139	AI 543 × AI 542	16	AH-8180	DIM 312 × PDI 1513
2	AH-4142	AI 546 × AI 542	17	AH-8181	DIM 302 × PDI 638
3	AH-4158	AI 541 × AI 542	18	AH-8194	DIM 334 × PDI 639
4	AH-4164	RNG 2 × AI 542	19	AH-8323	DDM 207 × PDI 639
5	AH-4167	RNG 143 × AI 542	20	AH-8371	PDM 4131 × PDI 1513
6	AH-4271	AI 544 × AI 542	21	AH-8628	DIM 342 × PDI 638
7	AH-4509	AI 507 × AI 544	22	AH-8720	D 23 × PDI 1513
8	AH-4520	AI 510 × AI 540	23	AH-8721	D 24 × PDI 638
9	AH-4540	AI 514 × AI 545	24	AH-8722	D 24 × PDI 639
10	AH-4551	AI 518 × AI 541	25	AH-8728	D 36 × PDI 639
11	AH-8067	CDM 1330 × PDI 638	26	AH-8744	D 44 × PDI 1513
12	AH-8089	CDM-318 × PDI 639	27	AH-8753	D 55 × PDI 1513
13	AH-8106	DDM-309 × PDI 638	28	AH-8798	D 92 × PDI 1513
14	AH-8127	DIM-310 × PDI 638	29	Bio-9544	National check
15	AH-8178	DIM-312 × PDI 638	30	P-3304	Commercial check

Supplementary Table S3. Mean grain yield of thirty field corn hybrids which were tested in five environments

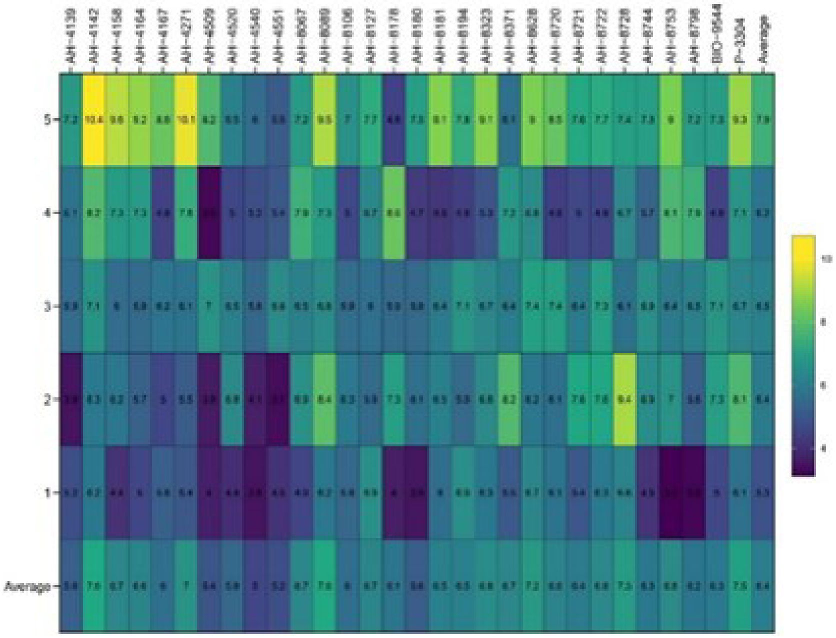
S. No.	Hybrids	Mean Yield
1	AH-8089	7.63
2	AH-4142	7.62
3	P-3304	7.45
4	AH-8728	7.25
5	AH-8628	7.21
6	AH-4271	6.99
7	AH-8323	6.84
8	AH-8753	6.79
9	AH-8722	6.75
10	AH-8067	6.70
11	AH-4158	6.69
12	AH-8371	6.67
13	AH-8127	6.66
14	AH-4164	6.61
15	AH-8720	6.58
16	AH-8181	6.49
17	AH-8194	6.48
18	AH-8721	6.40
19	BIO-9544	6.31
20	AH-8744	6.26
21	AH-8798	6.17
22	AH-8178	6.13
23	AH-4167	6.04
24	AH-8106	5.99
25	AH-4520	5.82
26	AH-4139	5.65
27	AH-8180	5.56
28	AH-4509	5.36
29	AH-4551	5.17
30	AH-4540	4.97

Supplementary Table S4. Comparison of the mean grain yield ranking and stability biplot ranking of thirty field corn hybrids

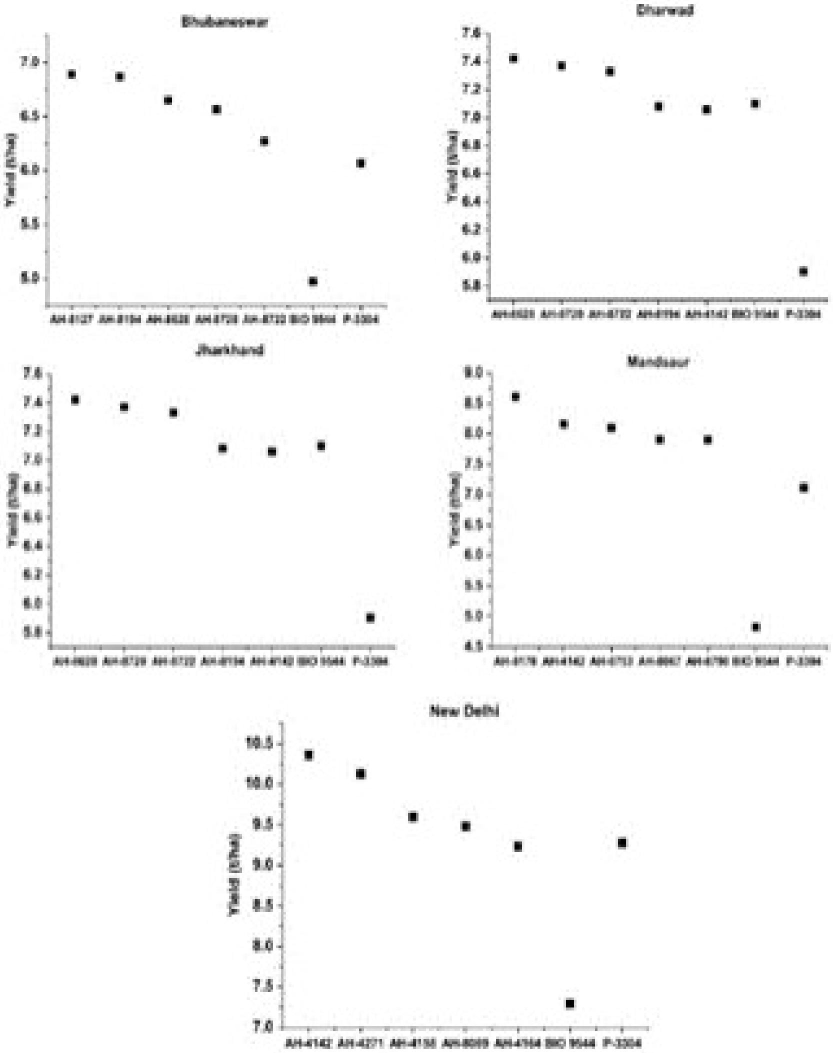
Hybrid rank	Mean Yield of Ranking	Stability Biplot Ranking
1	AH-8089	AH-8127
2	AH-4142	AH-4551
3	P-3304	P-3304
4	AH-8728	AH-8089
5	AH-8628	AH-8180
6	AH-4271	AH-4540
7	AH-8323	AH-8744
8	AH-8753	AH-8628
9	AH-8722	AH-8106
10	AH-8067	AH-4520
11	AH-4158	AH-4139
12	AH-8371	AH-8721
13	AH-8127	BIO-9544
14	AH-4164	AH-8323
15	AH-8720	AH-4158
16	AH-8181	AH-4164
17	AH-8194	AH-4142
18	AH-8721	AH-8722
19	BIO 9544	AH-8720
20	AH-8744	AH-4167
21	AH-8798	AH-8067
22	AH-8178	AH-8181
23	AH-4167	AH-8194
24	AH-8106	AH-4271
25	AH-4520	AH-8753
26	AH-4139	AH-8798
27	AH-8180	AH-8728
28	AH-4509	AH-4509
29	AH-4551	AH-8371
30	AH-4540	AH-8178



Supplimentary Fig. 1. Ranking of 30 field corn hybrid based on BLUP of grain yield among the tested environments



Supplimentary Fig. 2. Heat map of average grain yield of 30 field corn hybrids tested in five environments



Supplimentary Fig. 3. Comparison of top five field corn hybrids with respective checks in five tested environments