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Stability models regulate the adaptation of male sterility-based chilli hybrids for agro-ecologically diverse regions of north-western Himalayas

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Chilli cultivars are highly sensitive to diverse agroclimatic conditions and the present investigation provide a significant contribution by identifying high-yielding and stable hybrids for wider adaptation. The study was conducted in seven diverse environments by following conventional farming under field conditions in five locations of North-western Himalaya along with naturally ventilated polyhouse conditions using conventional and natural farming practices using 16 genotypes to identify the most stable ones for fruit yield and its attributes. Joint regression and AMMI analysis revealed significant Genotype × Environment interaction for all the traits. Eberhart and Russel (E-R) model revealed DPCHYB 10 (627.68 g/plant) and DPCHYB 5 (583.50 g/plant) as top ranked with stability for fruit yield. The AMMI1 biplot identified DPCHYB 2 as most resilient and productive across environments for fruit number and fruit yield which was also described by mean vs. stability biplot of GGE. Further, GGE suggested E5 (Berthin) as the most representative and discriminating environment for fruit yield. 'Which won where' biplot represented hybrid DPCHYB 10 as stable and high yielding with wider adaptability in most of the environments except Palampur (E1). DPCHYB 5 was the most responsive and adaptive in E1 that was also depicted as stable by E-R.

Keywords Eberhart and Russell, AMMI, GGE biplots, Mega environments, Stability, Adaptability, Male sterility

Chilli (*Capsicum annuum* L. var. *annuum*) is known for its delicious and pungent taste and is a major spice crop worldwide particularly in tropical Asia and equatorial America[1]. It is consumed fresh or in dried forms and is the second most significant solanaceous vegetable after tomato. It is originated from South and Central America having chromosome number 2n = 2x = 24 and genome size of 3.48Gb[2]. It is a rich source of vitamin C, carotenoids, capsaicinoids, and capsinoids which have potential applications in cosmeceutical, food, spice, and pharmaceutical industries[1,3]. Capsaicin is the major cause of pungency in chilli which have varied preventive and beneficial uses in medicines (allopathic and ayurveda) and defence weapon industry[3,4]. Chilli is also known as hot pepper, paprika, red peppers, cayenne peppers, pimento, and capsicum in different parts of the world[5], and is cultivated over an area of 2.06 million ha with a total production of 38.3 million tons and average productivity of 18.59 t ha^{-1}[6].

It is a vital constituent of Indian cuisine and valuable cash crop which is cultivated over an area of 419 thousand hectares with production of 4436 thousand MT with productivity of 10.59 MT/ hectare[7] during summer-rainy season as rainfed crop and during autumn/spring-summer season under irrigated conditions[8]. India is the largest exporter of chilli globally with a share of 30% of its total production and has exported 2,732 metric tonnes of green chillies worth 234.5 million USD in 2023-24[9]. A considerable loss to chilli production is recorded due to its inherent sensitivity to environmental fluctuations[10]. The productivity of chilli can be enhanced in the shortest span of time by adopting hybrids which in general are uniform for different attributes

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along with resistance to various biotic and abiotic stresses. Male sterility is a crucial mechanism for controlled pollination and is widely exploited in commercial hybrid seed production of chilli. More than twelve monogenic recessive male sterile mutants have been discovered from natural sources and mutagenesis techniques[11].

Genotype-environment interaction (GEI) is a major concern and can seriously destabilize efforts to select superior genotypes[12]. It is, therefore, essential to identify phenotypically stable genotypes with wider adaptability to varied climatic conditions across environments[13]. Such stable genotypes can be commercial exploited as they find favour by the farmers on account of high productivity vis-à-vis economic returns. It will further help in extenuating future worries viz., climate change, declining natural resources, and varied biotic and abiotic concerns etc. Multi-Environment Trials (MET) are conducted to evaluate advanced breeding lines or hybrids to regulate their stability and adaptability before recommendation for cultivation.

The assessment of GEI provides an idea of buffering potential of the population. The main result of GEI interaction would be to significantly reduce the influence of environment on the final appearance of plants[14]. A genotype with low GEI (stable) possesses a little or no change in the performance regardless of the weather vagaries. GEI reduces the predictability of genotypes performance in target environments. One of the major factors in plant breeding is the selection of appropriate test locations because it accounts for GE and maximizes gain from selection[15]. It is, therefore, necessary to evaluate varieties/ hybrids in multilocation to identify the most promising ones based on the parameters of stability and adaptability[16]. The identification of stable and high yielding cultivars/hybrids by the partitioning of genotype, environment, and GEI using various statistical tools forms the main objective of MET data analysis[17].

A single stability model may not be representative to regulate the performance of hybrids over the environments and may lead to inconsistent conclusions about their stability. There are three groups of stability parameter namely, one associated only with yield and has least information on stability, second consider yield and stability simultaneously (AMMI, GGE biplot) while third group focus on stability and show little/no association with yield (joint regression analysis of Eberhart and Russel[18]. Earlier, the Eberhart and Russell[18] regression model has been extensively used to assess linear (regression, bi) and nonlinear (deviation from regression, $S^{-2}di$) components of GEI variation with independent response and considers both yield and stability with prediction of a particular genotypes for specific environments[18]. The stability of genotypes cannot reliably be predicted from this approach because it considers response of genotype to environment to be univariate issue which is otherwise a multivariate situation.

The AMMI biplot is a valuable tool for identifying stable and high-performing genotypes across varying environments. The AMMI offers various elucidations and information by dividing the main effect and interaction effects[19], and is relatively effective for expecting G × E interaction[20]. Identification of site-specific genotypes following AMMI needs authentication of yield of the genotypes[21] and mainly focusing G × E interaction and ignore main effects of genotypes. Yan et al.[22] developed a biplot technique that was named as GGE biplot that graphically represents the main effect of genotype and, Genotype × Environment (G + G×E or GGE) effects and is an efficient method based on principal component analysis (PCA) to fully explore multi-environment trial data. The most interesting aspect of the GGE biplot is its ability to represent the 'Which-won-where' pattern of a genotype by environment data set. The genotypes in the GGE biplots that fall on the vertices of the polygons represent their degree of performance in a specific environment[15]. The earlier researchers have also employed these different models to predict stability and adaptability of chilli genotypes/hybrids in different growing conditions across globe[23–27]. Keeping these aspects in view, the present investigation was planned with objectives to compare the effectiveness of the Eberhart and Russell joint regression model, AMMI, and GGE biplot analysis to identify high yielding and stable GMS based chilli hybrids. This will simultaneously help to recommend hybrids for cultivation with least influence of climate fluctuations and better adaptation to biotic and abiotic stresses.

Materials and methods

Experimental material and layout plan

The present investigation was carried out involving 12 chilli hybrids and four checks (Table 1) which were evaluated at seven diverse environments during summer 2021 viz., field conditions at the Research Farm of the Department of Vegetable Science and Floriculture, College of Agriculture, Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya, Palampur (E1), conventional farming under polyhouse conditions at Palampur (E2), natural farming under polyhouse conditions at Palampur (E3), field conditions at Bajaura (E4), Berthin (E5), Mandi (E6) and Dhaulakuan (E7). The characteristics of the different environments and soil properties are presented in Table 2 that clearly depicts the varied agro-climatic conditions of different locations, situated at an elevation of 468 m to 1290 m above mean sea level with humid temperate to sub-tropical climatic conditions. The soil texture varied from clay to sandy clay loam while soil reaction varied from slightly acidic (5.6) to neutral (7.1) with medium organic carbon, N, P and K contents in the soil of the respective environments. The weather data across the environments has been presented in Fig. 1 which clearly revealed diversity in temperature, rainfall, and humidity in the respective environments. E2 and E3 represent cultivation of chilli under naturally ventilated polyhouse conditions and hence the crop had not received direct rainfall.

The experimental material was sown in the nursery bed of size 3 m × 1 m × 15 cm and seedlings were ready for transplanting in about eight weeks after seed sowing in the respective environments. The seedlings of the respective hybrids and check genotypes were laid out in Randomized Complete Block Design with three replications at each location by transplanting as detailed in Table 3. Each genotype was planted in 1.8 m × 1.8 m plots consisting of 16 plants in each replication with inter and intra row spacing of 45 cm × 45 cm, respectively.

S.No.	Genotypes‡	Pedigree
1	DPCHYB 1	GMS 9 – 2× DPCH 10
2	DPCHYB 2	GMS 9 – 2 ×DPCH 40
3	DPCHYB 3	GMS 11 – 2 ×VVG
4	DPCHYB 4	GMS 29 – 2 ×VVG
5	DPCHYB 5	GMS 29 – 2 ×DPCH 10
6	DPCHYB 6	GMS 29 – 2 ×DPCH 40
7	DPCHYB 7	GMS 9 – 2× VVG
8	DPCHYB 8	GMS 9 – 2× DPCH 38
9	DPCHYB 9	GMS 11 – 2 ×DPCH 10
10	DPCHYB 10	GMS 26 – 1 ×PBC 535
11	DPCHYB 11	GMS 26 – 1× DPCH 27
12	DPCHYB 12	GMS 9 – 2 × DPCH 101
13	Him Palam Mirch 1	Open pollinated variety, recommended for Himachal Pradesh (state check variety)
14	Him Palam Mirch 2	Open pollinated variety, recommended for Himachal Pradesh (state check variety)
15	Surajmukhi	Open pollinated variety, recommended for Himachal Pradesh (state check variety)
16	CH-27†	Hybrid, national check

Table 1. List of genotypes along with their pedigree. † denotes the source as PAU Ludhiana, Punjab, while genotypes without a symbol developed at CSKHPKV Palampur.

Location	Elevation (m)	Latitude/longitude	Climate	pH	Texture	Bulk density (Mgm^{-3})	OC (%)	N (kg/ha)	P (kg/ha)	K (kg/ha)
Palampur (Kangra)	1290	32^0 6′ N and 76^0 3′ E	Humid temperate	5.7	Clay loam	1.31	0.68	248	13.5	136.5
Bajaura (Kullu)	1089	31°8’ N and 77° E	Sub-humid temperate	6.3	Silt Loam	1.34	0.73	305	22	195
Berthin (Bilaspur)	645	31°2’ N and 76° 4′ E	Sub-tropical	7.1	Loam	1.35	0.65	290	18	185
Sundernager (Mandi)	861	31°5’ N and 76° 9′ E	Sub-humid temperate	6.9	Sandy clay Loam	1.32	0.62	310	20	203
Dhaulakuan (Sirmaur)	468	$30^0$4′ N and 71^0 5′ E	Sub-tropical	6.7	Sandy loam	1.34	0.63	295	21	190

Table 2. Characteristic features of different environments and soil properties.

Cultural practices

A three-disc tractor was used to plough the field under field conditions followed by a tractor-driven rotavator while soil in the polyhouse was prepared using power tiller under both conventional and natural farming systems. The appropriate amount of well-rotten farmyard manure @ 20 tonnes per hectare was mixed into the soil during field preparation. The fertilizers were administered at 75: 60: 60 kg N, P_2O_5 and K_2O per hectare, with half of the required N, full P_2O_5 and K_2O applied at transplanting time and the remaining N applied in two equal splits at one-month intervals. Under field conditions, irrigation was used one week before planting and shortly after transplanting to ensure optimal plant establishment in the soil and then every 7–10 days intervals until the monsoon arrived. On the other hand, drip irrigation system was used to apply water under polyhouse conditions at every alternate day. To keep the fields weed-free, three manual weedings were performed at 3–4 weeks intervals under field conditions.

Natural farming practice includes the application of *Ghanjeevamrit* (made from Indian cow dung, cow urine, gram flour, soil, and Jaggery in 10:5:1:1:1) @ 250 kg/ha by incorporating in the soil at the time of transplanting and subsequently during the flower initiation stage. Moreover, a 10% *Jeevaamrit* solution (dissolving 1 kg *Ghanjeevamrit* in 10 L of water) was sprayed after three weeks regularly until the last harvest.

Data recording and statistical analysis

The observations were recorded on five competitive plants selected randomly from each entry over the replications for nine traits *viz.*, days to flowering, days to first harvest, primary branches per plant, plant height (cm), fruit length (cm), fruit diameter (cm), green fruits per plant (number), green fruit yield per plant (g), and harvest duration (days).

The pooled analysis of variance was undertaken after examining the homogeneity of experimental errors following Bartlett's test using SAS v.9.1 software.The analysis of the stability performance of genotypes under different environments was done as per the model suggested by Eberhart and Russell[18]following OPSTAT by PAU Ludhiana and DOSBox 0.74-3 by TNAU. The AMMI and GGE biplots were constructed using the basic model of Gauch[28] and Yan and Kang[29] using Eigen vector distance matrix through software R-Package version 4.3.2[22,30].

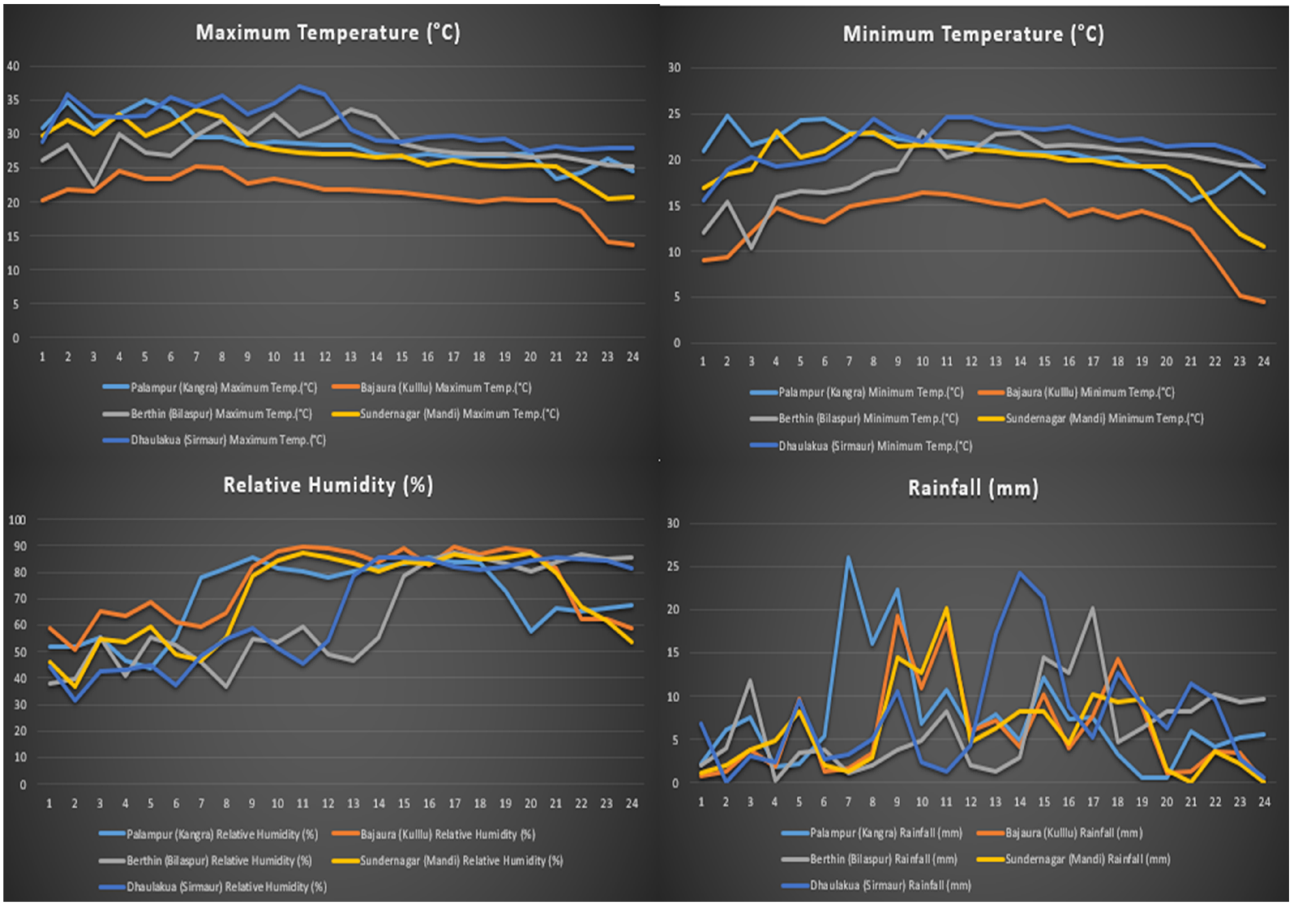

Fig. 1. Maximum temperature, minimum temperature, relative humidity and rainfall of all environments during growing season at different locations.

Sr. No.	Environment/Location	Date of nursery sowing	Date of Transplanting
1	E1- Vegetable Research Farm, Palampur, Kangra	26/02/2021	06/05/2021
2	E2- Natural ventilated polyhouse, Vegetable Research Farm, Palampur, Kangra (Conventional farming)	26/02/2021	20/05/2021
3	E3- Natural ventilated polyhouse Vegetable Research Farm, Palampur, Kangra (Natural farming)	26/02/2021	12/05/2021
4	E4- HAREC, Bajaura, Kullu	05/05/2021	14/06/2021
5	E5- KVK, Berthin, Bilaspur	20/02/2021	06/04/2021
6	E6- KVK, Sundernagar, Mandi	31/03/2021	20/05/2021
7	E7- HAREC, Dhaulakuan, Sirmaur	05/03/2021	20/04/2021

Table 3. Date of nursery sowing and transplanting of hybrids at different environments/locations.

Results

Analysis of variance and mean performance

The analysis of variance (Supplementary Table S1) for individual environments revealed that the mean sum of squares due to genotypes were significant for majority of the traits across environments except days to flowering at Bajaura (E4) indicating differences in the performance of different hybrids for yield and yield attributes irrespective of the impact of environments. The mean performance of different hybrids (Supplementary Table S2 to S10) showed a considerable variation for yield and yield related traits that construed enormous scope for improvement of chilli. Hybrid DPCHYB 10 consistently performed as top ranked for fruit yield in most of the environments except E1 with average fruit yield of 627.68 g per plant across environments with an advantage of 66.11% over the best yielding check variety Him Palam Mirch 2 (377.86 g). DPCHYB 5 recorded maximum fruit yield in E1 with mean fruit yield of 583.50 g over environments. Both these hybrids significantly superseded remaining hybrids and check varieties/hybrid (S-A8). The other hybrids viz., DPCHYB 12, DPCHYB 8 and DPCHYB 6 got ranking among top five hybrids for green fruit yield. The correlation between weather parameters and fruit yield revealed a positive linear relationship between mean yield and average maximum/minimum

Component	Relative humidity	Minimum temperature	Maximum temperature
Minimum temperature	−0.89		
Maximum temperature	−0.90	0.98	
Fruit yield per plant	−0.36	0.32	0.21

Table 4. Correlation of weather conditions with fruit yield (Pooled over environments).

Sr. No	Component	df	Days to flowering	Days to first harvest	Number of primary branches per plant	Plant height (cm)	Fruit length (cm)	Fruit diameter (cm)	Fruits per plant	Green fruit yield per plant (g)	Harvest duration (days)
1	Genotypes	15	27.37^{*+}	49.95^{*+}	0.45	1059.43^{*+}	16.09^{*+}	0.14^{*+}	2726.28^{*+}	68556.00^{*+}	98.63^{*+}
2	Environments	6	1170.66^{*+}	1338.63^{*+}	14.71*+	25536.64^{*+}	0.16	0.10^{*+}	7947.37^{*+}	139424.32^{*+}	381.85^{*+}
3	G × E	90	6.20*	9.77*	1.23*+	284.69*	0.38*	0.003*	314.31*	2742.35*	17.84*
4	Environments + G × E	96	78.98^{*+}	92.82^{*+}	0.48	1862.93^{*+}	0.36*	0.01^{*+}	791.37^{*+}	11284.97^{*+}	40.59^{*+}
5	Environments (Linear)	1	7024.00^{*+}	8031.81^{*+}	2.07*+	153219.87^{*+}	0.98^{*+}	0.64^{*+}	47684.25^{*+}	836546.00^{*+}	2291.12^{*+}
6	G × E (Linear)	15	8.76*	12.47*	88.27*+	1136.65^{*+}	0.37*	0.003*	561.02^{*+}	3066.96*	17.56*
7	Pooled deviation (Non-Linear)	210	5.34*	8.65*	0.33	107.15*	0.35*	0.003*	248.41*	2510.08*	16.77*
8	Pooled error	335	2.69	3.28	0.48	18.36	0.09	0.0009	20.39	60.94	8.04

Table 5. Joint regression analysis (Eberhart and Russel model) of variance for different yield attributes. * Significant at $p = 0.05$ when tested against pooled error; $^{+}$ significant at $p = 0.05$ when tested against pooled deviation.

temperature (Table 4) while it was negative with relative humidity indicating the adverse effect of humidity on fruit yield.

Join regression analysis

The results of joint regression analysis proposed by Eberhart and Russell[18] revealed that the mean sum of squares due to genotypes and environments were significant for most of the traits exceptnumber of primary branches per plant (Table 5). The mean sum of squares due to GEI were significant for all the traits. Combined environment and genotype × environment interaction [E + (G × E)] variance when tested against pooled error and pooled deviation construed the significance for majority of the traits except number of primary branches. G × E (linear) found to be significant for all the traits when tested against pooled error mean sum of squares directing to proceed for stability analysis.

Individual regression analysis and estimation of stability parameters of individual genotypes

The genotypes *viz.*, DPCHYB 2, DPCHYB 4, and DPCHYB 5 were stable both for early flowering and first fruit picking across the environments along with DPCHYB 7 and DPCHYB 10 for flowering and DPCHYB 1 and DPCHYB 6 for first picking with average response (b_i=1) and non-significant deviation from regression ($S^2d_i = 0$) [Table 6]. In contrary, DPCHYB 6 for early flowering and DPCHYB 11 for first harvest had regression coefficient value more than one (1.10) indicating better response under favourable conditions while DPCHYB 12 for both these traits and DPCHYB 1 for flowering revealed regression coefficient less than one indicating their better response under unfavourable environments. The hybrids DPCHYB 8 and DPCHYB 9 for fruit length (Table 6) and that of DPCHYB 1, DPCHYB 2, DPCHYB 5, DPCHYB 6, DPCHYB 11 and DPCHYB 12 for harvest duration (Table 7) demonstrated stable and predictable performance ($S^2{}_{di} = 0$ and $b_i = 1$). In contrast, hybrids namely, DPCHYB 1, DPCHYB 2, DPCHYB 3, DPCHYB 5, DPCHYB 6, DPCHYB 10 and DPCHYB 11 for fruit length, DPCHYB 8 for fruit diameter (Table 6), DPCHYB 1, DPCHYB 3, DPCHYB 4, DPCHYB 12, Him Palam Mirch 1 and Him Palam Mirch 2 for primary branches, DPCHYB 3, DPCHYB 5, DPCHYB 9 and DPCHYB 10 for plant height, and DPCHYB 7 and DPCHYB 8 for harvest duration (Table 7) had significant deviation from regression pointing towards their unpredictable performance. Besides, DPCHYB 4, DPCHYB 7 and DPCHYB 11 for plant height and DPCHYB 10 for fruit diameter revealed better response under favourable conditions ($b_i > 1$) whereas, DPCHYB 1 and DPCHYB 8 for plant height, and DPCHYB 9 for harvest duration had better response under unfavourable environments ($b_i < 1$).

All hybrids exhibited significant deviations from the regression ($S^2{}_{di} = 0$) for green fruits per plant and green fruit yield indicating unpredictable performance (Table 7). However, based on regression coefficient (b_i), hybrids namely, DPCHYB 2, DPCHYB 5 and DPCHYB 8 for both fruit number and fruit yield, DPCHYB 4, DPCHYB 6 and DPCHYB 8 for fruits per plant and DPCHYB 1, DPCHYB 10 and DPCHYB 12 for green fruit yield showed average response (b_i=1) indicating stable performance. Further, DPCHYB 12 for green fruits per plant and DPCHYB 6 for green fruit yield with b_i>1 indicating their suitability under favourable environmental conditions. On the other hand, four genotypes viz., DPCHYB 8, DPCHYB 10, DPCHYB 11 and Surajmukhi

Genotypes	Days to flowering			Days to first harvest			Fruit length (cm)			Fruit diameter (cm)		
	Mean	b_i	S^{-2}_{di}	Mean	b_i	S^{-2}_{di}	Mean	b_i	S^{-2}_{di}	Mean	b_i	S^{-2}_{di}
DPCHYB 1	50.00	0.88 ± 0.05*	0.33	68.95	0.87 ± 0.09	3.33	9.18	3.86 ± 2.79	0.45*	0.87	1.04 ± 0.08	0.0002
DPCHYB 2	47.71	0.99 ± 0.05	0.28	67.48	1.08 ± 0.08	2.46	9.21	0.89 ± 2.18	0.26*	0.86	0.82 ± 0.23	0.002
DPCHYB 3	49.36	1.15 ± 0.12	5.26*	70.81	1.03 ± 0.30	43.03*	8.53	−2.38 ± 3.88	0.90*	0.80	1.06 ± 0.36	0.0054*
DPCHYB 4	48.40	1.13 ± 0.08	1.57	69.71	0.85 ± 0.11	5.28	8.22	3.01 ± 1.46	0.10	0.82	1.18 ± 0.11	0.0004
DPCHYB 5	48.00	1.06 ± 0.11	4.85	68.60	1.09 ± 0.07	1.55	10.26	2.09 ± 2.78	0.45*	0.86	0.77 ± 0.09*	0.0004
DPCHYB 6	49.14	1.10 ± 0.03*	−0.48	69.24	1.11 ± 0.06	0.54	9.66	4.22 ± 1.88	0.19*	0.85	1.32 ± 0.16*	0.001
DPCHYB 7	50.05	0.94 ± 0.07	1.14	71.71	0.87 ± 0.14	8.49*	8.06	−2.79 ± 2.35	0.31*	0.82	1.01 ± 0.18	0.0012
DPCHYB 8	50.26	1.24 ± 0.10*	3.25	68.86	1.00 ± 0.13	7.43*	8.63	2.95 ± 1.21	0.06	0.95	1.38 ± 0.31	0.004*
DPCHYB 9	48.88	1.12 ± 0.12	5.87*	69.31	1.03 ± 0.04	−0.36	9.28	3.97 ± 1.43	0.09	0.86	1.02 ± 0.28	0.0032*
DPCHYB 10	49.05	1.02 ± 0.11	4.49	72.64	1.21 ± 0.19	16.12*	10.99	1.07 ± 2.19	0.26*	1.09	1.63 ± 0.13*	0.0006
DPCHYB 11	49.64	1.04 ± 0.15	8.33*	70.81	1.12 ± 0.04*	−0.28	8.73	1.13 ± 2.30	0.30*	0.89	0.84 ± 0.06*	0.0002
DPCHYB 12	48.88	0.77 ± 0.11*	4.84	70.45	0.87 ± 0.05*	0.16	8.15	1.52 ± 1.33	0.08	0.83	0.98 ± 0.19	0.0014
Him Palam Mirch 1(C)	51.81	0.94 ± 0.09	2.64	72.60	0.88 ± 0.10	4.10	6.22	−2.20 ± 2.46	0.34*	0.80	0.78 ± 0.12	0.0006
Him Palam Mirch 2 (C)	52.02	0.90 ± 0.13	6.21*	72.36	0.93 ± 0.10	3.80	7.28	−2.16 ± 1.91	0.19*	1.07	0.44 ± 0.36	0.0052*
Surajmukhi (C)	55.17	0.71 ± 0.14*	7.69*	76.76	0.72 ± 0.12*	5.67	4.99	2.34 ± 2.11	0.24*	0.86	1.18 ± 0.36	0.0052*
CH-27(C)	52.86	1.00 ± 0.19	14.83*	76.60	1.35 ± 0.20	19.67*	6.77	−1.52 ± 4.17	1.04*	1.34	0.56 ± 0.78	0.0248*
Grand Mean	50.08	1.00		71.06	1.00		8.38	1.00		0.91	1.00	
S.E (m) ±	0.97	0.11		1.24	0.14		0.25	2.49		0.02	0.30	
Critical difference ($P \leq 0.05$)	2.62			2.55			0.49			0.05		

Table 6. Individual regression analysis and estimates of stability parameters for days to flowering, days to first harvest, fruit length (cm) and fruit diameter (cm). *Significant deviation at $P \leq 0.05$; C represents check variety.

were suitable for all the environments with average responsiveness (bi = 1) and non-significant deviation from regression ($S^2_{di} = 0$).

AMMI biplot

The AMMI analysis revealed highly significant effects of environment, genotype, and genotype × environment interaction (GEI) for all the traits (Table 8). Among the sources of variation, environment effects were markedly higher than that of genotype and interaction for days to flowering, days to first harvest, plant height, fruits per plant, fruit yield per plant and harvest duartion. The first two principal components (PC1 and PC2) explained major portion of the total GEI variation for all the traits. The environment and genotype effects were illustrated simultaneously by generating AMMI1 (IPCA1 vs. Mean) and AMMI2 (IPCA2 vs. IPCA1) biplots. The AMMI1 biplot revealed that genotypes namely, DPCHYB 8[8], DPCHYB 2[2], and DPCHYB 4[4] for fruits per plant (Fig. 2A), and DPCHYB 2[2] for fruit yield per plant (Fig. 2B), were the most resilient and highly productive across environments. In contrast, genotypes DPCHYB 9[9] and DPCHYB 11[11] for fruits per plant and Him Palam Mirch 2[14], Surajmukhi[15], and Him Palam Mirch 1[13] for yield per plant, though stable, exhibited low performance and are thus not recommended for selection. Genotypes DPCHYB 12[12], DPCHYB 6[6] and DPCHYB 7[7] for fruits per plant and DPCHYB 10[10], DPCHYB 5[5], DPCHYB 12[12] and DPCHYB 8[8] for fruit yield showed high productivity but were positioned far from the origin and were unstable. DPCHYB 1[1] and Him Palam Mirch-1[13] for fruits per plant were located close to the IPCA1 origin, suggesting general stability across environments. Environments E1 and E6 for fruits per plant, and E1 and E4 for yield per plant showed high additive genotypic main effects, indicating their suitability for discriminating among genotypes.

The AMMI2 biplot for fruits per plant demonstrated that environments E6, E4, E3, E5, and E7 were more stable while E1 and E2 had greater interaction effects (unstable environments) (Fig. 2C). Notable genotype-environment associations included DPCHYB 2[2] and CH 27[16] in E5, E6 and E7, DPCHYB 3[3] in E4, Surajmukhi[15] in E2, DPCHYB 12[12] in E3, and DPCHYB 7[7] in E1were observed. Similarly, AMMI2 biplot for yield per plot indicated that E1 and E6 are located farther away from the biplot origin than environments E3, E4, E5, E2, and E7. DPCHYB 3[3] and DPCHYB 10[10] in E4 and E2, CH 27[16] in E3 and E6, DPCHYB 1[1] and DPCHYB 7[7] in E1, and DPCHYB 12[12] in E5 were found to be the highest yielding genotypes in the respective environments (Fig. 2D). These interactions aid to identify genotypes for targeted environments or recommend those with broader adaptability.

GGE biplot

A short vector indicates that the test environment is unrelated to other environments. The environment vector view of the GGE biplot explained 78.45, 76.57, 75.33, 87.60, 95.09, 95.06, 78.99, 78.63 and 92.67% of the overall GEI variance for days to flowering (Fig. 3A), days to first harvest (Fig. 3B), number of primary branches (Fig. 3C), plant height (Fig. 3D), fruit length (Fig. 3E), fruit diameter (Fig. 3F), green fruits per plant (Fig. 3G), harvest duration (Fig. 3H) and green fruit yield per plant (Fig. 4D), respectively. The seven environments were divided into two groups for fruit yield with E1, E5 and E3 in first group while E4, E6, E7 and E2 in the other

Genotypes	Number of primary branches per plant			Plant height (cm)			Fruits per plant			Green fruit yield per plant (g)			Harvest duration (days)		
	Mean	b_i	S^{-2}_{di}	Mean	b_i	S^{-2}_{di}	Mean	b_i	S^{-2}_{di}	Mean	b_i	S^{-2}_{di}	Mean	b_i	S^{-2}_{di}
DPCHYB 1	4.66	1.02 ± 0.58	1.71*	92.00	0.84 ± 0.06*	22.83	114.43	0.69 ± 0.18	86.27*	462.12	0.85 ± 0.23	2693.52*	92.38	1.07 ± 0.27	7.58
DPCHYB 2	4.47	1.20 ± 0.60	1.82*	83.47	0.73 ± 0.07*	46.19*	126.10	0.60 ± 0.26	190.26*	471.50	0.87 ± 0.23	2641.31*	93.95	1.48 ± 0.32	12.22
DPCHYB 3	4.68	0.81 ± 0.55	1.50*	95.71	1.36 ± 0.15*	196.69*	113.53	1.04 ± 0.49	720.21*	346.49	1.00 ± 0.31	4909.20*	89.33	1.78 ± 0.49	31.16*
DPCHYB 4	4.68	0.77 ± 0.57	1.65*	109.63	1.52 ± 0.02*	−1.36	119.95	0.66 ± 0.24	164.99*	420.44	0.71 ± 0.15	1152.95*	89.24	1.27 ± 0.34	13.65
DPCHYB 5	4.26	0.79 ± 0.51	1.28*	101.26	1.06 ± 0.15	199.93*	135.68	1.27 ± 0.26	188.26*	583.50	1.27 ± 0.24	2901.93*	95.14	0.81 ± 0.18	2.05
DPCHYB 6	4.41	1.31 ± 0.30	0.32	96.96	1.38 ± 0.14*	171.47*	135.48	0.90 ± 0.30	256.70*	509.96	1.42 ± 0.13*	929.68*	95.05	0.72 ± 0.32	12.12
DPCHYB 7	4.60	1.66 ± 0.33	0.46	98.96	1.34 ± 0.05*	17.84	126.50	1.47 ± 0.46	627.70*	367.07	0.80 ± 0.28	4084.28*	93.14	0.71 ± 0.58	44.91*
DPCHYB 8	4.73	1.03 ± 0.34	0.49	86.27	1.07 ± 0.15	208.94*	133.78	0.84 ± 0.13	47.09*	527.86	1.22 ± 0.15	1094.30*	94.76	1.11 ± 0.38	18.45*
DPCHYB 9	4.62	1.10 ± 0.50	1.23*	99.27	1.12 ± 0.09	63.75*	96.60	0.93 ± 0.21	127.05*	367.55	0.68 ± 0.15*	1135.34*	91.19	0.68 ± 0.14*	0.31
DPCHYB 10	4.67	1.06 ± 0.42	0.79	93.96	1.12 ± 0.08	61.53*	107.25	0.72 ± 0.14*	51.42*	627.68	1.46 ± 0.28	4076.60*	89.81	0.30 ± 0.32*	12.17
DPCHYB 11	4.10	1.07 ± 0.30	0.34	101.28	1.37 ± 0.09*	73.56*	104.10	1.04 ± 0.26	194.67*	397.71	0.93 ± 0.27	3705.77*	91.52	0.97 ± 0.18	1.80
DPCHYB 12	4.72	0.82 ± 0.63	2.03*	79.47	0.46 ± 0.15*	213.52*	152.31	1.83 ± 0.39*	437.32*	533.04	1.19 ± 0.27	3910.07*	91.86	1.16 ± 0.10	−1.14
Him Palam Mirch 1(C)	4.57	0.84 ± 0.48	1.11*	69.19	0.52 ± 0.02*	−0.56	114.00	1.16 ± 0.41	492.84*	323.10	0.88 ± 0.16	1245.07*	89.95	1.06 ± 0.24	5.86
Him Palam Mirch 2 (C)	4.94	1.00 ± 0.59	1.79*	73.69	0.52 ± 0.12*	128.22*	98.80	0.66 ± 0.12*	34.19	377.86	0.99 ± 0.07	255.93*	85.95	0.99 ± 0.45	25.68*
Surajmukhi(C)	4.57	0.68 ± 0.42	0.81	72.15	0.79 ± 0.11*	107.80*	112.21	1.86 ± 0.27*	203.63*	282.99	0.94 ± 0.16	1371.84*	83.00	1.15 ± 0.11	−0.87*
CH-27(C)	83.81	0.73 ± 0.54	39.58*	76.38	0.81 ± 0.11	106.22*	68.08	0.33 ± 0.13*	43.28*	369.30	0.78 ± 0.27	3728.59*	3.94	0.84 ± 0.53	1.39*
Grand Mean	90.63	1.00		89.35	1.00		116.08	1.00		435.51	1.00		4.54	1.00	
S.E (m) ±	1.73	0.35		4.36	0.11		6.65	0.30		21.12	0.23		1.73	0.35	
Critical difference ($P \leq 0.05$)	4.53			6.85			7.22			12.49			4.53		

Table 7. Individual regression analysis and estimates of stability parameters for primary branches per plant, plant height (cm), fruits per plant, green fruit yield per plant (g) and harvest duration. *Significant deviation at $P \leq 0.05$; C represents check variety.

Source	df	Mean sum of squares								
		Days to flowering	Days to first harvest	Fruit length (cm)	Fruit diameter (cm)	Primary branches per plant	Plant height (cm)	Fruits per plant	Fruit yield per plant (g)	Harvest duration (days)
Environment	6	21071.9*	24095.1*	3.0	1.9*	264.8*	459658.8*	141131.0*	2511214.0*	6873.3*
Replication (Environment)	14	69.6	103.3	2.9	0.0	1.3	526.5	246.0	1330.0	184.0
Genotypes	15	1231.8*	2247.5*	724.5*	6.4*	20.3	47674.6*	122580.0*	3090000.0*	4438.5*
Genotype × Environment (GEI)	90	1676.6*	2639.2*	103.2*	1.0*	334.1*	76868.2*	82608.0*	740000.0*	4817.1*
PC1	20	711.1	1410.4	48.5	0.6	214.2	53957.1	37331.0	304000.0	2256.5
PC2	18	479.7	565.1	30.1	0.2	95.8	12547.0	24504.0	238000.0	1692.3
PC3	16	311.3	358.3	14.5	0.1	9.8	7950.8	10014.0	121000.0	616.0
PC4	14	157.8	228.8	5.6	0.0	6.6	1453.1	5631.0	42700.0	217.5
PC5	12	16.7	76.6	4.3	0.0	4.6	959.8	4948.0	33900.0	32.8
PC6	10	0.0	0.0	0.0	0.0	3.0	0.4	480.0	76.8	1.9
Residuals	210	566.6	689.6	19.8	0.2	100.9	3855.3	2146.0	12800.0	1689.3
Total	425	26293.1	32414.0	956.6	10.6	1055.4	665451.7	431319.0	7095020.8	22819.3

Table 8. Analysis of variance (ANOVA) based on AMMI model for yield and yield attributes of Chilli hybrids.

(Fig. 4A). All the environments formed an acute angle indicating positive correlation wherein E4 and E6 were highly correlated with very close environment vector.

The discriminativeness and representativeness analysis (Fig. 4B) revealed the longest vectors for E1, E4, E5 and E2 for green fruit yield, E1, E3and E6 for days to flowering, E3 for days to first harvest, E5 for fruit length, E2 for fruit diameter, E2 and E3 for plant height and green fruits per plant, and E6 for harvest duration suggesting these environments as the most informative and discriminative which would help effectively in differentiating between genotypes. The environments E5 for green fruit yield and fruit length, E1 for days to flowering, E2 for fruit diameter, plant height and green fruits per plant and E7 for harvest duration were characterised by a longer vector that creates a smaller angle with the AEC abscissa line is considered optimal for the identification and selecting superior genotypes.

The mean vs. stability biplot analysis (Fig. 4C) construed the desirable performance of DPCHYB 10 and DPCHYB 5 for green fruit yield and fruit length, DPCHYB 5 and DPCHYB 4 for early flowering and tall plants, DPCHYB 2 and DPCHYB 5 for early harvesting, DPCHYB 10 for broad fruits, DPCHYB 12 and DPCHYB 5 for more green fruits per plant, and DPCHYB 5 and DPCHYB 6 with longer harvest duration. The genotypes which were located close to the AEC showed better stability *e.g.*, DPCHYB 2 for early flowering, number of fruits per plant and green fruit yield per plant, DPCHYB 5 for early flowering, fruit length, and harvest duration and that of DPCHYB 10 for fruit length and number of primary branches.

'Which won where'biplot divided the environments into two sectors and that of genotypes into five sectors (Fig. 4D). Based on the position of hybrids on the polygon's vertices, DPCHYB 10 was the winning genotype based on its better performance for fruit yield across the environments except E1 where DPCHYB 5 was the most responsive. In addition, DPCHYB 8 and DPCHYB 6 also showed average stability across the environments while DPCHYB 12 and DPCHYB 2 showed the similar response in E1. Further, GGE biplot for flowering (Fig. 3A) revealed that E1, E2 and E3 held in the sector with Surajmukhi[15] as the most responsive genotype for these environments. Similarly, CH-27[16] for flowering in E4, E5, E6 and E7 (Fig. 3A), CH-27[16] and DPCHYB 10[10] for early harvest in E6, E7, E5 and E4 (Fig. 3B), DPCHYB 10[10] in E6, DPCHYB 12[12] in E1, E7, E5 and E4 and Him Palam Mirch 1[13] in E2 and E3 for primary branches (Fig. 3C), DPCHYB 4[4] in E1, E2, E3 and E5 for plant height (Fig. 3D), DPCHYB 10[10] for fruit length (Fig. 3E) and fruit diameter (Fig. 3F) in all environments, and DPCHYB 12[12] across environments except E4 for fruits per plant (Fig. 3G) were clear winner and stable hybrids for the respective traits. Similarly, DPCHYB 5[5] in E2 and E7, DPCHYB 2[2] in E4 and E5 and DPCHYB 6[6] in E6, E1 and E3 for harvest duration (Fig. 3H) were the most responsive and winning genotypes.

Discussion

The chilli breeders have to plan their heterosis breeding programme as per the aspirations of the stakeholders for hybrids with medium to long fruits, high yield and wider adaptability. Keeping this in view, male sterility derived hybrids were synthesized involving diverse inbred lines. It is essential to evaluate these hybrids for stability and wider adaptability for which, multi-location assessment for yield and associated characteristics is important to release them for cultivation in the state or different zones with variable climatic conditions[31]. The climatic conditions in the north-western Himalayas range from humid subtropical to dry temperate and the development of hybrids with consistent yield performance across environments is necessary and is of utmost significance. G×E interaction is a serious challenge before breeders while evaluating genotypes through multiple environment trials[32]. To handle this issue, multiple statistical models *viz*., Eberhart-Russell (E-R) joint regression model, AMMI and GGE *etc.* support plant breeders to assess the performance of genotypes across variable environmental conditions that allow to identify the best genotypes for a specific or range of environments[29,33]. E-R model is broadly used to make decisions on advancement of genotypes, and the present study was aimed to compare the E-R with AMMI and GGE biplot analysis.

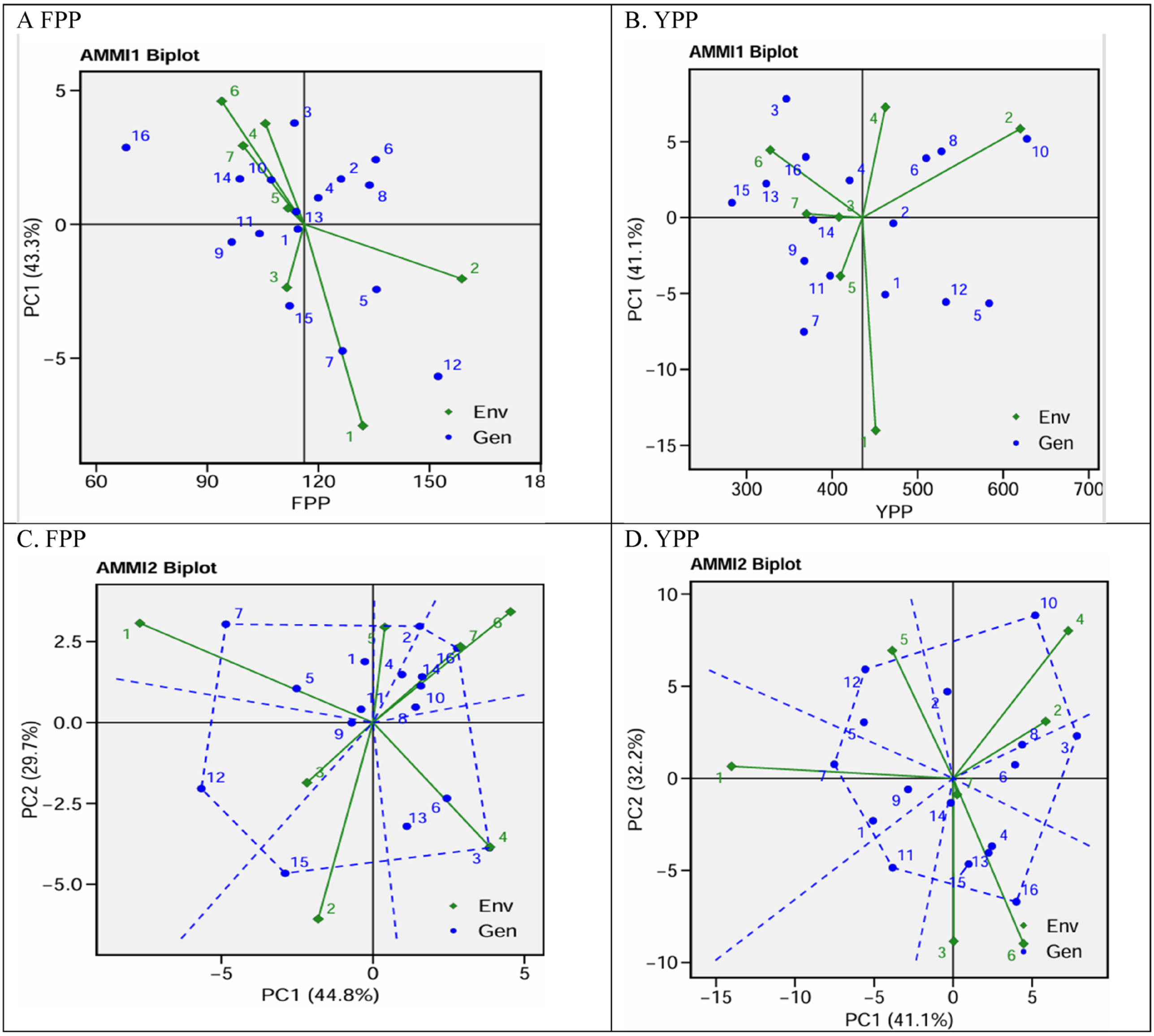

Fig. 2. Additive main effects and multiplicative interaction (AMMI) biplots illustrating G × E interactions of the 16 chilli genotypes in seven locations: **(A)** AMMI 1 biplot for fruits per plant (FPP) **(B)** AMMI 1 biplot for fruit yield per plant (YPP) **(C)** AMMI 2 biplot for fruits per plant (FPP) **(D)** AMMI 2 biplot for fruit yield per plant (YPP); where, green lines represented with 1–7 depicts environments at Palampur[1], Conventional farming under poly house at Palampur[2] and Natural farming under polyhouse at Palampur[3], Bajaura[4], Berthin[5], Sundernagar[6] and Dhaulakuan[7;*]Representation of genotypes as 1–16 in blue colour dotted lines where 1: DPCHYB 1, 2: DPCHYB 2, 3: DPCHYB 3, 4: DPCHYB 4, 5: DPCHYB 5, 6: DPCHYB 6, 7: DPCHYB 7, 8: DPCHYB 8, 9: DPCHYB 9, 10: DPCHYB 10, 11: DPCHYB 11, 12: DPCHYB – 12, 13: Him Palam Mirch 1, 14: Him Palam Mirch 2, 15: Surajmukhi, 16:CH-27.

E-R joint regression model, AMMI and GGE analyses revealed substantial G×E effects for fruit yield and its attributes based on evaluation of hybrids across environments indicating the involvement of diverse inbred lines as parents along with variation among test environments. The earlier researchers have also found strong genotypic and G×E impact on fruit yield and associated characters[34]. Hence, it is necessary to use stability parameters to identify wider adaptive genotypes. Further, the significance of combined environment and G×E interaction [E(G×E)] components of variance (Table 5) demonstrated the impact of environments and their interactions with genotypes on the performance of hybrids. The linear and non-linear components of environments had a significant influence on majority of the traits. Tembhurne and Rao[35], Datta and Jana[36], Raghavendra et al.[37], Barchenger et al.[38] and Ozukum and Seyie[39] have also observed the significance of linear component of GEI on different traits of chilli. A significant GEI affect the relative ranking/performance of genotypes across environment and hampers breeding progress during selection and advancing genotypes to successive selection steps[40].

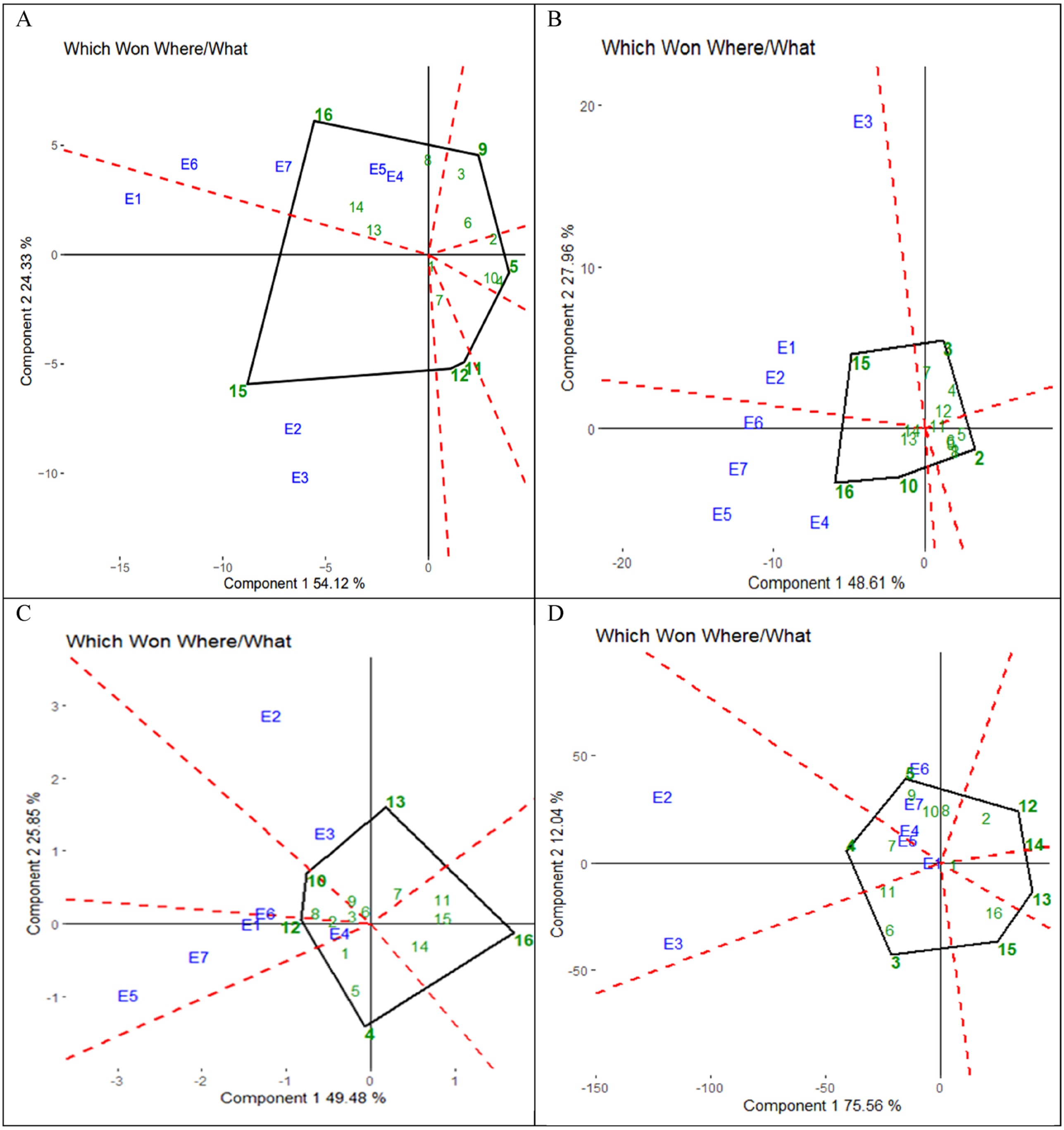

Fig. 3. Which won where G + GE biplots for **(A)** Days to flowering **(B)** Days to first harvest **(C)** Primary braches per plant **(D)** Plant height **(E)** Fruit length **(F)** Fruit diameter **(G)** Fruits per plant **(H)** Harvest duration. Where, "E" represents the environments Palampur (E1), Conventional farming under polyhouse at Palampur (E2) and Natural farming under polyhouse at Palampur (E3), Bajaura(E4), Berthin(E5), Sundernagar, Mandi (E6) and Dhaulakuan (E7) *Representation of genotypes as 1–16 where 1: DPCHYB 1, 2: DPCHYB 2, 3: DPCHYB 3, 4: DPCHYB 4, 5: DPCHYB 5,6: DPCHYB 6, 7: DPCHYB 7, 8: DPCHYB 8, 9: DPCHYB 9, 10: DPCHYB 10, 11: DPCHYB 11, 12: DPCHYB – 12, 13: Him Palam Mirch 1, 14: Him Palam Mirch 2, 15: Surajmukhi, 16:CH-27.

The regression coefficient variance for all the characters suggested heterogeneous response of genotypes to environmental fluctuations[41]. The commercially available hybrids should have improved mean performance vis-a-vis stability across environments[15,29]. However, variable response of different genotypes was recorded for mean fruit yield and yield attributes besides stability (Table 5). Eberhart and Russell[18] define a stable genotype that has high mean performance, regression coefficient (b_i) close to unity, and the deviation from regression (S^2_{di}) near to zero. High mean performance along with wider stability ($b_i = 1$ and $S^2_{di} = 0$) of DPCHYB 10 for fruit

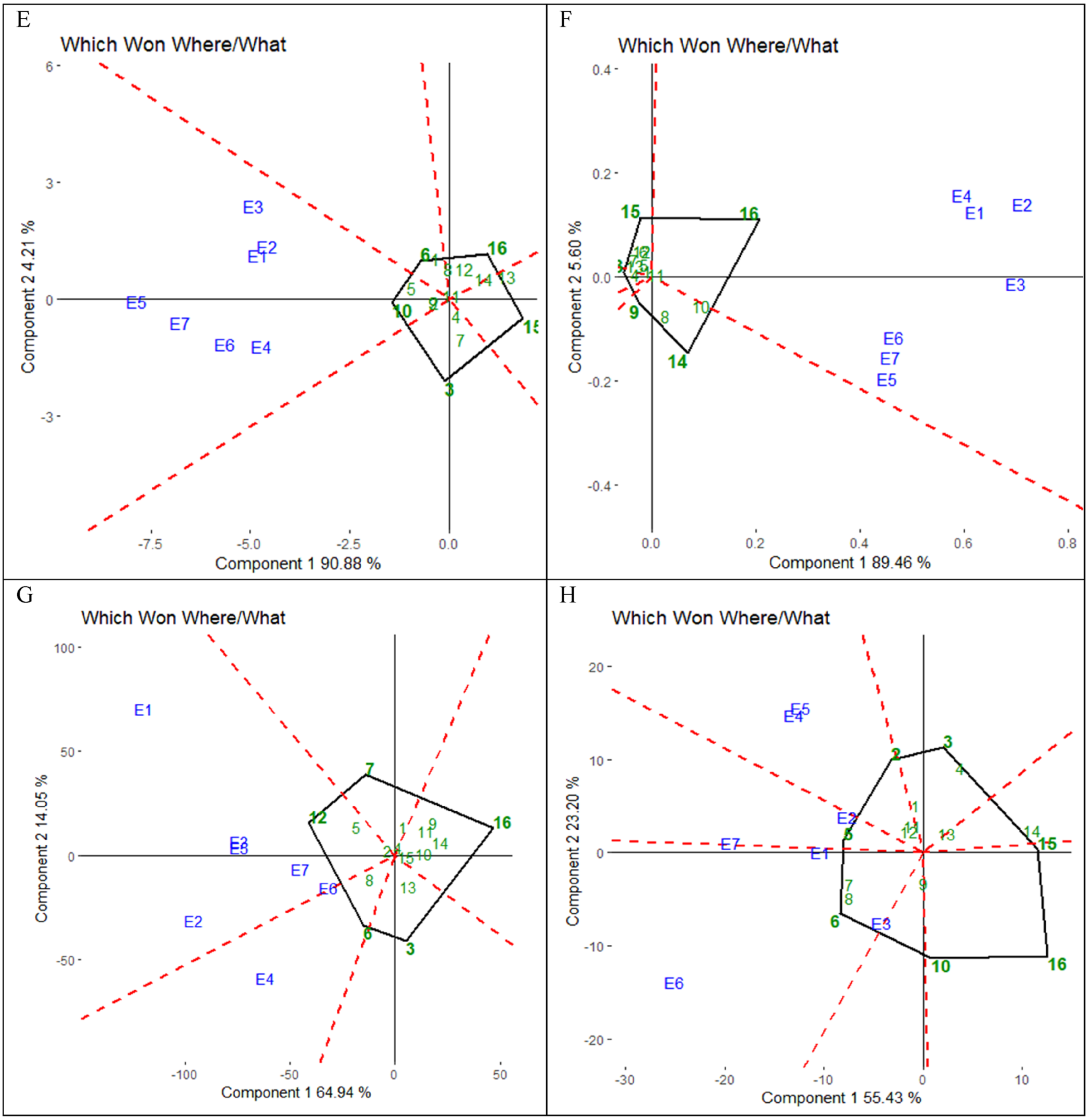

Fig. 3. (continued)

yield and yield attributes in comparison to check Him Palam Mirch-2 categorized it as the most suitable hybrids across environments. Similarly, DPCHYB 2 and DPCHYB 5 also showed promise based on their superiority and stability with unit regression coefficient and non-significant deviation from regression ($S^2_{di} = 0$) for fruit yield, early flowering, number of fruits and harvest duration than check variety. Therefore, these hybrids can be considered as the most desirable with high yield potential and were insensitive to the variable environmental conditions. The earlier research findings using Eberhart and Russel model have also successfully identified chilli hybrids using variable inbred lines with wider adaptability and superior yield performance[23,25,27,42,43]. Eberhart and Russell method identified the most stable hybrids but could not reliably detect the high yielding hybrids.

The AMMI biplot is a valuable tool for dissecting genotype-by-environment interaction (GEI) along with identifying stable and high-performing genotypes across varying environments[28]. The magnitude of mean sum of squares due to environment was higher than genotype indicating strong environmental influence on different traits (Table 8). The first two principal components (PC1 and PC2) explained more than 70% of the total GEI variation for most of the traits that clearly demonstrated the suitability of the AMMI model in capturing the crossover interaction and identifying stable genotypes for specific and wider adaptation. Genotype-environment

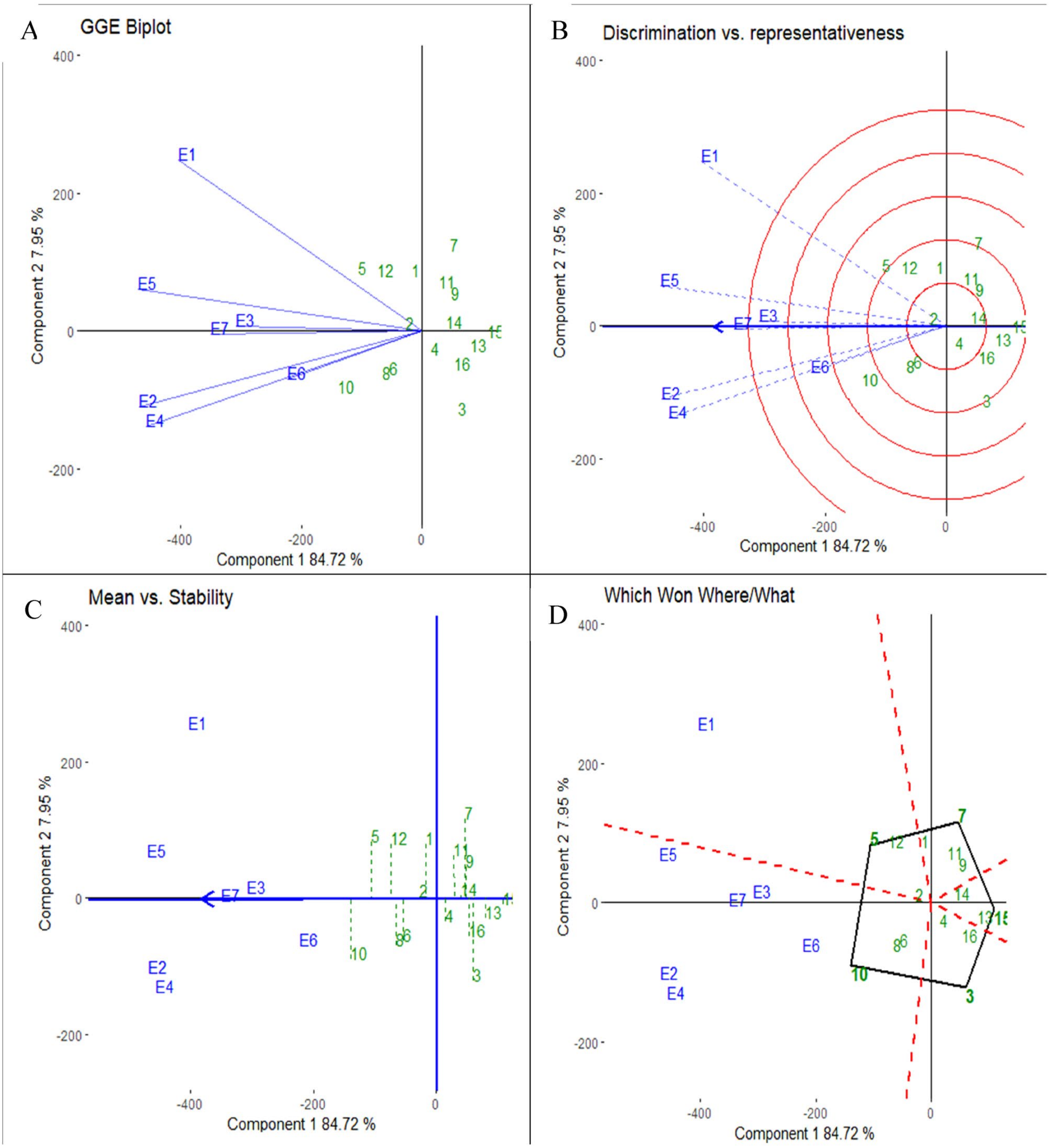

Fig. 4. G + GE biplots for yield per plant **(A)** An environment vector view biplot ; **(B)** Discrimitiveness vs. representativeness biplot ; **(C)** Means vs. Stability biplot . The single arrowed horizontal line represents the AEC abscissa and the direction of AEC abscissa arrowhead indicates increasing yield. The vertical projections on the AEC abscissa indicates stability (greater the projection, higher is the instability); **(D)** "Which won where" biplot . Where, "E" represents the environments *i.e.* Palampur (E1), Conventional farming under polyhouse at Palampur (E2) and Natural farming under polyhouse at Palampur (E3), Bajaura (E4), Berthin (E5), Sundernagar (E6) and Dhaulakuan (E7). *Representation of genotypes as 1–16 where 1: DPCHYB 1, 2: DPCHYB 2, 3: DPCHYB 3, 4: DPCHYB 4, 5: DPCHYB 5, 6: DPCHYB 6, 7: DPCHYB 7, 8: DPCHYB 8, 9: DPCHYB 9, 10: DPCHYB 10, 11: DPCHYB 11, 12: DPCHYB – 12, 13: Him Palam Mirch 1, 14: Him Palam Mirch 2, 15: Surajmukhi, 16:CH-27.

interactions are visually represented by the distance from the biplot origin that help to predict adaptability[20]. A short vector length and proximity to the origin in the biplot signify environmental stability and are considered ideal conditions for selecting consistent genotypes[19]. Accordingly, AMMI1 biplot revealed that genotypes DPCHYB 8, DPCHYB 2, and DPCHYB 4 for fruits per plant (Fig. 2A), and DPCHYB 2 for yield (Fig. 2B) were the most resilient across environments. The AMMI2 biplot further enhanced this interpretation by partitioning mega-environments and identifying genotypes with specific adaptations such as nutrient availability and climate influence on genotype performance[27]. In chilli, agronomic traits like fruit number, fruit length, and fruit diameter had significant impact on fruit yield and showed sensitivity to environmental fluctuations, emphasizing the relevance of GEI analysis[26]. Environments and genotypes close to the biplot origin were associated with low interaction effects and higher stability[28], thus validating the AMMI2 model's suitability for identifying genotypes with broad or specific adaptation across diverse environments *e.g.* DPCHYB 3 and DPCHYB 10 in E4 and E2, DPCHYB 1 and DPCHYB 7 in E1, and DPCHYB 12 in E5 for green fruit yield per plant (Fig. 2D).

GGE biplot has an edge over AMMI biplot on account of better graphical representation based on mega environment analysis and classify genotypes to specific environment or as wider adaptive genotype by describing G + GE. Further, the discriminating vs. representativeness of the GGE biplot is effective to evaluate test environments, which is otherwise not possible in AMMI analysis[17,44]. Accordingly, the most promising and highly stable genotypes may be recommended for large scale commercial cultivation in target environments[45]. These aspects favour GGE biplot to be very popular as a comprehensive tool in quantitative genetics and plant breeding. The environment-vector aspect of the GGE biplot (Fig. 4A) indicated positive correlation among majority of test environments by forming acute angle for fruit yield, fruit length, fruit diameter, plant height, green fruits per plant and harvest duration suggesting the suitability of expression of these traits across the environments[15,46–48]. Further, the 'Discriminative vs. representative' view of GGE biplots (Fig. 4B) described that the environment E5 for green fruit yield and fruit length, E1 for days to flowering, E2 for fruit diameter, plant height and green fruits per plant and E7 for harvest duration had a long vector and a small angle with the AEC abscissa that suggest these environments as the most suitable for the identification of superior genotypes according to the traits of interest. Further, the mean vs. stability GGE biplot (Fig. 4C) identified hybrids DPCHYB 2[2] as the most stable hybrid for fruit yield based on their closeness to the origin and short vector as depicted by a circle with an arrow on the AEC. Anilkumar et al.[49] and Sahmat et al.[26] have also observed differences in stability performance of genotypes for number of green fruits per plant in different environments.

'Which won where' is the most attractive feature of GGE biplot as it displays the winning genotypes along with interaction patterns between genotypes and environments in the polygon view of the GGE biplot[50] in MET data analysis (Fig. 4D). This provides an opportunity to evaluate and understand the likely presence of various mega-environments in the manifestation of traits of interest and adaptation of genotypes under certain mega-environments[15,51]. The genotypes with superior performance and better adaptability would be the ones which are present at the vertices of the polygon along with environments aspect. Keeping this in view, DPCHYB 10 showed superiority for fruit yield in majority of the environments indicating better adaptability with stable performance except E1. DPCHYB 5 had the similar response only in E1. In contrary, DPCHYB 3, DPCHYB 7 and Surajmukhi are present at the vertices but do not represent any environment and hence, were poor performer across environments[26]. This pattern of genotype and environment interactions along with presence of different mega environment cannot be predicted by Eberhart and Russell model[18]. "Which won where" seems to be ideal for 'exploiting' the GE interactions, though recommendation of genotypes to specific locations must be made with caution as certain times, the variation explained by the PC1 and PC2 of the GGE model might be too low. Also, this two-dimensional model explains only two principal components at a time and there is probability that some of the projections might be placed outward in a third dimension[13,52].

Conclusions

Based on the present investigation, it can be concluded that DPCHYB 10 was identified as the most stable hybrid across environments as predicted by both Eberhart and Russel model and 'Which won where' of GGE biplot analysis. AMMI depicted DPCHYB 2 as the most stable hybrid across environments which was also described by mean vs. stability biplot of GGE and E-R. Similarly, DPCHYB 5 revealed stability across environments based on E-R with the same expression in E1 based on GGE. DPCHYB 10 (627.68 g/plant) and DPCHYB 5 (583.50 g/plant) expressed yield advantage of 66.11 and 54.42% over the best check variety Him Palam Mirch 2 (377.86 g/plant). E3 and E7 identified as the most representative environments that provided supportive testing conditions for identifying hybrids with high stability for green fruit yield per plant. The hybrids DPCHYB 10 and DPCHYB 5 could be recommended to the stakeholders for cultivation after thorough evaluation by conducting onfarm trials at farmer's field.

Data availability

The datasets generated and/or analyzed during the current study are presented in the main manuscript and as additional supporting files. Further, any additional information can be obtained from the corresponding author on sensible request.

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Author contributions
V.S. conducted the experiment and analyzed data and manuscript writing; A.S. conceptualized the research, planning and execution of experiments, data interpretation, writing of manuscript; N.K., N.R., and S. helped in material preparation and data collection.

Declarations

Competing interests
The authors declare no competing interests.

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