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Research Article

Stability and performance analysis of seed yield and component traits in sunflower using AMMI and GGE biplots

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Abstract
Genotype × Environment interaction is an important parameter to identify performing varieties adapted for cultivation across diverse environments. The present study intended to identify the best-performing and stable sunflower hybrids across different seasonal conditions of Andhra Pradesh, India. Thirty-three sunflower hybrids, along with three checks, were evaluated over three growing seasons *Rabi* 2022-23 (E1), *Kharif* 2023 (E2), and *Rabi* 2023-24 (E3) at the Regional Agricultural Research Station in Nandyal. The combined analysis of variance demonstrated that genotype, environment, and their interaction had significant effects on seed yield and its associated traits. Based on AMMI analysis, the genotypes SH 2671 and SH 2731 showed high mean and less interaction with seasonal conditions for seed yield and oil yield traits. The GGE biplot analysis indicated that the hybrids SH 2736, SH 2731, SH 2667, SH 2671 and SH 2664 showed high mean and less variation over different seasonal conditions for seed yield and oil yield traits. The seasonal conditions showed good discriminativeness and representative abilities for E1, E2 and E3 conditions. The which-won-where view biplot showed that the hybrids SH 2723 and SH 2729 are the best performers in E1 and E2 conditions for seed yield and oil yield traits. Overall, the hybrids SH 2723, SH 2730, SH 2729, SH 2731 and SH 2671 can be suggested for cultivation over different seasonal conditions.

Keywords: G × E interaction, AMMI, GGE, Stability, Sunflower

INTRODUCTION

Sunflower (*Helianthus annuus* L.), a vital oilseed crop, was first introduced for cultivation in India in 1972 through Russian varieties like Peredovick (EC 68414) and Armavirski (EC 68415). Globally, the major sunflower cultivating countries are Russia, Ukraine, the European Union, Argentina and Turkey. In India, sunflower is grown over an area of 1.51 lakh ha with production and productivity of 1.72 lakh tonnes and 1144 kg ha^{-1}, respectively (www.indiastat.com). Among the oilseed crops, it occupies fourth place in area and production after soybean, mustard and groundnut in India. In India, the major sunflower growing states are Karnataka, Orissa, Haryana, Maharashtra, Bihar and West Bengal. In India, this crop is often referred to as the 'crop of all seasons' due to its day neutrality, broad adaptability, short growth cycle, high yield potential, and excellent oil quality (Reddy *et al.*, 2024)

Maximising productivity is the major goal of any crop improvement programme. The crop improvement in sunflower is somewhat difficult due to self-incompatibility and outbreeding nature. Sunflower yield is a multifaceted trait governed by various component traits that are impacted by environmental conditions (Ahmed *et al.*, 2021). Oil content is a crucial trait affecting sunflower oil yield, and it is largely influenced by environmental variations (Jafari *et al.*, 2024). Therefore, the main focus of sunflower breeders is to develop high seed and oil yielding hybrids with stable performance over locations and seasons.

The successful cultivation and production of sunflower depend upon both the genotype's genetic potential and environmental conditions. The genotype × environment interaction is an important parameter derived from variation in uncontrolled factors, which vary from location to location and year to year (Binodh *et al.*, 2009). The major focus is to identify a stable genotype widely adaptable to different climatic situations to overcome these factors. A wide range of statistical models has been created to examine the genotype × environment interaction in multi-environment studies. Among them, the additive main effects and multiplicative interaction (AMMI) and genotype (G) + genotype × environment (GGE) biplot techniques are the most widely used techniques for analysing genotype × environment interactions (Rahmati *et al.*, 2024). So far, these techniques have been broadly applied to identify the stable genotypes in multi-location trials. Radic *et al.* (2020) employed AMMI analysis to determine the stable genotypes for germination rate, seed yield and protein content over multi-environment trials in sunflower. In light of these considerations, the current investigation was focused on the evaluation of genotype × environment interaction among 33 sunflower hybrids and three checks over three seasons to identify stable hybrids suitable for cultivation.

MATERIALS AND METHODS

The study utilized 36 diverse genotypes, comprising 33 hybrids developed at the Regional Agricultural Research Station, Nandyal, along with three hybrid checks (**Table 1**). These genotypes were evaluated using a randomized block design with three experimental replications during *Rabi* 2022-23 (E1), *Kharif* 2023 (E2), and *Rabi* 2023-24 (E3) at the Regional Agricultural Research Station, Nandyal. Planting of each genotype was done in two rows with a row length of 3m and with 60 cm spacing between the rows and with 30 cm spacing between the plants within a row. All agronomic and plant protection practices recommended by Acharya N. G. Ranga Agricultural University were followed to ensure healthy crop growth. The observations for days to 50% flowering and days to maturity were taken on a plot basis. The data for other yield and related traits were collected from five randomly selected plants of each genotype across all replications. The oil content (%) was estimated by NMR (Nuclear Magnetic Resonance) Spectrometer installed at the ICAR- Indian Institute of Oilseeds Research, Hyderabad by using a random sample of cleaned and dried seeds from each entry. Further, oil yield on hectare basis was calculated using the following formula, oil yield (kg/ha) = (seed yield (kg/ha) × oil content (%))/100. The mean of the observations were subjected to AMMI and GGE analyses using R software with the 'metan' package.

The model below was employed for AMMI analysis to predict the performance of genotypes over three seasons.

$$Y_{ij} = \mu + g_i + e_j + \Sigma\lambda_k + \alpha_{ik}y_{jk} + R_{ij}$$

Where Y_{ij} represents the yield of the i^{th} genotype in j^{th} environment, μ is the overall mean, g_i represents the effect of i^{th} genotype, e_j represents the effect of j^{th} environment, λ_k represents the square root of the eigenvalue corresponding to the k^{th} principal component axis, α_{ik} and y_{jk} are the principal component scores for the k^{th} PCA axis of the i^{th} genotype and j^{th} environment, respectively and R_{ij} is the residual effect. The combined statistical analysis of variance was computed based on the data of seed yield and oil yield from the genotypes evaluated in the study. The GGE biplot method was employed to study the discriminativeness power and representativeness ability of test environments, which-won-where pattern of GGE, ranking of genotypes across the testing environments and ranking of test environments.

RESULTS AND DISCUSSION

Analysis of genotypic performance in individual environments namely, *Rabi* 2022-23, *Kharif* 2023 and *Rabi* 2023-24 showed that significant differences among genotypes were observed in every season of evaluation. Further, the pooled ANOVA showed significant effect for genotypes (G), environment (E) and their G×E interaction (**Table 2**). This warrants stability analysis. The maximum coefficient of variation was recorded for the traits seed yield (kg/ha) and oil yield (kg/ha) were 7.84 and 7.76, respectively over seasons. Aboye and Edo (2024) reported that high variability and inconsistent performance for the seed yield trait across different environments in sunflower.

Stability analysis by the AMMI model: The ANOVA for AMMI revealed that the genotypic (G), environmental (E), and genotype-by-environment interaction (G×E) variances were significant across all evaluated traits in sunflower (**Table 3)**. The IPCA I and IPCA II showed significant effects for days to 50% flowering, days to maturity, 100-seed weight, seed yield per plant, seed yield (kg/ha) and oil yield (kg/ha). The percent variation explained by IPCA I and IPCA II for seed yield (kg/ha) was 91.5% and 8.5%, whereas it was 84.5% and 15.5%, respectively, for oil yield (kg/ha). Thus, AMMI analysis provides a comprehensive summary of G×E interaction by computing the principal component scores of genotype and environment (Nowosad *et al.*, 2016). Although many morphological traits are crucial for yield improvement in sunflower, the seed yield and oil yield are the primary traits of interest due to their direct impact on productivity and economic value. Additionally, these traits are highly influenced by environmental factors; therefore, these two traits were considered for G × E analysis to identify genotypes that perform consistently across seasons.

The mean and IPCA scores concerning seed yield (kg/ha) were shown in **Table 4** and **Fig. 1A** and **Fig. 1B**. As per AMMI biplot 1 (**Fig. 1A**), the check NDSH 1012 recorded high mean value compared to other checks. The stable genotypes, SH 2671, SH 2731, SH 2664 and SH 2667 recorded high mean with IPCA value nearer to zero. Yasar *et al.* (2023) reported that genotypes with near-zero IPCA scores showed broad adaptation for seed yield, while higher scores indicated narrow adaptation. The

Table 1. List of genotypes and source of origin

S.No	Genotypes	Parentage	Source
1	SH2823	ARM 249A × GMU 736	Regional Agricultural Research Station, Nandyal
2	SH2805	ARM 249A × RHA GP6-96	Regional Agricultural Research Station, Nandyal
3	SH2801	CMS 107A × RHA GP6-96	Regional Agricultural Research Station, Nandyal
4	SH2821	CMS 110A × GMU 736	Regional Agricultural Research Station, Nandyal
5	SH2806	CMS 17A × RHA GP6-96	Regional Agricultural Research Station, Nandyal
6	SH2865	ARM 243A × NDI 56	Regional Agricultural Research Station, Nandyal
7	SH2853	ARM 243A × NDI 50	Regional Agricultural Research Station, Nandyal
8	SH2862	ARM 243A × NDI 55	Regional Agricultural Research Station, Nandyal
9	SH2868	ARM 243A × NDI 61	Regional Agricultural Research Station, Nandyal
10	SH2844	ARM 243A × NDI 43	Regional Agricultural Research Station, Nandyal
11	SH2850	ARM 243A × NDI 49	Regional Agricultural Research Station, Nandyal
12	SH2838	ARM 243A × NDI 36	Regional Agricultural Research Station, Nandyal
13	SH2864	CMS 17A × NDI 56	Regional Agricultural Research Station, Nandyal
14	SH2859	ARM 243A × NDI 52	Regional Agricultural Research Station, Nandyal
15	SH2826	ARM 243A × NDI 24	Regional Agricultural Research Station, Nandyal
16	SH2841	ARM 243A × NDI 39	Regional Agricultural Research Station, Nandyal
17	SH2858	CMS 17A × NDI 52	Regional Agricultural Research Station, Nandyal
18	SH2832	ARM 243A × NDI 34	Regional Agricultural Research Station, Nandyal
19	SH 2736	ARM 248A × PM 81	Regional Agricultural Research Station, Nandyal
20	SH 2735	NDLA 13 × PM 81	Regional Agricultural Research Station, Nandyal
21	SH 2737	IMS 1A × PM 81	Regional Agricultural Research Station, Nandyal
22	SH 2723	CMS 30A × GMU 106	Regional Agricultural Research Station, Nandyal
23	SH2730	NDLA 13 × GMU 325	Regional Agricultural Research Station, Nandyal
24	SH2733	HA 112A × GMU 325	Regional Agricultural Research Station, Nandyal
25	SH2729	CMS 30A × GMU 325	Regional Agricultural Research Station, Nandyal
26	SH2731	ARM 248A × GMU 325	Regional Agricultural Research Station, Nandyal
27	SH2732	IMS 1A × GMU 325	Regional Agricultural Research Station, Nandyal
28	SH 2623	NDLA 5 × TSG 297	Regional Agricultural Research Station, Nandyal
29	SH 2667	NDLA 5 × RHA 1232	Regional Agricultural Research Station, Nandyal
30	SH 2689	CMS 30A × PM 81	Regional Agricultural Research Station, Nandyal
31	SH 2671	NDLA 4 × GMU 804	Regional Agricultural Research Station, Nandyal
32	SH 2664	CMS 30A × RHA 1114	Regional Agricultural Research Station, Nandyal
33	SH 2674	CMS 30A × GMU 804	Regional Agricultural Research Station, Nandyal
34	NDSH 1012	Check 1	Regional Agricultural Research Station, Nandyal
35	KBSH 44	Check 2	University of Agricultural Sciences, Bangalore
36	KBSH 78	Check 3	University of Agricultural Sciences, Bangalore

Table 2. Pooled ANOVA of quantitative traits of Sunflower

Trait	Mean sum of squares				CV
	Genotype	Environment	G × E	Pooled error	
Degrees of freedom	35	2	70	210	
Days to 50% flowering	18.48***	104.67***	4.47***	0.89	1.79
Days to maturity	22.65***	212.79***	5.76***	0.90	1.08
Plant height (cm)	3077.04***	1491.10***	285.55***	54.19	5.33
Head diameter (cm)	16.58***	2.14*	6.66***	0.62	4.76
100 seed weight	1.69***	8.78***	0.99***	0.08	5.75
Seed yield per plant (g)	181.48***	100.11***	4.11**	2.99	7.84
Seed yield (Kg/ha)	559017***	308350***	12671**	9215	7.84
Oil content (%)	32.41***	4.38**	1.20***	0.63	2.31
Oil yield (Kg/ha)	82523***	27908***	1654**	1068	7.76

*,**,*** significance at 5%,

Table 3. ANOVA for stability (AMMI) for interactive traits

Trait	IPCA I		IPCA II	
	MSS	% Explained	MSS	% Explained
Days to 50% flowering	6.49***	74.7	2.33***	25.3
Days to maturity	9.08***	81.1	2.24***	18.9
Plant height (cm)	501.3***	90.3	57.1	9.7
Head diameter (cm)	12.58***	96.6	0.46	3.4
100 seed weight (g)	1.80***	92.9	0.15**	7.1
Seed yield per plant (g)	7.32***	91.5	0.72*	8.5
Seed yield (Kg/ha)	22547***	91.5	2215*	8.5
Oil content (%)	1.88***	80.4	0.49	19.6
Oil yield (Kg/ha)	2717***	84.5	528*	15.5

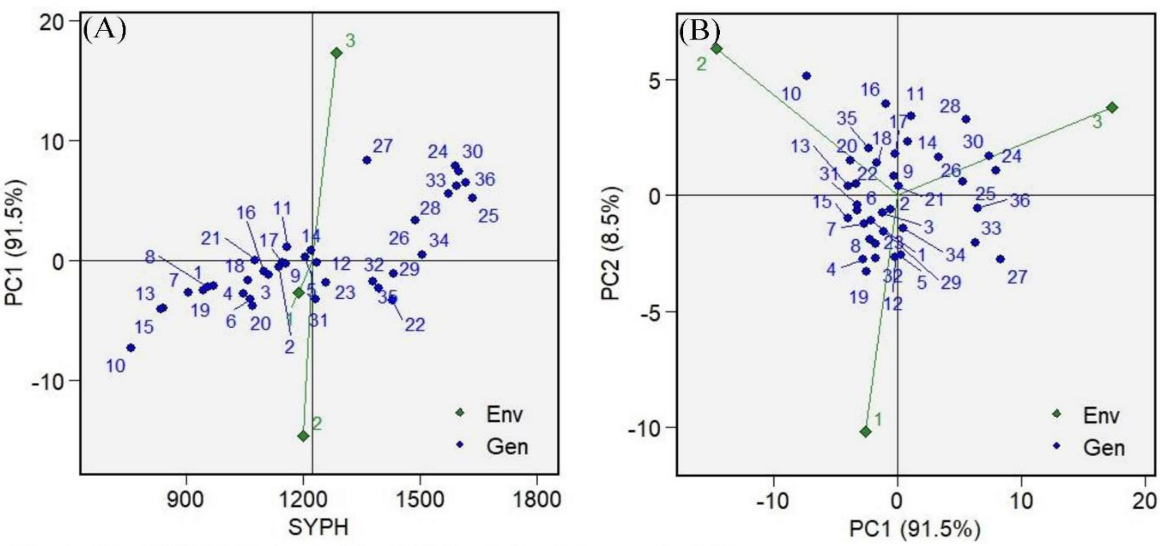

Fig. 1. (A) AMMI Biplot 1, (B) AMMI Biplot 2 for seed yield

genotypes SH 2805, SH 2865, SH 2832, SH 2671 and SH 2731 were nearer to zero and hence less interacting with different testing seasonal conditions. Whereas, considering both biplots, the genotypes SH 2671 and SH 2731 showed high mean seed yield and less interaction with seasonal conditions and can be recommended for cultivation in all seasons.

The mean and IPCA scores for oil yield (kg/ha) are presented in **Table 4** and **Fig. 2A** and **Fig. 2B**. Based on AMMI biplot 1, the check NDSH 1012 was observed to record high mean and IPCA value nearer to zero and hence stable over different seasons. Among the genotypes, SH 2731, SH 2667, SH 2671, SH 2664 and SH 2868 recorded high mean IPCA values nearer to zero and hence stable. The AMMI biplot 2 (**Fig 2B**) showed that the genotypes SH 2731, SH 2667, SH 2671, SH 2664 and SH 2868 were found to be having IPCA values nearer to zero and hence less interacting with different testing seasonal conditions. Based on AMMI analysis, the genotypes SH 2671 and SH 2731 were identified to be stable for both seed yield (kg/ha) and oil yield (kg/ha) and can be recommended for all seasons. Abu (2023) reported a similar kind of result for oil yield in sunflower by highlighting that genotypes near the midpoint are more stable under varying environmental conditions.

Stability analysis by the GGE model: The GGE biplot analysis was utilized to evaluate G×E interactions and genotype stability for seed and oil yield in the study. The GGE biplot technique is advantageous than AMMI analysis, since it mainly interprets the G×E interaction and identifies the better performance of a variety in a specific environment, enabling the identification of mega-environment (Kumar and Kumar, 2021).

GGE biplot analysis for seed yield (kg/ha): Based on the biplot, the genotypes SH 2736, SH 2735, SH 2737, SH 2723, SH 2730, SH 2733, SH 2729, SH 2731, SH 2732, SH 2667, SH 2689, SH 2671, SH 2664 and SH 2674 were identified as above average performers for seed yield in E1 (**Fig 3A**). The genotypes SH 2805, SH 2801, SH

Table 4. Mean and IPC scores of the genotypes and environments for seed yield and oil yield traits

Code	Genotype	Seed yield (kg/ha)			Oil yield (kg/ha)		
		Mean	IPCA I	IPCA II	Mean	IPCA I	IPCA II
1	SH2823	971.02	-2.15	-1.09	316.63	-2.15	-2.91
2	SH2805	1137.33	-0.57	-0.61	410.96	-0.21	-0.42
3	SH2801	1111.97	-1.22	-0.75	380.06	-0.10	0.44
4	SH2821	1046.58	-2.78	-2.77	368.86	-1.58	-2.29
5	SH2806	1204.51	0.26	-2.59	373.01	-0.23	-3.34
6	SH2865	1156.58	-0.27	0.84	394.46	-0.42	0.91
7	SH2853	758.18	-7.29	5.15	256.55	-4.78	2.99
8	SH2862	1158.56	1.11	3.41	389.07	0.89	1.80
9	SH2868	1234.11	-0.16	-2.66	461.84*	-0.17	-0.51
10	SH2844	840.85	-3.95	0.40	277.12	-2.25	0.14
11	SH2850	1220.55	0.82	2.30	415.98	0.23	1.44
12	SH2838	833.76	-4.03	-1.00	284.78	-2.72	-0.72
13	SH2864	1099.64	-0.91	3.96	341.06	-0.44	1.95
14	SH2859	1145.91	-0.21	1.78	379.19	0.71	1.56
15	SH2826	1058.62	-1.66	1.39	368.97	-0.43	1.75
16	SH2841	944.18	-2.53	-3.26	318.64	-1.47	-1.15
17	SH2858	1070.63	-3.83	1.50	336.55	-2.25	0.71
18	SH2832	1077.13	0.05	0.40	406.11	0.18	0.97
19	SH 2736	1430.19*	-3.32	0.53	512.50*	-2.27	0.69
20	SH 2735	1257.97	-1.81	-2.07	433.01	-1.10	-1.08
21	SH 2737	1589.45*	7.92	1.08	533.31*	4.24	0.37
22	SH 2723	1634.61*	5.23	0.58	605.87*	3.33	0.12
23	SH2730	1489.12*	3.35	1.68	543.97*	2.35	0.27
24	SH2733	1363.05*	8.36	-2.74	470.93*	4.84	-1.83
25	SH2729	1572.06*	5.53	3.26	525.58*	2.49	1.90
26	SH2731	1431.52*	-1.10	-1.56	517.70*	-0.41	-1.14
27	SH2732	1598.01*	7.38	1.69	556.01*	4.08	0.89
28	SH 2623	1232.00	-3.25	-0.43	416.52	-1.56	-0.78
29	SH 2667	1379.40*	-1.75	-2.70	487.76*	-0.99	-1.50
30	SH 2689	1592.14*	6.24	-2.04	573.88*	3.88	-1.39
31	SH 2671	1505.71*	0.49	-1.41	481.68*	-0.45	-0.21
32	SH 2664	1392.49*	-2.34	2.02	474.79*	-1.34	0.93
33	SH 2674	1617.40*	6.48	-0.53	576.60*	3.80	-0.41
34	NDSH 1012	1065.39	-3.22	-0.63	379.94	-0.34	2.10
35	KBSH 44	905.32	-2.66	-1.23	261.59	-2.36	-1.60
36	KBSH 78	955.29	-2.19	-1.90	333.42	-0.98	-0.67
E1	*Rabi* 2022-23	1187.60	-2.64	-10.17	409.94	-1.86	-7.08
E2	*Kharif* 2023	1200.08	-14.64	6.35	414.16	-8.44	4.59
E3	*Rabi* 2023-24	1285.76	17.28	3.82	439.65	10.29	2.49
	Mean	1224.48			421.25		
	SE	38.35			14.73		
	CD (0.05)	89.21			30.38		

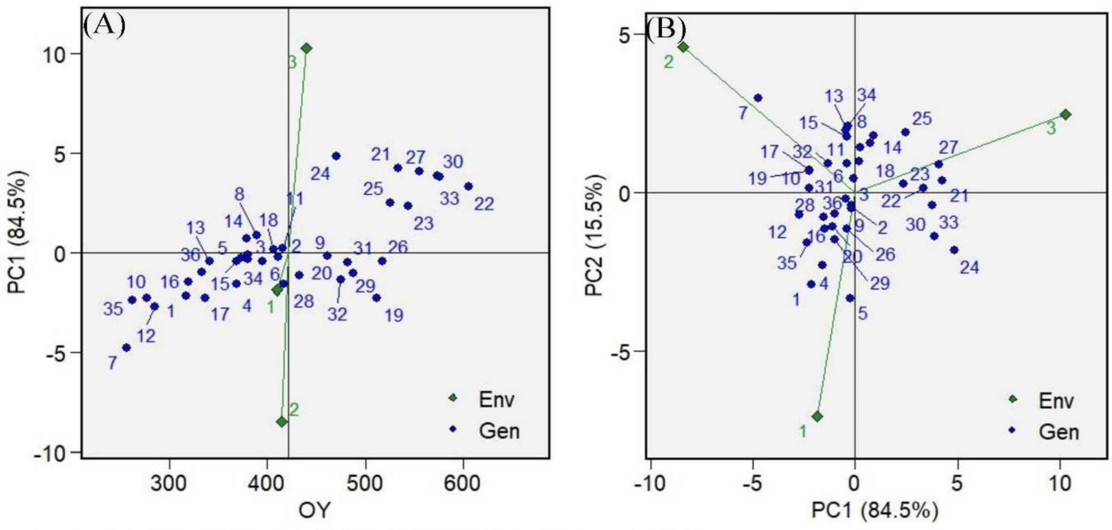

Fig. 2. (A) AMMI Biplot 1, (B) AMMI Biplot 2 for seed yield

2806, SH 2865, SH 2862, SH 2868, SH 2850, SH 2859 and SH 2623 were found to be near average performers in E1. The genotypes SH 2736, SH 2737, SH 2723, SH 2730, SH 2733, SH 2729, SH 2731, SH 2732, SH 2667, SH 2689, SH 2671 and SH 2674 were above average performers in E2 (**Fig 3A**). The genotypes SH 2805, SH 2801, SH 2806, SH 2865, SH 2862, SH 2868, SH 2850, SH 2859, SH 2735 and SH 2623 were identified as near average performer in E2. The genotypes SH 2736, SH 2737, SH 2723, SH 2730, SH 2729, SH 2731, SH 2732, SH 2667, SH 2689, SH 2671, SH 2664 and SH 2674 were identified as above average performer in E3 (**Fig 3A**). The genotypes SH 2806, SH 2868, SH 2850, SH 2735 and SH 2623 are near average performer and other are poorer than average performer in E3.

The genotype mean performance and stability for seed yield trait is shown in biplot **Fig. 3B**. Based on the average environment coordination (AEC) line, the genotypes SH 2736, SH 2730, SH 2731, SH 2667, SH 2671 and SH 2664 are showing high means and less variation over environments. Whereas other genotypes showed higher variation with the environment. Further, the 'which-won-where' pattern of the GGE biplot effectively visualized genotype performance across seasonal conditions for the seed yield trait (**Fig. 3C**). The genotypes positioned at the vertices of the polygon represent those with either best or poor performance in one or more environments. The genotypes SH 2723, SH 2729, SH 2733 and SH 2732 were the best performers in E1, E2 and E3. The GGE biplot's 'which-won-where' pattern served to identify the best-performing genotypes across environments. (Choudhary *et al.*, 2019).

The effect of different testing seasonal conditions on the seed yield trait is depicted in **Fig. 3D**. The different seasonal conditions E1 and E2, as well as E1 and E3 were correlated, whereas no correlation existed between E2 and E3. E3 was the discriminating environment, followed by E2 and E1. Further, the distance between environmental vectors showed that E1 and E2 were in one group and E3 was in another group. Thus, due to the similar G×E interaction in E1 and E2, testing genotypes in a single season is adequate for future assessments. The GGE biplot environment vector view showed the comprehensive depiction of the association between testing conditions, highlighting the impact of seasonal variation on sunflower genotypes (Farooq *et al.*, 2023). The representativeness of the different seasonal conditions is shown in **Fig. 3E**. The seasonal condition E1 forms a small acute angle with average environmental coordination and hence it is the most representative seasonal condition. The condition E3 was the discriminative and hence *Rabi* season can serve to select the most adaptable and stable performing genotypes. The environments characterized by long vectors are more discriminating in genotype selection than those with short vectors (Baraki *et al.*, 2020). The GGE biplot depicted the center of a concentric circle on the average environment coordinate, facilitating the identification of the ideal testing season for seed yield. The seasonal condition E1 is nearest to the origin and hence it is an ideal condition for selecting the most adaptable genotypes across different seasonal conditions. The E3 was observed to be the poorest condition. According to Akter *et al.* (2015), the ideal environment distinguishes tested genotypes while representing the target environment. Further, as per the ideal viewpoint of GGE biplot, the ranking of genotypes was in the order of SH 2729 > SH 2723 > SH 2730 > SH 2731 (**Fig. 3F**). The results of the present study are following the earlier reports, where the ranking considers both mean performance and genotype stability over environments (Qamar *et al.*, 2023).

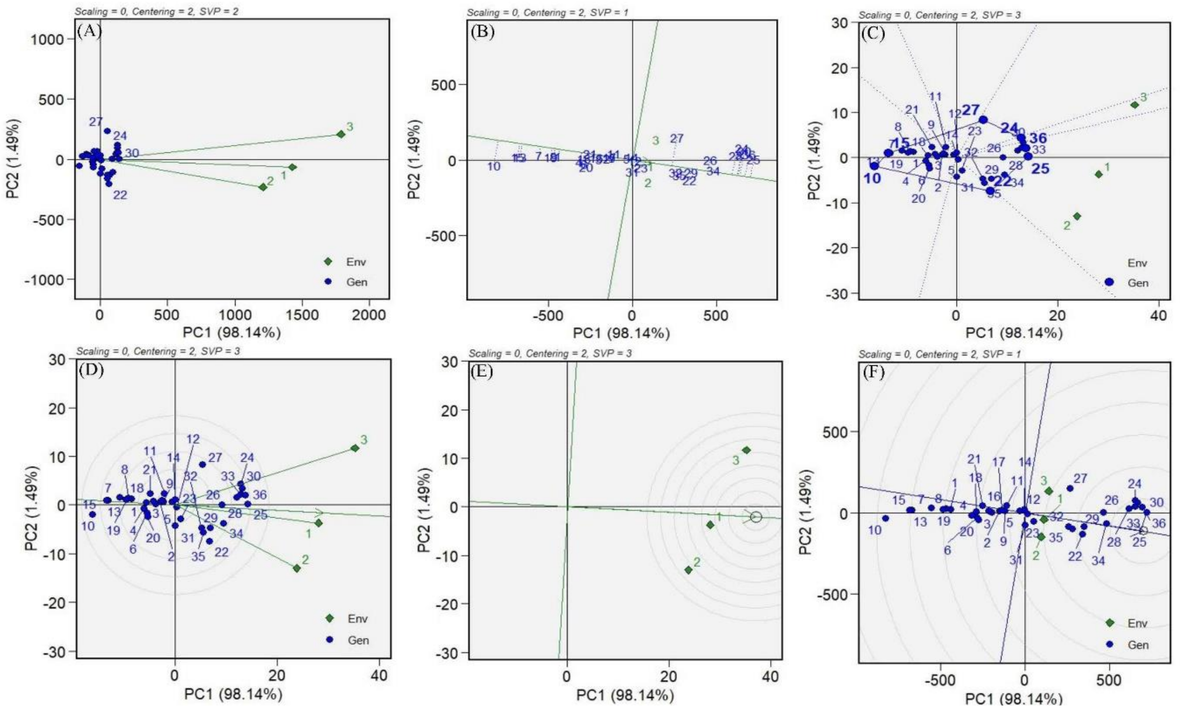

Fig. 3. GGE biplots for seed yield (A) Genotypic view of biplot, (B) Mean vs Stability, (C) Which- won-where biplot, (D) Discriminativeness vs representativeness, (E) Ranking environments, (F) Ranking genotypes

GGE biplot analysis for oil yield (kg/ha): The genotypic view for oil yield trait in relation with different seasonal conditions showed in biplot (**Fig. 4A**). The genotypes SH 2868, SH 2736, SH 2737, SH 2723, SH 2730, SH 2733, SH 2729, SH 2731, SH 2732, SH 2667, SH 2689, SH 2671, SH 2664 and SH 2674 were the above average performers in E1. The genotypes SH 2805, SH 2801, SH 2865, SH 2862, SH 2850, SH 2832, SH 2735, SH 2623 and NDSH 1012 were near average performers and other are poorer than average performer in E1. The genotypes SH 2868, SH 2736, SH 2737, SH 2723, SH 2730, SH 2733, SH 2729, SH 2731, SH 2732, SH 2667, SH 2689, SH 2671, SH 2664 and SH 2674 recorded above average performance in E2. The genotypes SH 2805, SH 2865, SH 2862, SH 2850, SH 2832, SH 2735 and SH 2623 were near average performers and others were poorer than average performer in E2. The genotypes SH 2736, SH 2737, SH 2723, SH 2730, SH 2733, SH 2729, SH 2731, SH 2732, SH 2667, SH 2689, SH 2671, SH 2664 and SH 2674 were the above average performer in E3. The genotypes SH 2805, SH 2850, SH 2735 and SH 2623 were near average performer and the other are poorer than average performer in E3.

The genotype mean performance and stability for oil yield trait is shown in the biplot **Fig. 4B**. Based on the average environment coordination (AEC) line, the genotypes SH 2736, SH 2731, SH 2667, SH 2671 and SH 2664 are exhibiting high mean and less variation over environments. The which-won-where visualization of the GGE biplot highlighted that the genotypes SH 2723, SH 2729, SH 2674, SH 2733, SH 2732, SH 2689 and SH 2674 are best performers in E1, E2 and E3 (**Fig. 4C**). The which-won-where graphical representation enables the top performing genotype identification, thereby it facilitates further improvement of performance and adaptability to various environmental conditions through crop breeding (Ahmed *et al.*, 2020).

The effect of different testing seasonal conditions on the oil yield trait is depicted in **Fig. 4D**. Like seed yield , the seasonal conditions E1 and E2 are in one group and E3 is in another group. The E1 is the most representative seasonal condition as it forms a small acute angle with average environmental coordination (**Fig. 4E**). Further, the E1 environment is ideal for identifying genotypes adaptable for oil yield. Whereas, E3 is the discriminative seasonal condition for the oil yield trait. The genotypes were ranked according to the ideal perspective of the GGE biplot in the order of SH 2729 > SH 2731 > SH 2667 > SH 2723 > SH 2730 and others (**Fig. 4F**). The assessing of genotypes for stability and performance across environments enhances breeding efficiency and crop yield (Dos Santos *et al.*, 2019).

This study utilized AMMI and GGE analyses to investigate genotype × environment interactions affecting seed yield and related traits in sunflower. The sunflower hybrids SH 2723 and SH 2729 in *Rabi* 2022-23 (E1) and *Rabi* 2023-24 (E3) conditions and SH 2733 and SH 2732 in *Kharif* 2023 (E2) condition showed specific adaptability. Besides, *Rabi* 2022-23 (E1) serves as the optimal seasonal condition

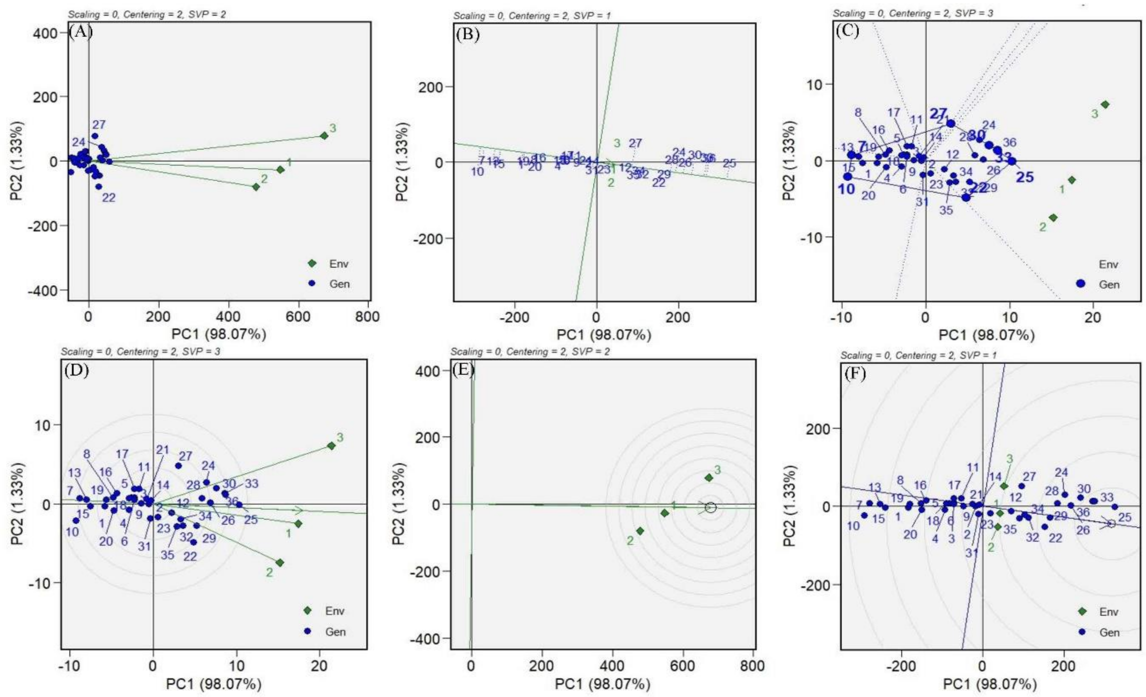

Fig. 4. GGE biplots for oil yield (A) Genotypic view of biplot, (B) Mean vs Stability, (C) Which- won-where biplot, (D) Discriminativeness vs representativeness, (E) Ranking environments, (F) Ranking genotypes

for selecting adaptable genotypes based on seed and oil yield traits. Overall, the hybrids SH 2723, SH 2730, SH 2729, SH 2731 and SH 2671 showed superiority with high mean and stability over three different seasonal conditions and can be considered for further investigation before commercial cultivation. Further, these hybrids provide a basis for developing inbred lines to increase adaptability under diverse climatic conditions.

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