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Original scientific article

STABILITY AND GENOTYPE X ENVIRONMENT ANALYSIS FOR SEED AND OIL YIELD PARAMETERS AMONG INBRED LINES OF SUNFLOWER (*Helianthus annuus* L.)

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Stability analysis was carried out for 44 sunflower inbreds evaluated for four seasons 2018-2021 using Additive Main Effects and Multiplicative Interaction (AMMI) model, which reveals significant interactions between inbreds and environment for seed yield per plant. Based on AMMI analysis 14 inbreds were found stable for seed yield while 15 inbreds were identified having stable oil yield across environments. The stable inbreds for both the traits as per AMMI analysis were OPH96, OPH98, SF3R, P147R, P107R, OPH118, OPH73, HRAHA5, P121R, P150R, P140R and SF1R. Similarly genotype x environment (G x E) analysis on the same set of inbreds was carried out based on GGE model which lead to discrimination of environments as well as identification of stable inbreds for both seed and oil yield. The superior inbreds identified using GxE biplot were OPH137, OPH76, OPH102 and OPH122. The superior inbreds based on the factor analysis index were OPH 102, OPH 75, OPH 86, OPH 76, P150R2, OPH 122 and OPH 150.
Keywords: AMMI, BLUPs, GGE biplot, Multi Trait Stability Index, Stability

INTRODUCTION

Sunflower ranks fourth in terms of acreage (27.87 Mha), production (57.26 MMT) and consumption of oil (20.47 MMT) worldwide after palm oil, soybean oil and rapeseed-mustard oil (ANONYMOUS, 2022) and third in terms of market share. India is one of the major consumer of

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sunflower seed oil (third largest in the world), most of which is imported from countries like Ukraine, Russia and Argentina thus making it an important crop for food and economic security. Sunflower not only contains higher percentage of oil content but the sunflower oil is considered to be of premium quality for human consumption owing to its tasteless and odourless property. Sunflower seed oil is rich in polyunsaturated fatty acids including linoleic acid and oleic acid which play a fundamental role in human nutrition and health (GAFFARI *et al.*, 2020).Sunflower seeds are also rich in protein, minerals, vitamin, and oil that are used in the nutritional and pharmaceutical industries (DARVISHZADEH *et al.*, 2011). Sunflower has wider adaptability and can be grown under a wide range of agro-climatic conditions due to its photo and thermo - insensitive nature, however, its performance is largely influenced by environment. Seed and oil yield are both complex quantitative traits and are highly influenced by environment, which results in the scale or rank shift in performance of different inbreds. This relative shift of inbred performance from one environment (or year) to another is known as genotype x environment interaction (GxE). To evaluate such interactions multi-environment evaluation trials are conducted and studies regarding stability of inbreds or prediction of inbreds in different environments can be done. Based on the general or specific adaptability of the inbreds to different kinds of environments they can be selected for different breeding programmes. Among various methods Additive Main Effects and Multiplicative Interaction (AMMI) analysis is one of the popular parametric but multivariate methods to predict adaptation and stability of genotypes. In sunflower the AMMI model has been successfully employed for estimation of stability of inbreds or hybrids by MOUSAVI *et al.*, 2016, KHOMARI and MOHAMMADI, 2017, JOCKOVIC *et al.*, 2019, SOFALIAN *et al.*, 2019 and ANSARIFARD *et al.*, 2022. Among the graphical stability methods, the GGE biplot analysis is a very useful tool for identification of the best performing genotype in an environment, to determine the discriminating ability and representativeness of environments for genotypes evaluation, to identify the most appropriate environment for a given genotype, to determine the interrelations between environments, and finally to compare and rank genotypes by the average yield and stability (YAN and TINKER, 2005; RANA *et al.*, 2021). The GGE biplot analysis has been utilized in sunflower by POURDAD and MOGHADDAM, 2013, ANSARIFARD *et al.*, 2020 and GHAFFARI *et al.*, 2021. The present study aimed to investigate the effects of variable environments on the performance of sunflower inbreds, estimate genotype–environment interaction and determine the most stable and most adaptable inbreds of sunflower for development of superior sunflower hybrids. Furthermore a multi trait selection index was used for selection superior inbreds based on FAI-BLUP (Factor Analysis Index based Best Linear Unbiased Predictions) which has been reported superior to direct selection for complex traits like seed yield as well as indirect selection based on harmonic mean of performance and stability index of genotypes (COSTA *et al.*, 2023)

MATERIAL AND METHODS

*Experimental layout and material*s

Fourty four sunflower inbreds were evaluated for four consecutive years at sunflower experimental area, Punjab Agricultural University, Ludhiana at 30°54' N, 75°47'E and 247 m above mean sea level. The inbreds were raised during the spring seasons of 2018, 2019, 2020 and 2021. The details related to weather during growing season during the years of evaluation are mentioned in the Table 1. The inbreds were manually sown using hill sowing method on 21.2.2018, 24.2.2019, 18.2.2020 and 20.2.2021 during the four years respectively. Two 3m long rows which were 60 cm apart constituted one plot and the plants were spaced at 30 cm distance from each other. Two to three seeds were sown per hill to ensure proper plant stand and only one plant was retained at 30 days after sowing. All the recommended cultural practices for raising sunflower during the spring season were adopted to raise a healthy crop. Bagging of individual plants was done to ensure self pollination.

Table 1.Weather data for the growing seasons 2018- 2021

Year	Max Temp ^{0}C			Min temp ^{0}C			RH I % Max			RH I % Min			RH II % Max			RH II % Min			Rainfall (mm)		
	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
2018	28.3	34.6	41.6	12.3	18.7	21.8	92	71	64	63	35	42	82	64	43	34	21	18	85.4	20.8	73.4
2019	34.8	39.6	42.1	5.6	18.0	23.1	89	73	66	53	34	40	69	45	33	29	19	9	27.0	25.4	98.2
2020	29.1	35.5	43.2	14.5	18.2	20.8	94	71	66	61	35	44	81	66	43	37	21	15	84.0	29.4	33.8
2021	33.3	38.4	40.3	10.6	17.6	21.8	97	66	71	64	45	52	61	34	46	25	12	27	12.2	8.2	70.8

RH I: Relative Humidity (Moisture-Saturated) , RH II: Equilibrium Relative humidity, I: Pre-flowering, II: Flowering stage, III: Seed filling stage

Data observation and statistical analysis

The data was observed from 5 randomly selected plants and average was recorded for seed yield per plant (g). Oil content was estimated using Nuclear Magnetic Resonance Spectrometry from a random sample drawn out of entire plot and oil yield per plant was calculated using formula, % oil content x seed yield per plant (g). Descriptive statistics and Analysis of variance was carried out for pooled data and heterogeneity of environment variances was checked. The correlation coefficients among environments were calculated based on Pearsons method. Mixed model analysis was done using indicating both inbreds and environments as random factors. Adaptability and phenotypic stability analyses of i^{th} genotype in j^{th} environment were performed through AMMI method and Genotype by Genotype x Environment analysis was done (ZOBEL *et al.*, 1988; GAUCH and ZOBEL,1997). The different AMMI indexes were estimated for comparing the inbreds *viz*., AMMI stability parameter (ASTAB), AMMI stability index (ASI), AMMI stability value (ASV), sum across environments of absolute value of GEI modelled by AMMI (AVMAGE), Annicchiarico's D parameter values (DA), Zhang's D parameter (DZ), sum of averages of the squared eigen vector values (EV), stability measure based on fitted AMMI model (FA), modified AMMI stability index (MASI), modified AMMI stability value (MASV), Sums of the absolute value of the IPC scores (SIPC), absolute value of the relative contribution of IPCs to the interaction (ZA) and weighted average of absolute scores (WAAS) and selection of superior inbreds was done using top ranking inbreds based on most of the AMMI indexes. The analysis were done using stats, psych and metan packages of R software (OLIVOTO and LUCIO, 2020). Multi trait selection index was also calculated using metan package of R software.

RESULTS

The descriptive statistics suggests that ample variation was present for both seed and oil yield among sunflower inbreds tested across four environments as depicted in Figure. 1. The seed yield ranged from 5.0 to 50 g per plant whereas, oil yield per plant varied from 1.83 to 22.9 g/ plant. The standard error for seed yield was higher (0.883) in comparison to oil yield per plant (0.363). Heteroscedasticity among environment variances was observed as per Bartlett's test for homogeneity for both the parameters. The pooled ANOVA revealed significant differences among inbreds, environment main effects as well as inbred x environment interactions (Table 2). The results imply that across years the inbreds performed variably for both the parameters and not only that even environment has impacted the seed yield and oil yield significantly. This means that it is important to evaluate sunflower inbreds under different environments so as to clearly interpret which inbreds are high yielding. The presence of significant interactions inhibits selection of superior inbreds across environments thus stability analysis was carried out using AMMI model.

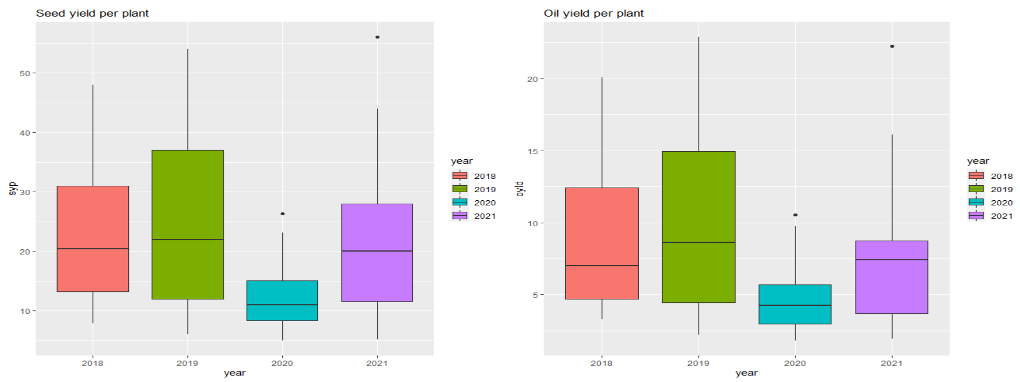

Figure 1. Boxplots showing variation present for seed and oil yield per plant among the inbreds in different years

Table 2. Pooled analysis of variance for seed and oil yield per plant

Source of Variation	Degrees of freedom	Seed Yield per Plant	Oil Yield per Plant
Inbred	43	239.77***	46.126***
Year	3	1823.48***	292.347***
Inbred:Year	128	114.14*	18.07*
Residual	28	57.6	8.56

* P<0.05; *** P<0.001

AMMI analysis for seed yield

The analysis of variance as per AMMI model also suggests significant inbred x environment interactions apart from significant environment and inbred main effects (Table 3) for seed yield per plant. The interaction effects are further divided into three principal components explaining 52.6%, 32% and 15.4% variation respectively for seed yield per plant. Several AMMI indexes for the trait were estimated for ranking the inbreds and inbreds OPH96 (27.0 g), RHA 265 (21.85 g), RHA83R6 (20.71 g), HRAHA5 (13.25 g), P140R (12.3 g) and SF1R (8.78 g) were ranked as top most stable inbreds based on all stability indexes while P147 R, LTRR 341 and OPH73 were included in top ranking inbreds based on almost all AMMI indexes (Table 4).Among environments, year 2019 was high yielding with average yield of 27.22 g per plant across inbreds while year 2020 was least yielding with average yield of 12.04 g per plant. Based on the data observed for seed yield per plant the environments 2018 and 2020 revealed maximum correlation (r=0.38, p= 0.01), followed by year 2019 and 2020 (r= 0.32, p= 0.04) which were significant at 5% level of significance. Year 2021 was found to have no significant correlation with any of the environments (Figure 2).

Table 3. AMMI analysis of variancefor seed and oil yield per plant

Source	Df	Seed Yield per Plant			Oil Yield per Plant		
		Mean Sq	Proportion	Accumulated	Mean Sq	Proportion	Accumulated
ENV	3	1823.48***			292.35***		
REP(ENV)	12	71.31			10.99		
GEN	43	239.77***			46.13***		
GEN:ENV	128	114.14*			18.07*		
PC1	45	888.82***	52.6	52.6	146.76***	54.0	54.0
PC2	43	566.77***	32.0	84.6	86.80***	30.5	84.5
PC3	41	285.07***	15.4	100.0	46.13***	15.5	100.0
Residuals	16	47.32			6.74		
Total	331	326.46			53.29		

* P<0.05; *** P<0.001

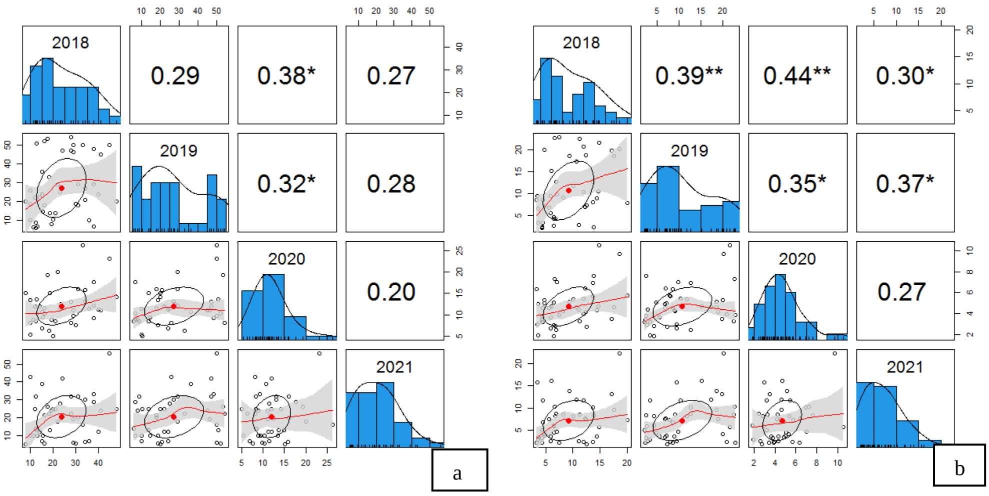

Figure 2.Correlation coefficient among environments for seed yield (a) oil yield per plant (b)

The biplot where seed yield was plotted against PC1 reveals that OPH 137 was highest yielding inbred and exhibited less interaction with environment. The other inbreds which had low IPCA1 scores and thus were less influenced by environments were OPH 96, OPH 98, RHA 265, SF3R, P147R, P 107R, LTRR 341, OPH 118, OPH73, HRAHA5, P121R, P150R1, P140R and SF1R. The inbreds which had IPCA scores considerably deviating from zero and thus revealed higher interactions with environment were OPH 92, OPH 74, P143 R and OPH 90. Furthermore, year 2019 was highest yielding environment and simultaneously exerted highest interaction effect. Rest of the environments exhibited more or less similar interaction effects (Figure 3a). When IPCA1 and IPCA2 were plotted on a biplot it was observed that year 2018 and 2020comprised one mega-environment whereas 2019 and 2021 exhibited no association with other environments. OPH74, P143R and OPH50 were found performing better during 2019 whereas, SF3R, RHA6DI, OPH139 performed better during 2021. Under the conditions prevailing during 2018 and 2020 the inbreds OPH124, OPH 45, OPH 99 and OPH 109 were found better performing for the trait seed yield per plant (Figure3b).

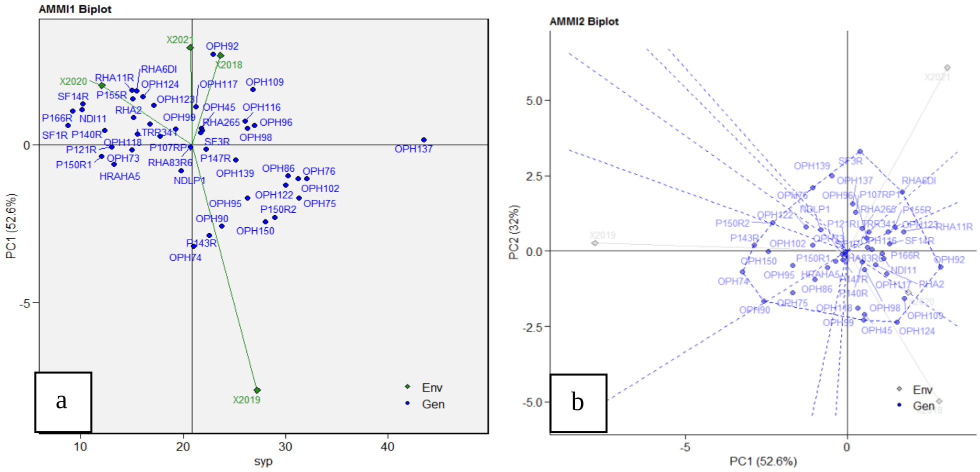

Figure 3. AMMI biplot for GEI based on IPCA scores (a) and AMMI biplot based on interaction PC1 and PC2 for seed yield per plant

AMMI analysis for oil yield

As per the AMMI analysis for oil yield per plant, partitioning of inbred x environment interaction effects into three principal components explained 54.0%, 30.5% and 15.5% variation respectively (Table 3). As per multiple AMMI indexes inbreds OPH96 (10.87 g), RHA83R6 (8.85 g), RHA 265 (7.55 g), HRAHA5 (5.14 g), P140R (4.70 g) and SF1R (2.96 g) were ranked as top most stable inbreds for oil yield per plant. Inbreds P147 R (7.20 g), P 107R P1 (6.09 g) and OPH 73 (5.18 g) were among the top ranking as per most of the AMMI indexes (Table 5). Year 2019 exhibited a high oil yield of 10.78 g/ plant across inbreds while the year 2020 was least yielding with average oil yield of 4.68 g/plant. When correlation among environments were evaluated, maximum correlation was present among year 2018 and 2020 (r= 0.44, p=0.00). This was followed by correlation between year 2019 and 2018 (r= 0.39, p=0.01), between year 2019 and 2021 (r=0.37, p=0.01), between year 2019 and 2020 (r=0.35, p=0.02) and among year 2018 and 2021 (r=0.30, p=0.05) as depicted in Figure2.

The biplot where oil yield per plant was plotted against first principal component reveals that OPH 137 was highest yielding inbred and exhibited less interaction with the environment. The other inbreds which had low IPCA1 scores and thus were less influenced by environments were OPH 96, OPH 139, OPH 98, RHA 83 R6, OPH45, SF3R, NDLP1, OPH 118, P147R, P 107R P1, OPH73, P121R, HRAHA5, P150R1, P140R and SF1R. The inbreds which had IPCA scores considerably deviating from zero and thus revealed higher interactions with environment were OPH 92, OPH 74, P143 R, OPH 90, OPH150 and P 150 R2. As depicted in the Figure 4a, year 2019 was highest yielding environment and simultaneously exerted the highest interaction effect. Rest of the environments exhibited association between their interaction effects. The biplot among IPCA1 and IPCA2 scores revealed that performance of inbreds were similar during 2020 and 2018 while other environments allowed discrimination of inbreds based on oil yield per plant. Based on the polygons as seen in Figure 4b OPH74, P143R, OPH150, OPH 90 and P150 R2 exhibited higher oil yield under high yielding environments. During year 2021 SF3R, RHA6DI and OPH139 were found performing better while OPH 109 and OPH 99 were best performing during year 2018. OPH 92 was best performing inbred for oil yield per plant under low yielding environment.

Table 4. Stability indexes based on AMMI model for seed yield per plot

GEN	Mean	ASTAB	ASI	ASV	AVAMGE	DA	DZ	EV	FA	MASI	MASV	SIPC	ZA	WAAS
HRAHA5	13.25	0.95	0.37	1.16	13.67	7.91	0.12	0.01	62.53	0.38	1.62	1.69	0.07	0.58
LTRR341	16.74	1.23	0.40	1.25	17.43	8.84	0.14	0.01	78.15	0.41	1.82	1.92	0.08	0.64
NDI11	10.10	2.82	0.59	1.85	18.84	13.14	0.22	0.02	172.66	0.62	2.27	2.59	0.10	0.85
NDLP1	19.83	1.36	0.49	1.53	18.47	9.77	0.14	0.01	95.36	0.49	2.05	1.95	0.09	0.73
OPH102	32.08	5.72	0.57	1.79	27.84	17.24	0.34	0.04	297.34	0.66	2.80	3.41	0.12	0.96
OPH109	26.80	8.32	1.05	3.26	36.91	23.01	0.37	0.05	529.35	1.08	4.66	4.99	0.20	1.68
OPH116	26.03	1.55	0.40	1.24	18.83	9.49	0.17	0.01	90.01	0.43	1.59	1.80	0.07	0.57
OPH117	21.25	2.03	0.68	2.11	21.23	12.44	0.16	0.01	154.80	0.68	2.53	2.02	0.10	0.88
OPH118	15.50	3.84	0.63	1.96	25.23	15.58	0.25	0.02	242.77	0.63	3.99	2.64	0.10	0.84
OPH122	30.00	3.01	0.72	2.26	25.77	14.41	0.22	0.02	207.72	0.74	2.82	2.93	0.13	1.06
OPH123	17.10	2.03	0.69	2.15	18.84	12.49	0.16	0.01	155.89	0.69	2.46	2.13	0.10	0.90
OPH124	16.05	7.98	1.10	3.44	42.83	23.42	0.34	0.04	548.55	1.10	5.52	4.23	0.19	1.61
OPH137	43.53	5.61	0.51	1.58	25.67	17.21	0.33	0.04	296.33	0.57	3.71	3.49	0.11	0.85
OPH139	25.18	6.48	0.83	2.61	37.07	20.39	0.32	0.03	415.69	0.84	5.25	3.20	0.13	1.08
OPH150	28.05	7.35	1.28	4.01	39.26	23.41	0.32	0.03	548.04	1.30	4.18	3.64	0.17	1.47
OPH45	21.80	5.75	0.73	2.27	30.91	18.73	0.31	0.03	350.90	0.74	4.58	3.66	0.14	1.11
OPH73	15.00	1.25	0.09	0.29	13.07	7.52	0.17	0.01	56.57	0.19	1.15	1.37	0.04	0.29
OPH74	21.03	11.30	1.71	5.35	49.31	30.00	0.38	0.05	899.76	1.72	5.53	4.54	0.23	2.02
OPH75	31.33	5.69	1.00	3.11	32.37	19.92	0.29	0.03	396.92	1.01	4.13	4.02	0.18	1.48
OPH76	31.25	6.53	0.87	2.73	40.77	20.42	0.32	0.04	416.88	0.89	4.81	4.17	0.17	1.39
OPH86	30.25	5.10	0.60	1.88	32.87	16.72	0.31	0.03	279.64	0.66	3.12	3.73	0.14	1.10
OPH90	23.75	9.64	1.46	4.56	44.87	27.02	0.36	0.04	730.06	1.46	5.49	4.70	0.23	1.96
OPH92	22.93	8.73	1.52	4.74	44.49	26.45	0.33	0.04	699.65	1.52	4.86	3.86	0.20	1.75
OPH95	26.25	3.60	0.90	2.82	26.87	16.45	0.22	0.02	270.76	0.91	3.04	2.88	0.13	1.15
OPH96	27.00	0.79	0.35	1.08	12.93	7.21	0.11	0.00	51.98	0.35	1.42	1.52	0.06	0.53
OPH98	26.25	2.36	0.34	1.06	18.02	11.04	0.22	0.02	121.91	0.39	2.03	2.45	0.09	0.68
OPH99	19.30	5.50	0.78	2.42	34.62	18.81	0.29	0.03	353.81	0.78	4.83	3.01	0.13	1.03
P107RP1	17.76	2.37	0.44	1.36	20.98	11.82	0.20	0.01	139.73	0.45	2.84	2.34	0.09	0.67
P121R	13.05	2.89	0.04	0.12	18.41	11.30	0.26	0.02	127.73	0.26	1.70	1.80	0.04	0.31
P140R	12.30	1.05	0.27	0.84	12.43	7.54	0.14	0.01	56.91	0.30	1.36	1.67	0.06	0.49
P143R	22.51	9.43	1.52	4.74	43.93	27.00	0.36	0.04	729.24	1.53	4.86	4.12	0.20	1.74
P147R	22.25	1.51	0.12	0.38	14.07	8.31	0.18	0.01	69.13	0.22	1.35	1.62	0.05	0.35
P150R1	12.05	5.18	0.22	0.70	27.07	15.36	0.34	0.04	236.06	0.41	2.41	2.93	0.09	0.65
P150R2	28.94	7.04	1.25	3.90	35.48	22.97	0.31	0.03	527.75	1.26	4.36	4.16	0.19	1.66
P155R	15.10	3.02	0.81	2.51	24.13	14.99	0.20	0.01	224.67	0.81	2.95	2.77	0.13	1.10
P166R	9.23	2.49	0.56	1.75	19.03	12.35	0.21	0.01	152.64	0.59	2.11	2.30	0.09	0.76
RHA11R	15.03	3.42	0.93	2.92	26.69	16.48	0.21	0.01	271.75	0.93	3.15	2.43	0.13	1.13
RHA2	15.15	2.35	0.48	1.49	18.83	11.66	0.21	0.01	135.91	0.51	2.08	2.50	0.10	0.78
RHA265	21.85	0.84	0.34	1.06	12.72	7.45	0.11	0.00	55.57	0.34	1.75	1.46	0.06	0.52
RHA6DI	15.48	6.74	1.09	3.40	37.03	21.90	0.31	0.03	479.67	1.09	4.93	3.88	0.18	1.55
RHA83R6	20.71	0.03	0.05	0.16	2.25	1.35	0.02	0.00	1.81	0.06	0.28	0.30	0.01	0.09
SF14R	10.20	2.59	0.69	2.14	22.33	13.36	0.20	0.01	178.42	0.70	2.37	2.45	0.11	0.90
SF1R	8.78	1.04	0.32	1.00	13.63	7.74	0.14	0.01	59.95	0.34	1.31	1.55	0.06	0.49
SF3R	21.71	11.03	1.07	3.35	42.99	26.55	0.42	0.06	705.13	1.07	6.90	3.86	0.16	1.28

Table 5. Stability indexes based on AMMI model foroil yield per plant

GEN	Mean	ASTAB	ASI	ASV	AVAMGE	DA	DZ	EV	FA	MASI	MASV	SIPC	ZA	WAAS
HRAHA5	5.14	0.26	0.17	0.57	4.54	2.51	0.11	0.00	6.32	0.18	0.76	0.86	0.05	0.28
LTRR341	6.13	0.54	0.28	0.90	7.48	3.76	0.15	0.01	14.14	0.28	1.30	1.24	0.08	0.43
NDI11	3.47	1.04	0.41	1.35	8.18	5.24	0.21	0.01	27.49	0.43	1.52	1.52	0.10	0.54
NDLP1	7.69	0.60	0.29	0.95	7.91	3.97	0.15	0.01	15.73	0.29	1.37	1.31	0.09	0.45
OPH102	13.41	3.12	0.41	1.35	13.33	8.03	0.40	0.05	64.53	0.48	2.12	2.57	0.14	0.72
OPH109	10.27	4.22	0.72	2.34	17.20	10.34	0.42	0.06	106.93	0.73	3.58	3.49	0.22	1.16
OPH116	9.89	0.60	0.26	0.86	7.04	3.81	0.17	0.01	14.50	0.28	1.12	1.29	0.08	0.42
OPH117	8.34	0.83	0.46	1.51	8.23	5.12	0.16	0.01	26.23	0.46	1.64	1.25	0.10	0.57
OPH118	6.16	1.66	0.41	1.34	10.39	6.46	0.26	0.02	41.70	0.41	2.49	1.80	0.11	0.58
OPH122	11.13	1.03	0.39	1.29	9.79	5.19	0.20	0.01	26.92	0.40	1.63	1.74	0.11	0.60
OPH123	5.55	0.92	0.45	1.49	7.97	5.28	0.18	0.01	27.84	0.45	1.73	1.51	0.11	0.61
OPH124	5.27	1.96	0.63	2.06	14.12	7.60	0.26	0.02	57.70	0.63	2.61	2.09	0.16	0.86
OPH137	17.69	2.51	0.26	0.85	10.52	7.05	0.36	0.04	49.66	0.33	2.14	2.23	0.10	0.49
OPH139	10.50	3.33	0.57	1.86	16.55	9.11	0.37	0.05	83.00	0.57	3.50	2.57	0.16	0.81
OPH150	11.41	3.13	0.90	2.96	16.63	9.94	0.32	0.03	98.79	0.91	3.02	2.31	0.18	1.01
OPH45	7.87	1.70	0.41	1.35	10.64	6.53	0.26	0.02	42.64	0.42	2.50	1.87	0.12	0.60
OPH73	5.18	0.73	0.10	0.34	6.23	3.68	0.20	0.01	13.51	0.16	0.91	1.12	0.05	0.26
OPH74	9.09	5.30	1.19	3.90	21.90	13.02	0.41	0.06	169.58	1.19	4.02	3.20	0.25	1.41
OPH75	13.23	2.79	0.68	2.23	13.34	8.74	0.33	0.04	76.39	0.69	2.93	2.84	0.19	1.02
OPH76	11.73	1.76	0.52	1.70	13.66	6.88	0.26	0.02	47.33	0.52	2.37	2.23	0.15	0.80
OPH86	12.60	2.28	0.43	1.42	14.02	7.21	0.33	0.04	52.03	0.47	2.27	2.56	0.15	0.77
OPH90	9.81	3.87	0.95	3.10	18.41	10.90	0.36	0.04	118.74	0.95	3.61	2.74	0.22	1.22
OPH92	8.08	3.09	0.92	3.02	16.79	10.02	0.31	0.03	100.40	0.92	3.14	2.24	0.19	1.07
OPH95	10.75	1.50	0.59	1.93	11.62	6.74	0.23	0.02	45.44	0.59	2.10	1.92	0.14	0.77
OPH96	10.87	0.18	0.12	0.40	3.31	2.01	0.09	0.00	4.03	0.13	0.64	0.71	0.04	0.22
OPH98	9.68	0.98	0.26	0.85	7.79	4.65	0.22	0.02	21.66	0.28	1.48	1.65	0.09	0.48
OPH99	7.48	1.98	0.47	1.55	13.02	7.14	0.28	0.03	50.99	0.47	2.74	1.90	0.13	0.67
P107RP1	6.09	0.60	0.18	0.59	6.25	3.62	0.17	0.01	13.13	0.20	1.26	1.15	0.06	0.29
P121R	4.69	0.98	0.11	0.36	6.95	4.26	0.23	0.02	18.17	0.18	1.09	1.34	0.06	0.30
P140R	4.70	0.35	0.22	0.70	4.41	2.95	0.13	0.01	8.71	0.23	0.83	0.89	0.06	0.30
P143R	8.59	3.82	0.93	3.06	17.38	10.68	0.37	0.05	114.00	0.94	3.20	2.79	0.21	1.12
P147R	7.20	0.80	0.03	0.11	6.22	3.78	0.21	0.01	14.30	0.14	0.91	1.02	0.04	0.18
P150R1	5.12	1.94	0.07	0.22	10.41	5.89	0.33	0.04	34.72	0.23	1.41	1.57	0.07	0.30
P150R2	11.72	3.52	0.91	2.98	16.31	10.37	0.35	0.04	107.48	0.91	3.29	2.92	0.22	1.19
P155R	4.69	0.50	0.35	1.16	6.39	3.95	0.13	0.01	15.64	0.35	1.24	1.07	0.08	0.45
P166R	3.08	0.99	0.39	1.27	7.19	5.05	0.20	0.01	25.54	0.40	1.45	1.43	0.09	0.50
RHA11R	4.51	0.89	0.50	1.64	9.19	5.41	0.17	0.01	29.28	0.50	1.68	1.15	0.10	0.57
RHA2	5.23	0.77	0.35	1.16	6.46	4.51	0.18	0.01	20.31	0.36	1.30	1.26	0.08	0.45
RHA265	7.55	0.18	0.16	0.53	3.54	2.20	0.08	0.00	4.86	0.16	0.79	0.67	0.05	0.24
RHA6DI	5.70	2.82	0.68	2.23	15.13	8.86	0.32	0.03	78.59	0.68	3.17	2.55	0.18	0.98
RHA83R6	8.85	0.00	0.02	0.05	0.36	0.22	0.01	0.00	0.05	0.02	0.06	0.07	0.00	0.02
SF14R	3.71	1.02	0.48	1.57	9.67	5.53	0.19	0.01	30.58	0.48	1.73	1.61	0.12	0.64
SF1R	2.96	0.42	0.25	0.83	5.72	3.29	0.13	0.01	10.81	0.26	0.97	1.04	0.07	0.36
SF3R	7.91	4.37	0.63	2.06	16.92	10.38	0.42	0.06	107.68	0.63	4.04	2.72	0.16	0.81

Genotype x Environment Analysis

Further the stability analysis was carried out based on GGE biplot analysis, a graphical technique of plotting principal component scores of the inbreds on two axis. GGE analysis revealed that the four principal components explained 55.55%, 79.23%, 17.75% and 3.03% variation respectively. Since 79.23% variation is explained by PC1 and PC2 the two principal components scores were plotted to identify the superior inbreds and evaluation of environments (Figure5a). The environment vectors on the biplot did not have more than 90^{o} angle between them which suggests that all the environments did not vary that much from each other, however, year 2019 and year 2021 were most dissimilar. The inbreds RHA 83 R6, OPH45, P147 R, P 107R P1 and OPH 99 were found most stable. The polygon plot reveals that year 2018, 2020 and 2021 formed a mega environment where inbred OPH 137, OPH 150, OPH 102, OPH 76, OPH 109, OPH 86 and OPH 122 were some of the best performing inbreds (Figure5b). Year 2019 on the other hand was different from rest of the environments and the inbreds found superior under this environment were P 150 R2 and OPH 95.

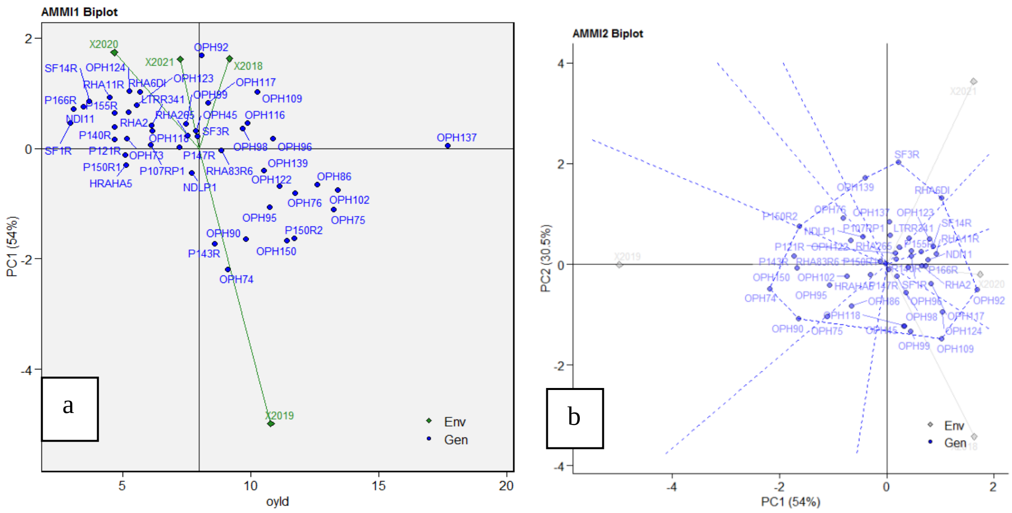

Figure 4. AMMI biplot for GEI based on IPCA scores (a) and AMMI biplot based on interaction PC1 and PC2 for oil yield per plant

The discriminative ability of environments were in the order 2019> 2021> 2018 > 2020 for seed yield per plant of inbreds (Figure5c). Based on both mean performance of inbreds and their stability for the parameter OPH 137, OPH 76, OPH 102, OPH 68, OPH 122 and OPH 139 can be selected as superior inbreds as revealed in Figure5d. Similarly for the parameter oil yield per plant GGE analysis was able to reduce the data into four principal components explaining 61.59%, 19.5%, 16.04 and 2.86% variation respectively. The first two principal components explained the cumulative variation of 81.08% and thus the two PCs were utilized to construct the biplots. Based on the biplot the environments again revealed higher association among themselves (Figure 6a). The inbreds that were found more stable were RHA 83R6, SF3R, LTRR 341, RHA 265, P 147R, NDLP1, OPH 123, OPH 99 and OPH 45. The polygon graph reveals that year 2021, 2018 and 2020 formed a mega environment where inbreds OPH 137, OPH 109, OPH150, OPH 75 and OPH 102 were having higher oil yield per plant. Under the conditions prevailing during 2019 only P 150 R2 exhibited higher oil yield per plant. While comparing both average oil yield per plant and stability of the inbreds OPH 137, OPH 102, OPH 86 and OPH 96 were found superior (Figure6b). Year 2019 and year 2021 were the most discriminating environments where as during 2018 and 2020 the inbreds performed relatively similar (Figure6c). Based on both mean performance of inbreds and their stability for the parameter OPH 137, OPH 102, OPH 86, OPH 76, OPH 122 and OPH 96 can be selected as superior inbreds as revealed in Figure 6d.

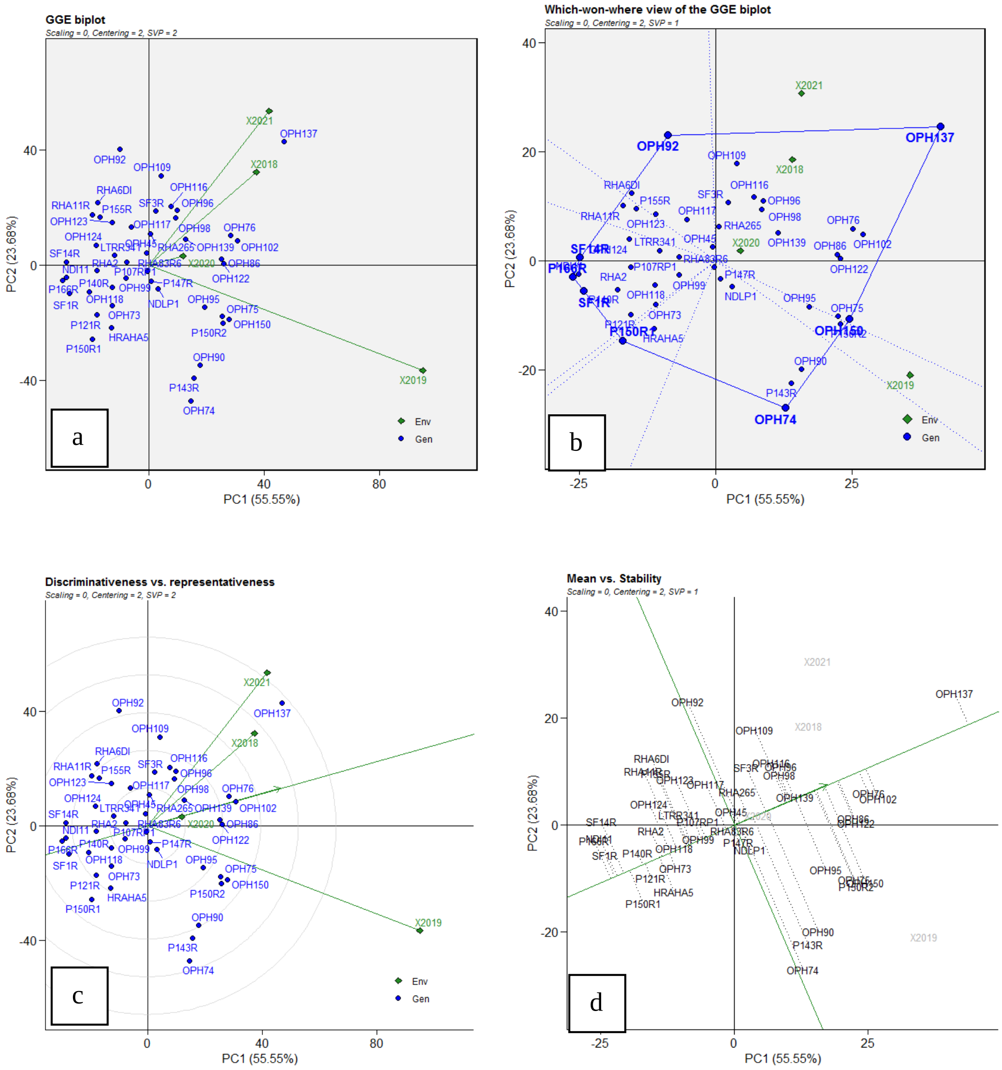

Figure 5. GGE biplot with inbreds plotted for PC1 and PC2 (a), which won where plot (b), discriminativeness *vs* representativeness of environments (c) and mean *vs* stability of inbreds(d) plotted for seed yield per plant

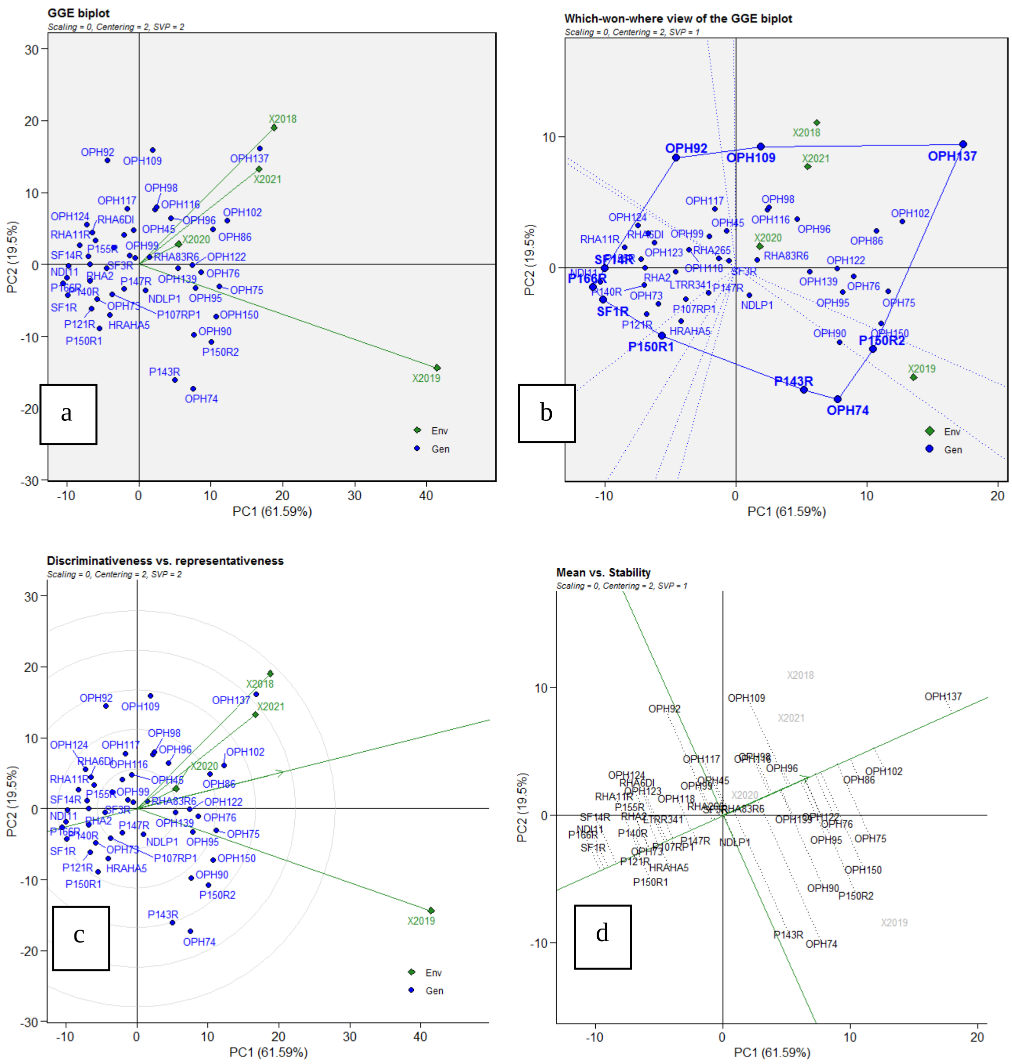

Figure 6. GGE biplot with inbreds plotted for PC1 and PC2 (a), which won where plot (b), discriminativeness *vs* representativeness of environments (c) and mean *vs* stability of inbreds plotted (d) for oil yield per plant

Mixed model analysis and multi trait index based analysis

The mixed model analysis of the multi environment data reveals that genotype, environment and genotype x environment interactions were all significant (at 1% level of significance). Low heritability of 16.8% and 22.0% was revealed for seed yield and oil yield parameter whereas, heritability on mean basis was 65.1% and 72.1% respectively. The model reveals high accuracy to selection of 80.7% and 84.9% for seed yield and oil yield respectively. The inbreds with higher BLUPs for seed yield were OPH137, OPH102, OPH 75, OPH 76, OPH

86, OPH 122 and P 150 R2; similarly the superior hybrids based on BLUP values for oil yield were OPH 137, OPH 102, OPH 75, OPH 86, OPH 76, P 150 R2 and OPH 150 (Figure7).Based on a multi trait index which incorporates factor analysis (FAI- BLUP selection index) the inbreds exhibiting superiority based on perse performance and stability were identified as OPH 102, OPH 75, OPH 86, OPH 76, P 150 R2, OPH 122 and OPH 150 which has been presented in Figure 8.

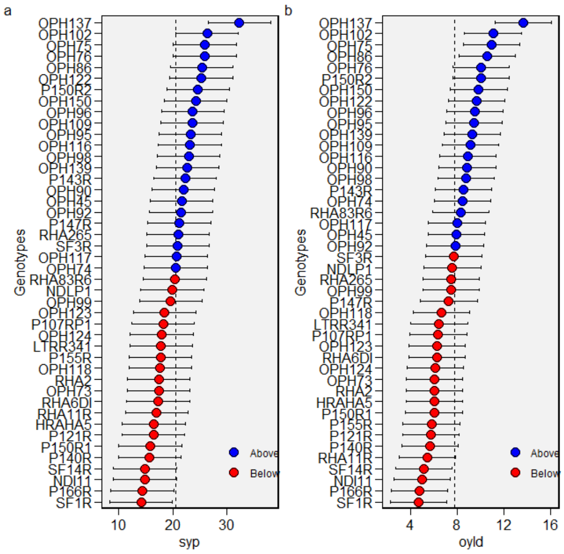

Figure 7.Superior inbreds identified based on BLUP values

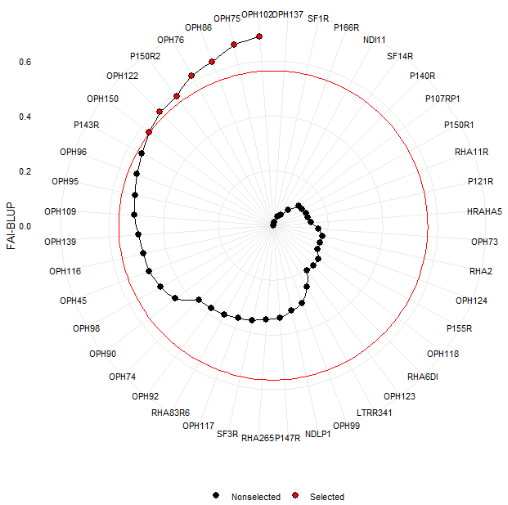

Figure 8.Genotype ranking based on multi trait selection index considering a selection intensity of 15%

DISCUSSION

AMMI analysis is a robust tool for separation of main effects of genotypes and environments as well as interaction effects, a number of stability indexes can be used for identification of inbreds which are superior with respect to both mean performance as well as stability across environments. The inbreds with superior stability indexes were identified. The ranking of inbreds based on several stability indexes didn't change much thus the superior inbreds could be identified with higher degree of confidence. Biplot graph constructed on the basis of AMMI model allow the identification of stable inbreds easily and also reveals that 2018 and 2020 exhibited higher correlation thus forming a mega-environment. AMMI analysis has been utilized by several researchers for identification of superior inbreds and identification of environments with higher association (STOJAKOVIĆ *et al.*, 2015). The GGE biplot on the other hand not only allows identification of stable genotypes, but also gives information regarding distinctiveness of environments for identification of environments suitable for differentiation of inbreds. Also the inbreds suitable for each and every environment were detected. The environments that exhibited high degree of correlation *viz*., 2020, 2018 and 2021formed one mega environment for both the seed yield and oil yield parameters. For seed yield environment 2021 and 2019 were more distinctive whereas for oil yield 2019 and 2018 were found more differentiating. Similarly the GGE biplot has been successfully utilized for identification of mega-environment and superior inbreds with high adaptability in sunflower (POURDAD and MOGHADDAM, 2013, ANSARIFARD, 2020), wheat (JAT *et al.*, 2017) and garden pea (RANA *et al.*, 2021) In the present investigation different sets of inbreds were identified by AMMI and GGE biplot analysis for seed yield while for oil yield one common inbred OPH 96 was identified as superior by both methods. Similar results where just a few genotypes were commonly identified by both methods were reported in sunflower by JOKOVIC *et al.*, 2019 and MEENA *et al.*, 2023; in barley by MORTAZAVIAN *et al.*, 2014, VAEZI *et al.*, 2017 and SOLONECHNY, 2018. However, for oil yield OPH96 was found superior by both AMMI as well as GGE analysis. The ranking of environments based on performance was same for both AMMI as well as GGE biplot however the correlation among environments differed. Furthermore, if we compare GGE biplot with mixed model analysis higher correlation exists between these two analysis for identification of superior inbreds. Multi-trait selection index however is the only method by which superior inbreds for both seed and oil yield along with higher adaptability can be identified simultaneously. Thus the FAI-BLUP selection index was most appropriate method for identification of better performing stable inbreds. FAI-BLUP index is suitable for combined genetic selection and can be used to achieve selection gains in all traits analyzed simultaneously; it is superior when compared with direct selection for GY traits, indirect selection based on harmonic mean of relative performance of genotypic values, and selection for stability (PEIXOTO *et al.*, 2021, ALMEIDA *et al.*, 2021 and COSTA *et al.*, 2023).

CONCLUSION

The superior inbreds based on both mean performance and stability for both seed yield as well as oil yield as per AMMI analysis were OPH96, OPH98, SF3R, P147R, P107R, OPH118, OPH73, HRAHA5, P121R, P150R, P140R and SF1R. Similarly, GGE biplot revealed that OPH137, OPH76, OPH102 and OPH122 were superior for both the traits. Finally, a multi trait index based on factor analysis was estimated for identification of superior inbreds for their mean performance as well as stability simultaneously for both the traits. The superior inbreds based on factor analysis index were OPH 102, OPH 75, OPH 86, OPH 76, P 150 R2, OPH 122 and OPH 150. In case of GGE biplot the 2019 was different than the rest of the three environments.

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ANALIZA STABILNOSTI I GENOTIP X SPOLJAŠNJA SREDINA ZA PARAMETRE PRINOSA SEMENA I ULJA KOD LINIJA SUNCOKRETA (*Helianthus annuus* L.)

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Izvod

Analiza stabilnosti je sprovedena za 44 genotipa suncokreta procenjene tokom četiri sezone 2018-2021., korišćenjem modela aditivnih glavnih efekata i multiplikativne interakcije (*AMMI*), koji otkriva značajne interakcije između genotipa i spoljašnje sredine za prinos semena po biljci. Na osnovu AMMI analize, utvrđeno je da je 14 genotipova stabilno za prinos semena, dok je 15 identifikovano sa stabilnim prinosom ulja u različitim sredinama. Stabilni genotipovi za obe osobine prema AMMI analizi bile su OPH96, OPH98, SF3R, P147R, P107R, OPH118, OPH73, HRAHA5, P121R, P150R, P140R i SF1R. Slično tome, analiza genotipa x spoljašnja sredina (*G x E*) na istom skupu genotipova je sprovedena na osnovu GGE modela, što je dovelo do diskriminacije sredina, kao i identifikacije stabilnih genotipova i za prinos semena i za prinos ulja. Superiorni genotipovi identifikovani korišćenjem GxE biplota bili su OPH137, OPH76, OPH102 i OPH122. Superiorni genotipovi na osnovu indeksa faktorske analize bile su OPH 102, OPH 75, OPH 86, OPH 76, P150R2, OPH 122 i OPH 150.

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