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Assessment of G × E interactions using AMMI, GGE biplot and stability analysis in blackgram (*Vigna mungo*)

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ABSTRACT

The experiment was conducted during rainy (*kharif*) 2020, winter (*rabi)* 2020–21, summer 2021, rainy (*kharif*) 2021 and winter (*rabi*) 2021–22 at National Pulses Research Station, Pudukkottai, Tamil Nadu to assess the stability over environments, G×E interaction through Finlay-Wilkinson, Eberhart and Russell model, AMMI analysis and GGE biplot model for grain yield using 20 blackgram [*Vigna mungo* (L.)] genotypes in five consecutive seasons with climatic variations. Based on stability analysis the genotypes, viz. VBG17021, VBG17030, VBG18034 and VBN 8 were identified as more stable genotypes across environments with high yielding. In the AMMI model G×E interaction analysis disclosed that a total of 93.7% of interaction was contributed by the first three principal components viz. IPCA1, IPCA2, and IPCA3. The genotypes VBG18048 (G_5), VBG17026 (G_{14}), VBG18034 (G_{18}) and VBG18032 (G_{11}) were recorded the IPCA1 values close to zero suggested that these were more stable across environments. The yield of these genotypes were also better than the best check variety VBN8. The genotypes, such as VBG18032 (G_{17}) and VBG18040 (G_{20}) had high positive IPCA1 values showed a positive interaction with the particular environments (E_2). Therefore, these genotypes can be recommended for the favourable environment E_2 (*kharif* 2020), whereas the genotypes VBG18043 (G_3) and VBG18047 (G_4) can be recommended for another favourable environments E_3 and E_5 (*rabi* 2020 and 2021). The results of AMMI biplot 1 and 2 and GGE biplot analysis, determined that VBG 18043 (G_3) was more stable genotype coupled with high yielding across seasons. The "which- won- where" model of GGE biplot analysis showed that the genotypes VBG18048 (G_5) and VBG18034 (G_{18}) were highly suitable for the *kharif* and *rabi* seasons and VBG17030 (G_{16}) was suitable for summer season. The analysis of all four models of G×E interaction clearly indicated that the genotype VBG18034 was identified as more stable in all the five environments.

Keywords: AMMI, Blackgram, GGE biplot, G × E interaction, Grain yield, Stability

Blackgram [*Vigna mungo* (L.)] is a highly suitable legume crop for rainfed environment and is grown throughout the year in India. It is an affordable protein source offering all the essential amino acids for people living in Asian and African countries as well as having the potential of fixing nitrogen in the soil with symbiotic association with soil bacteria rhizobium. Therefore, it not only provides protein to the underprivileged communities but also contributes to soil health through its nitrogen fixing properties. Due to its shorter duration, suitable for crop rotation after cereals to improve the soil fertility level as well as income to the farmers. India ranks as one of the largest producers and consumers of blackgram. As per the Agricultural Statistics Division, DES, MoAF&W, 2022 report, the production is around 2.78 m tonnes from 4.63 million hectare area and the productivity is 600 kg/ha. It accounts approximately 11% of India's overall pulse production, which amounted to 25.46 million tonnes in 2020–21. One of the major limitations in blackgram production is instability in the yield. Current climate change signifying the necessity to develop high yielding cultivars suitable for varying climatic conditions (Singh *et al.* 2019). Development of high yielding genotypes with more stability across the environments has been a challengeable obsession to the plant breeders (Alwala *et al.* 2010). There are many analyses that have been suggested to assess the stability of genotypes, among that, the regression coefficient analysis by Finlay and Wilkinson (1963) and Variation from regression by Eberhart and Russell (1966) are more popular. The genotype, genotype plus environment interaction is considered as important parameter to identify the ideal genotype for crucial environments in plant breeding programme (Rajalakshmi *et al.* 2021). G × E statistics are often analyzed and interpreted by few statistical methods, such as AMMI (additive main effects plus multiplicative interaction) and the genotype main effects plus genotype ×

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environment interaction effects (GGE biplot) analysis (Yan *et al.* 2007). In blackgram, G × E interaction was studied by Revanappa *et al.* (2012) and identified two stable genotypes for grain yield. A total of 40 genotypes were evaluated by Konda *et al.* (2009) in two seasons and three locations and identified four high yielding genotypes with stability. Yield and its attributing traits were evaluated in blackgram for 14 genotypes by Rita *et al.* (2016). To know the stability and G × E interaction of the 17 advanced breeding lines developed through pedigree method of breeding and three check varieties in blackgram, the present investigation was carries out over seasons on grain yield.

MATERIALS AND METHODS

Experiment material: The experiment was conducted during rainy (*kharif*) 2020, winter (*rabi)* 2020–21, summer 2021, rainy (*kharif*) 2021 and winter (*rabi*) 2021–22 at National Pulses Research Station, Pudukkottai (10°36 N latitude, 78°90 E longitude with an altitude of 93 msl), Tamil Nadu. A total of 20 blackgram genotypes [G_1, VBG17012; G_2, VBG18042; G_3, VBG18043; G_4, VBG18047; G_5, VBG18048; G_6, VBG18049; G_7, VBG18050; G_8, VBG18052; G_9, VBG18054; G_{10}, VBN 6; G_{11}, VBN 8; G_{12}, VBG17021; G_{13}, VBN10; G_{14}, VBG17026; G_{15}, VB17029; G_{16}, VBG17030; G_{17}, VBG18032; G_{18}, VBG18034; G_{19}, VBG18035; G_{20}, VBG18040] consisting of 17 advanced cultures developed through pedigree method of breeding and three check varieties, viz. Vamban 6, Vamban 8 and Vamban 10 were studied. *Kharif* season aligns with south-west monsoon, characterized by minimum rainfall, hot and humid condition. During this period, average maximum temperature range from 31.5–35.8°C, while minimum temperature range from 24.0–28.8°C. Conversely, the *rabi* season coincides with north-east monsoon, bring the highest rainfall. This season is typically marked by cooler and more pleasant temperatures, with mean maximum around 33.7°C and mean minimum approximately 24°C. In contrast, the summer experience extreme heat and scarce rainfall, with average maximum temperatures around 33.7°C and occasionally surpassing 40°C. The soil type is red lateritic soil *p*H ranged from 6.5–7.0. In the recent past, there is drastic change in climatic condition and also the rainfall distribution is not even. Hence, the yield performance of advanced genotypes were assessed in five consecutive seasons, viz. *kharif* (July–October) 2020 (E_2); *rabi* (November–January) 2020–21 (E_3); summer (Feb–May) 2021 (E_1); *Kharif* (July–October) 2021 (E_4); and *rabi* (December–March) 2021–22 (E_5) the weather data showed clear difference among the climatic condition (Table 1). The experiment was laid out in a randomized block design (RBD) replicated thrice. Each genotype was sown with the spacing of 30 cm × 10 cm in the plots with 3 m × 3 m size and single plant/hill was maintained. The entire packages of practices were carried out in order to harvest a successful crop and the plot grain yield was recorded in all five seasons from three replications.

Statistical data analysis: The recorded grain yield subjected to statistical analysis. The ANOVA was carried out in all the seasons using TNAU STAT. The stability was analyzed by regression model of Finlay-Wilkinson (1963) and Eberhart-Russell (EB-RU) (1966). GGE biplot Yan *et al.* (2001) and Yan (1999) and AMMI model (Zobel *et al.* 1988) were used to study the interaction between genotype and environment. The International Rice Research Institute, Philippines, developed the PB tools software (version 1.3), which was used to conduct the statistical analysis.

RESULTS AND DISCUSSION

Blackgram is a short-duration crop that is cultivated throughout the year in India. Hence, it is crucial to identify a stable genotype(s) that maintains consistent performance despite of environmental fluctuations. A seasonal analysis of data revealed through ANOVA that the genotypes examined in this study were significant across all five environments, highlighting a considerable level of genetic variation for the trait under study. Furthermore, a pooled analysis of variance was performed on the yield data collected over five seasons (Table 2) demonstrated the existence of heterogeneity among the genotypes studied and environments assessed, suggesting that both genotype and environment had a substantial impact. The genotype × environment interaction exhibited a significant variance, indicating that genotype performance varied across different seasons. Shanthi *et al.* (2007) also demonstrated comparable findings in blackgram. Due to the significant differences observed among genotypes, as well as between environments, G × E interaction concerning yield the data was utilized for stability analysis.

Finlay-Wilkinson (FW) regression (1963) and Eberhart and Russell (1966) stability analysis: The Finlay-Wilkinson (FW) regression analysis is a widely recognized technique that represents the first systematic method for evaluating the phenotypic stability of genotypes across different environments. This model utilizes two key parameters: the mean performance across all environments and the regression of performances in various environments against their respective means (Raman *et al.* 2012). Based on this, a regression value of one signifies average stability, while a value greater than one indicates below-average stability, and a value less than one suggests above-average stability (Finlay-Wilkinson 1963). Whereas the Eberhart and Russell (EB-RU) regression method has gained significant popularity over the past few decades due to its ability to separate genotype-specific variability into predictable (regression coefficient, bi) and unexpected (S^2d) components. This model, the yield, regression value (bi) and stability (variation from regression line (S^2d)) with regression will be utilized for selecting the ideal genotype(s) for the targeted environment. The mean yield, regression values and deviation from regression line are summarized in Table 3. Based on the bi value nearing one and non-significant S2d value along with yield performance, the genotypes namely VBG17021, VBG17030 and VBG18034 were identified as the high yielding genotypes with high stability. Among the check varieties, VBN8 exhibited the

Table 1 Weather data of different seasons

Standard week	Rainfall	Temperature		Standard week	Rainfall	Temperature	
		Max	min			Max	min
Kharif 2020 (E_2)				*Rabi* 2020 – 21 (E_3)			
23.07.20 – 29.07.20	20.0	34	24.2	29.10.20 – 04.11.20	-	33.2	24.4
30.07.20 – 05.08.20	5.4	34.4	24.9	05.11.20 – 11.11.20		31.7	23.2
06.08.20 – 2.08.20	11.2	34.6	24.5	12.11.20 – 18.11.20	85	31.3	23.4
13.08.20 – 9.08.20	0.0	35	24.9	19.11.20 – 25.11.20	8.0	30.5	22.0
20.08.20 – 6.08.20	55.0	35.2	25.0	26.11.20 – 02.12.20	36.5	27.0	22.8
27.08.20 – 2.09.20	25.6	33.7	23.6	03.12.20 – 09.12.20	151.5	25.8	21.7
03..09.20 – 9.09.20	24.3	32.6	23.9	10.12.20 – 16.12.20	19.0	29.0	21.3
10.09.20 – 6.09.20	27.4	33.6	24.0	17.12.20 – 23.12.20	11.6	26.8	23.4
17.09.20 – 30.09.20	12.0	33.9	24.0	24.12.20 – 31.12.20	3.9	30.5	23.8
24.09.20 -30.09.20	34.7	33.4	23.4	01.01.21 – 07.01.21	59.8	24.7	22.6
Total rainfall	215.6			08.01.21 – 14.01.21	170	27.6	23.1
				15.01.21 – 21.01.21	42.3	26.7	24.6
				Total rainfall	587.6		
Summer 2021 (E_1)				*Kharif* 2021 (E_4)			
26.02.21 – 04.03.21	-	32.0	27.0	09.07.21 – 15.07.21	-	35	25
05.03.21 – 11.03.21	-	34.8	24.0	16.07.2021 – 22.07.21	5.0	36	25
12.03.21 – 18.03.20	-	33.8	20.0	23.07.21 – 29.07.21	6.0	37.5	25
19.03.21 – 25.03.21	-	36.0	22.4	30.07.21 – 05.08.21	0	38	26
26.03.2021 – 01.04.2020	-	36.4	23.4	06.08.21 – 12.08.21	0	37	29
02.04.21 – 08.04.21	-	36.6	24.0	13.08.21 – 19.08.21	61.5	39	22
09.04.21 – 15.04.21	12	34.9	21.0	20.08.21 – 26.08.21	16.3	35	25
16.04.21 – 22.04.21	-	37.1	23.9	27.08.21 – 02.09.21	68.2	35	25
23.04.21 – 29.04.21	-	36.8	24.3	03.09.21 – 09.09.21	74.0	30	23
30.04.21 – 06.05.21	13	35.8	26.0	10.09.21 – 16.09.21	0	35	25
Total rainfall	25.0			Total rainfall	231.0		
Rabi 2021 – 22 (E_5)							
17.12.21 – 23.12.21	-	32.7	21.2				
24.12.21 – 31.12.21	25	38.8	27.7				
01.01.22 – 07.01.22	112	31.3	22.1				
08.01.22 – 14.01.22	-	31.1	17.3				
15.01.22 – 21.01.22	-	30.2	20.5				
22.01.22 – 28.01.22	-	30.7	20.7				
29.01.22 – 04.02.22	-	30.6	20.2				
05.02.22 – 11.02.22	-	35.9	20.9				
12.02.22 – 18.02.22	-	35.4	19.7				
19.02.22 – 25.02.22	-	36.5	22.7				
Total rainfall	137.0						

regression value (bi) approaching one and a non-significant S^2d values with high yield performance over environments, making it more suitable for all seasons compare to VBN10 and VBN6. Conversely, genotypes VBN6, VBN10 and VBG18040 were showed below average stability due to its high regression value (more than 1) and significant S^2d and can be recommended for favourable environments where the rainfall is good and moderate temperature prevailing. The results were in line with the findings drawn by Shanthi *et al.* (2007) and Manivannan *et al.* (2023). Genotypes VBG18054, VBG18052 and VBG18050 and VBN 6 recorded the regression value of below one and significant S^2d indicated its above average stability and these genotypes possess greater resistance to environmental fluctuations but

Table 2 Pooled ANOVA of multi-environmental data for yield

Source of variation	DF	MS
Block (R)	2	792.04
Genotype(G)	19	54760.707**
Environment (E)	4	780466.44**
Genotype × Environment (G×E)	76	20690.59**
Env + G×E	80	58678.03**
Env (Linear)	1	3121864.00
G×E (Linear)	19	28056.71
Pooled Dev	60	17322.97
Pooled Error	190	4664.51

* and **, Significance at 5% and 1% level.

Table 3 Finlay and Wilkinson regression parameters of stability for blackgram genotypes

Genotypes	Mean grain yield (Xi)	(bi)	S^2d
G_1, VBG17012	1094	0.84	22120.17
G_2, VBG18042	1063	1.59	14166.24
G_3, VBG18043	1118	1.38	1935.741
G_4, VBG18047	1180	1.29	12131.15
G_5, VBG18048	1288	0.84	58870.45
G_6, VBG18049	967	1.25	56948.69
G_7, VBG18050	994	0.70	6220.081
G_8, VBG18052	1141	0.60	19553.27
G_9, VBG18054	923	0.21	15127.6
G_{10}, VBN 6	1133	0.36	44.7389
G_{11}, VBN 8	1107	1.05	8905.026
G_{12}, VBG17021	1036	1.07	8520.677
G_{13}, VBN10	1003	0.84	10979.56
G_{14}, VBG17026	1205	0.66	18283.54
G_{15}, VB17029	1011	0.81	11817.73
G_{16}, VBG17030	1083	1.0	4254.405
G_{17}, VBG18032	917	1.34	28159.93
G_{18}, VBG18034	1260	0.95	10991.76
G_{19}, VBG18035	1145	1.15	7414.868
G_{20}, VBG18040	980	2.04	-1082.87

low yielders than the best check VBN 8 and this result was in consistent with findings of Kumawat *et al.* (2023). Yield is the main criteria of all the crops due to its low yielding nature compare to best varieties, these genotypes can be recommended as alternate variety where there is more environment instability similar results was also reported by Sridhar *et al.* (2023).

AMMI model G × E interaction analysis (Zobel et al. 1988): The AMMI (G × E interaction) model is a powerful tool for analyzing the interaction effect of genotypes and environments (GEI). By integrating both additive and multiplicative components, it proves to be a highly effective approach. Additionally, clustering genotypes that exhibit similar performance over environments can be easily achieved through the use of genotypic stability statistics alongside biplot analysis, (Singh *et al.* 2018). This analysis partitioned the main effects of treatments into G (Genotype), E (Environment) and G × E interactions (Njoroge *et al.* 2020). The ANOVA results from AMMI model indicated that the interaction principle component axes (IPCA1, IPCA2, and IPCA3) were statistically significant for grain yield, which is consistent with findings of Patel *et al.* (2022). Specifically, the three principal components, viz. IPCA1, IPCA2, and IPCA3contributed 54.1%, 24.4%, and 15.2% to the interaction respectively (Supplementary Table 1), highlighting the influence of Genotype plus Environment interaction on grain yield similar explanation of G × E interaction's impact on seed yield was provided by Zobel *et al.* (1988). Their assessment of predictions revealed that the AMMI model utilizing two interaction principal component axes was the most effective extrapolative model (Mohanlal *et al.* 2023).

A genotype is considered stable and high yielding, when it gives consistently high yield despite changes in its environment (Rajalakshmi *et al.* 2024). The minimal interaction of G × E effects are identified by IPCA1 scores that are close to zero indicating the genotypic stability. Moreover, the genotype and environment combinations share the same sign in their IPCA 1 scores produce positive specific interaction effects and combination of opposing signs leads to negative specific interaction effects (Sridhar *et al.* 2023). All the three check varieties recorded relatively lower IPCA values indicating greater stability (Fig. 1). Among these, VBN 8 is identified as the most stable based on yield and regression values, aligning with the finding of Manivannan *et al.* (2023). Due to its greater stability and high yielding nature this variety can be recommended for cultivation in Tamil Nadu for all the seasons. Among the 17 advanced cultures, the cultures namely VBG18048 (G_5), VBG17026 (G_{14}), VBG18034 (G_{18}) and VBG18032 (G_{17}) were recorded higher mean grain yield and surpassing that of the best performing check variety VBN 8 and their IPCA1 values were also near zero, indicating its high stability (Fig. 1). Based on high yielding nature and greater stability across environments these genotypes can be recommended for cultivation throughout the year in Tamil Nadu. The genotypes with greater yield and high positive ICPA1 values, viz. VBG18032 and VBG18040 can be recommended for favourable environments like E_2 and E_4 (*kharif* season), whereas VBG18043 (G_3) and VBG18047 (G_4) can be recommended for E_3 and E_5 (*rabi* seasons) environments and none of the genotype was suitable for E_1 (summer) environment. A similar study on blackgram mutant was conducted by Dhasarathan *et al.* (2021).

The environment possessing the longer spoke is deemed to be more interactive in AMMI biplot 2 (Fig. 1). Among the environments, E_3 (*rabi* 2020) is notable for having the longest spoke, indicating that this season was

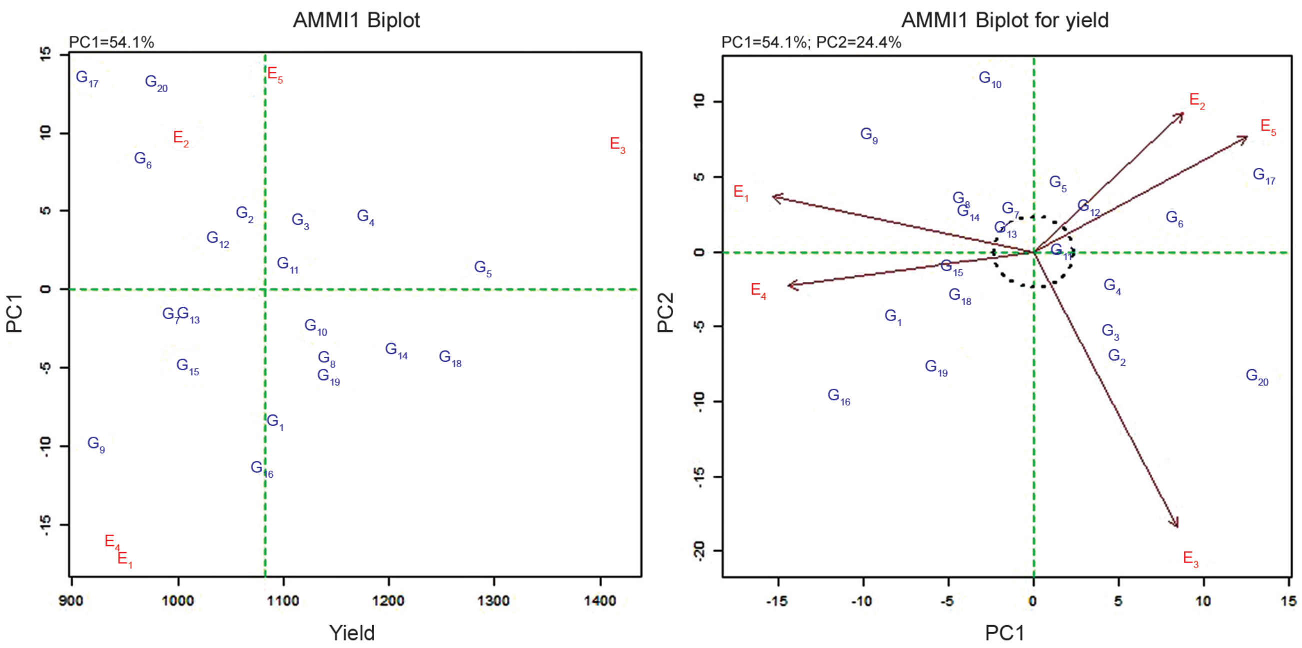

Fig. 1 Scattered distribution patterns of 20 blackgram genotypes and 5 environments presented in the AMMI model biplot 1 with grain mean yield (q/ha) and AMMI biplot 2 showing IPC1 and IPC2 scores.
Genotypes and Environment details are given under Materials and Methods.

more interactive and favorable than others. In terms of genotypes, closer to the origin are thought less interactive with environments. Specifically, genotypes VBN8 (G_{11}), VBN10 (G_{13}), VBG18043 (G_3) and VBG18050 (G_7) were recognized as less interactive to environments. Based on the results of AMMI biplot 1 and 2, revealed that VBN 8 (G_{11}) and VBG18043 (G_3) were the most stable genotypes with minimal interaction and high yielding type.

GGE biplot-stability analysis: The GGE-Biplot method was utilized to evaluate the interaction between genotype and environment, as well as the stability of the genotypes (Yan *et al.* 2001). Generally, the genotype and G×E interaction are crucial factors, which make the GGE-Biplot approach more advantageous than AMMI, particularly in emphasizing these elements (Yan *et al.* 2007). The G×E interaction pattern was analyzed using the GGE biplot, providing a clear understanding of which genotype excels in specific environments and facilitating the identification of mega environments for particular genotypes, similar to the AMMI model. In terms of recision, both the GGE and AMMI models are regarded as equally dependable (Gurmu *et al.* 2012).

Test environment relationship: Environmental vectors E_2 (*kharif* 2020) and E_5 (*rabi* 2021) along with E_1 (Summer 2021) and E_4 (*kharif* 2021) were exhibited a positive correlation, forming an acute angle. In contrast, the combination of E_1 (summer 2021) with E_2 (*kharif* 2020), E_3 (*rabi* 2020) and E_5 (*rabi* 2021) resulted in an obtuse angle, indicating a negative correlation (Fig. 2). These findings clearly indicated that, summer 2021 had negative correlation with *kharif* 2020, *rabi* 2020–21 and *rabi* 2021–22. The increased distance between environmental vectors suggested a lack of similarity in their capacity to differentiate among genotypes (Fig. 2). These findings clearly indicated that the fluctuations in climate condition during *kharif* and *rabi* seasons over successive years reflect the change in temperatures and weather patterns. E_4 (*kharif* 2021) had the longest environmental vector, indicating the highest level of discriminating ability, followed by E_1 (summer 2021) and E_2 (*kharif* 2020). Whereas the E_5 (*rabi* 2021) showed lowest discriminating ability. This implies that the *kharif season* was most discriminating than *rabi season*. However, Manivannan *et al.* (2023) argued that the *rabi* was most discriminating, with *kharif* being the least. This discrepancy may be attributed to significant environmental changes that have occurred over the past five years compared to earlier periods.

Ideal test environments and mega environments identification: The stability of the genotypes is represented by average environment coordinate (AEC) line that intersects the origin of the biplot (Yan 2001). The AEC line that is positioned farthest from the origin in a positive direction along the longest environmental vector serves as the centre of concentric circles. In this research, none of the environment is closest to the point, indicating that none can be considered an ideal test environment for selecting genotypes suitable for all climatic conditions. Fig. 2 showed ED that the E_1 and E_4 form a single mega environment (summer 2021 and *kharif* 2021) whereas E_2, E_3 and E_5 (*rabi* 2020–21, *kharif* 2020 and *rabi* 2021–22) were form another distinct mega environment.

Genotype evaluation based on GGE biplot: High and notable PC1 scores in various environments suggested improved discrimination among genotypes, whereas PC scores nearing zero typically (E_4) reflect an average environment (Yan 2001). This research analyzed both

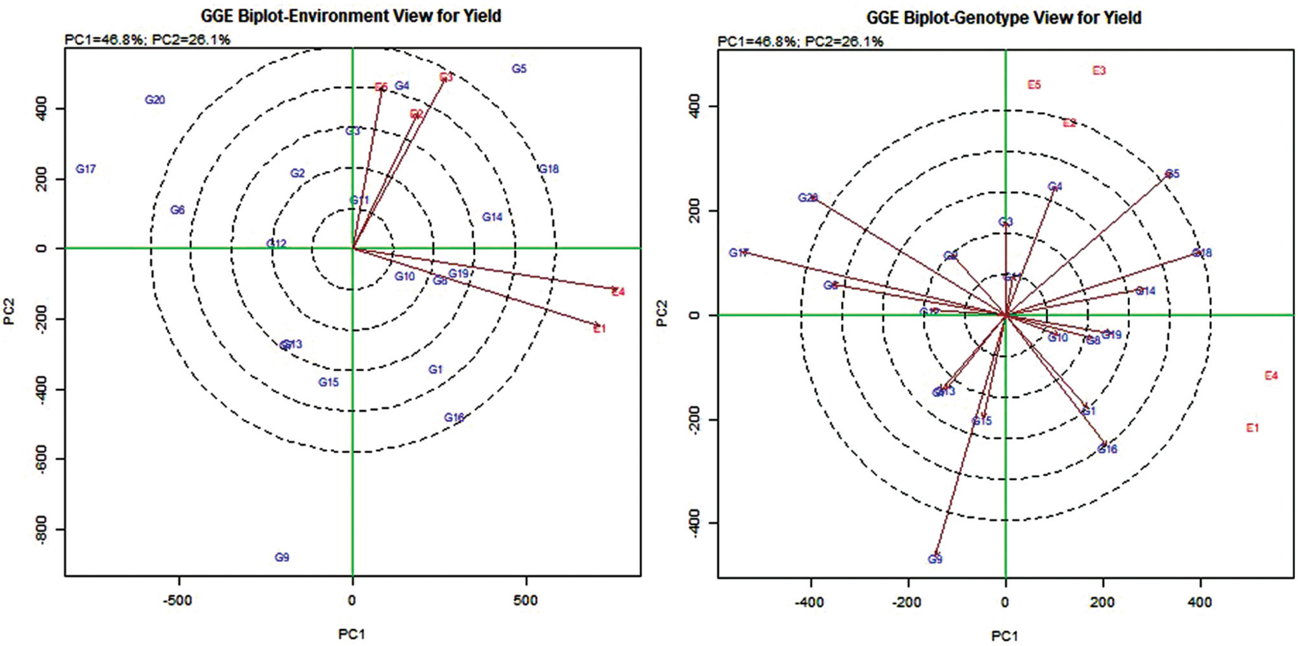

Fig. 2 Environment and genotypic view for seed yield per plant based on GGE Biplot. Genotypes and Environment details are given under Materials and Methods.

genotype and environmental vectors to better understand their specific interactions. In the E_4 (*kharif* 2021) environment, genotypes G_1 (VBG14012), G_3 (VBG18043), G_5 (VBG18048), G_7 (VBG18050), G_8 (VBG18052), G_{13} (VBN10) and G_{16} (VBG17030) performed above average, while G_{15} (VBG17029) and G_{19} (VBG18035) were close to average. The remaining of the genotypes exhibited below-average performance (Supplementary Fig. 1).

The Average Environment Coordinate (AEC) represents the more stable genotypes that perform at an average level. It indicates a higher average yield across environments, with a double arrowed line in the AEC coordinate indicating that the greatest variation in either direction. According to findings, genotypes, G_{13} (VBN10), G_{12} (VBG17021), G_{11} (VBN8), G_{10} (VBN6), G_5 (VBG18048), G_{14} (VBG17026), G_{15} (VBG17029) and G_{18} (VBG034) demonstrated greater stability, while others exhibited more interactive with the environments. An ideal genotype is characterized by a high yield coupled with stability across environments. Hence based on yield and stability, the genotypes, viz. G_7 (VBG18050), G_{13} (VBN10), G_{17} (VBG18032) and G_{18} (VBG18034) were recognized as ideal. G_{18} (VBG18034) was noted as good in yield and moderately interactive with the environment (Supplementary Fig. 2).

Which-won-where of GGE biplot: The "which- won-where" model of GGE biplot analysis effectively categorized genotypes into distinct sector, highlighting significant interactions between G × E. In this investigation, five locations were grouped into four sectors. It was observed that the genotypes located at the vertices of the polygon either excelled in one environment and under performing in another environment showed varied performance across multiple environments. For example, G_5 (VBG18048) and G_{18} (VBG18034) were outstanding performers in E_2 (*kharif* 2020), E_5 (*rabi* 2021) and E_3 (*rabi* 2020), while G_{16} (VBG17030) thrived in E_1 (summer 2020) and E_4 (*kharif* 2021) (Fig. 3) at the same time, these genotypes exhibited poor performance in other environments. The biplot was divided into different sectors by equality line, and the vertex of each sector had the winning genotypes. In the mega environment comprising E_2 (*kharif* 2020), E_3 (*rabi* 2020–21) and E_5 (*rabi* 2021); G_5 (VBG 18048) and G_{18} (VBG18034) (Fig. 3) emerged as the leading genotypes, while G_{16} (VBG 17030) excelled in other mega environments E_1(summer 2021) and E_4 (*kharif* 2021). Therefore, it is essential to select and deploy different genotypes tailored to each mega environment (Supplementary Fig. 3).

Blackgram is a key pulse crop in India, grown across various environments. Based on the entire four stability analysis models, AMMI and GGE-Biplot are highly effective statistical methods for analyzing genotype by environment and visually representing the nature of these interactions and the stability of cultivars across multiple environments. From these models, it can be inferred that the genotypes VBG17030 and VBG 18043 identified as more stable high yielding genotypes and can be recommended for all the seasons. It also can be concluded that the regression analysis and AMMI and GGE biplot models provided the most accurate predictions for the dynamic aspects of stability.

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