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Research Article

Stability analysis of single crosses derived from diverse inbred lines of maize (*Zea mays* L.)

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Abstract
An experimental study was conducted to estimate the stability of 36 single crosses of maize developed from 12 parental lines by using the Eberhart and Russell model over the three agroclimatic zones (Rajendranagar, Karimnagar and Madhira) of Telangana during *rabi*, 2021-22. The pooled analysis of variance indicated that environmental effect, hybrid effect and hybrid-environment interaction were significant for yield and yield related traits. The study revealed that eight hybrids *viz.,* BML-20 × PFSR-95, BML-20 × MGC-15, BML-20 × PFSR-46, BML- 20 × MGC-137, BML-11 × MGC-137, BML-11 × PFSR-46, PFSR-51 ×MGC-15 and PFSR-51 × MGC-137, exhibited higher mean and stable performance for grain yield, while the hybrids BML-11 × PFSR-46 and PFSR-51 × MGC-137 showed desirable mean values and stable performance for most of the yield related traits over the three locations. Environmental indices revealed Karimnagar as ideal test location for maize cultivation.

Keywords: Maize, Hybrids, Stability, genotype × environment interaction and yield

INTRODUCTION

Maize (*Zea mays* L.) is an annual crop with economic value that is expected to surpass wheat as the most important cereal crop in the world by 2025 (FAOSTAT, 2017 and Bhadmus *et al*., 2021). Globally, it is one of the most grown crops because it can adapt to different climatic conditions (Kamara *et al*., 2020) and also has various industrial and non-industrial uses. Genotype × environment interactions have immense value in any breeding programme. An interaction between a genotype and its environment is the cause for the expression of a phenotype. Certain genotypes do not exhibit the same morphological traits in every environment, while other genotypes exhibit different responses in different situations. The difference caused by lack of alliance between genetic and non-genetic reasons is known as genotype-environment interaction (Singh *et al*., 2018). G × E interactions pose a significant obstacle in achieving genetic control over variability (Nirmala kumari *et al*., 2014). It has seriously hampered efforts to rationalize breeding strategies and procedures for improved crop performance value. According to Allard and Bradshaw (1964), a variety is considered “well buffered” or exceptionally stable if it can modify its genotype on phenotypic circumstances in response to transient variations in the environment in such a way that yields a high and consistent financial return over time and space. Significant GEI causes the genotypes to act differently in various circumstances (Kalpande *et al*., 2025). Selecting superior genotypes for improved cultivar development can be severely limited by a large G × E interaction for a quantitative traits like grain yield (Kang and Gorman, 1989). Plant breeders need to understand the correlation between yield testing locations in order to select germplasm that is better adapted to various production environments or regions (Bubuche *et al*., 2025). A stable genotype possesses an unchanged or least changed performance regardless of any variation of the environmental conditions. In breeding for wide adaptation, the aim is to obtain a variety, which performs well in all the tested environments (Jayalakshmi *et al.,* 2024). Several stability analyses have been proposed to determine the linear relationship between genotypic performance and the environment. Among them, Eberhart and Russel (1966) proposed a model to test the stability of varieties under various environments. They defined that a stable variety is the one which shows i) high mean performance, ii) regression coefficient over the environments (bi=1) equal to unity and iii) a mean square deviation from regression ($S^2di = 0$) near to zero. The main aim of present study was to determine the stability of maize hybrids for yield and yield components over different environments by using Eberhart and Russell's (1966) stability model.

MATERIALS AND METHODS

The experimental material consists of 36 single crosses developed from twelve diverse maize inbreds (**Table 1**) using a line × tester mating design at Maize Research Centre, (MRC) Rajendranagar during *kharif*, 2021. These 36 single crosses were evaluated for yield and its attributing traits over the three agro-climatic zones of Telangana (MRC Rajendranagar, Agricultural Research Station, Karimnagar and Madhira) along with five hybrid checks (DHM 117, DHM 121, Bio 9544, NK 6240 and KNMH 4010131) to determine the stability of single crosses during *rabi*, 2021-22. The experiment was organized in a randomized complete block design with three replications. Each entry was sown in six rows of 4m length and followed a spacing of 0.6 × 0.2 m between row to row and plant to plant respectively. Based on the recommendations of PJTAU, crop management practices such as the application of 240:80:80 kg/ha of $N:P_2O_5:K_2O$, along with regular irrigation at critical growth stages (vegetative, tasseling and grain filling) were followed. Weed management involved a pre-emergence application of Atrazine at 0.50–0.75 kg/ha, followed by manual or mechanical weeding at 30–35 DAS. For plant protection, Carbofuran 3G granules at 25 kg/ha were applied to control stem borer, while Emamectin benzoate at 0.20 kg/ha was sprayed to manage fall army worm infestation. These interventions ensured the maintenance of optimal crop growth and performance. Data were recorded on randomly selected five competitive plants from each genotype per replication for the characters *viz.*, plant height (cm), ear height (cm), ear length (cm), ear girth (cm), number of kernel rows per ear, number of kernels per row and 100 seed weight (g). While days to 50% tasseling, days to 50% silking, days to maturity and grain yield (kg ha^{-1}) were recorded on the plot basis. The data were statistically analyzed by utilizing Indostat services following Eberhart and Russel's (1966) model.

Eberhart and Russell identified three parameters for estimating the stability of genotypes namely (i) the overall mean of each genotype over a range of environments, (ii) the regression of each genotype on the environmental index and (iii) a function of the squared deviation from the regression.

The model proposed by Eberhart and Russell (1966) is as follows:

$$Yij=\mu i+biIj+\delta ij$$

Where

Y_{ij}= Variety means of the i^{th} genotype in the j^{th} environment (i = 1, 2,......... g and j = 1,2….e).

μ_i= Mean of the i^{th} genotype over all environment

b_i= Regression coefficient that measures the response of the i^{th} genotype to varying environments.

I= Environmental index obtained as the mean of all the genotypes in the j^{th} environment minus the grand mean

δij= deviation from regression of the i^{th} genotype in the j^{th} environment

RESULTS AND DISCUSSION

The Pooled analysis of variance of 41 hybrids (36 single crosses and 5 checks) evaluated for stability across the three locations (**Table 2**) revealed that the hybrids possessed highly significant variability for all the traits evaluated. The mean squares due to environments were also significant for all the traits. Thus, these hybrids were divergent and possessed significant genetic variation for all these traits. The environments revealed the existence of significant differences for all the traits, confirming that the selected environments exhibited greater variability and influenced the expression of traits selected for stability studies. Mean squares due to G × E interaction revealed significant differences for all the traits indicating that the genotypes showed significant differential response to the changing environments. Similar results were reported by Patil *et al*. (2020) and Chouhan *et al*. (2021).

Environmental Indices: Estimates of environmental indices (Ij) are presented in the **Table 3**. It indicated that E_1 (Rajendranagar) was the favourable environment for ear height, ear length, ear girth, number of kernel rows per ear, 100 seed weight and grain yield. While E_2 (Karimnagar) was favourable for all the studied characters except 100 seed weight and E_3 (Madhira) was less favourable for all characters except days to maturity and plant height (cm).

Stability parameters: Assessment of the stability and adaptability of a genotype to different environments is useful for recommending cultivars for known conditions of cultivation. Parametric models based on simple linear

Table 1. List of Parental lines and their pedigree

S.No.	Lines	Pedigree
1	GP-35	Selected from CIMMYTlines
2	GP-111	Selected from CIMMYTlines
3	MGC-90	[CML373 × CML357]-B-1-4-B*10-#-BB
4	BML-20	Suwan1(D)b96-1-2-1-1-2-3-×-2-×-1-×b-×b
5	BML-11	SUVAN3-B96-1-3#X-1-2-1-1-3-xb-xb-xb-xb
6	PFSR-51	BPPTI-33 × CM-119
	Testers	
1	PFSR-95	BPPTI-35 × CM-207
2	PFSR-151	BPPTI-29 × CM-210
3	MGC-15	(AMDROUTI(DT-Tester)C1f2-36-b*5/(POP502C5#18/GEMN-0145)-B-21-2-1-1-B)-B-3-BB
4	MGC-137	(MARSSYN-155)-4-1-1-BB
5	PFSR-46	BPPTI-17 × CM-119
6	PFSR-129	BPPTI-14 × CM-210

regression analysis are among the most widely used to identify superior cultivars and include the method proposed by Eberhart and Russell (1966), which interprets the variance of the regression deviations (S^2di) as a measure of cultivar stability and the linear regression coefficient(b_i) as a measure of the cultivar adaptability.

For days to 50 % tasseling, the hybrids MGC-90 × PFSR-95, BML-11 × PFSR-151 and BML-11 × MGC-137 recorded lesser mean estimate than the population mean along with regression coefficient (bi) nearly equal to unity and non-significant minimum deviation from the regression coefficient (S^2di), which indicates that these hybrids exhibit stable performance for early tasseling in all the three environments. The hybrids namely GP-35 × MGC-137, GP-35 × PFSR-46, MGC-90 × PFSR-151, BML-20 × MGC-137 and BML-11 × PFSR-129 recorded stable performance under better environment for early tasseling. Six hybrids GP-111 × PFSR-95, GP-111 × PFSR-151, GP-111 × PFSR-46, BML-20 × PFSR-95, BML-11 × PFSR-95 and PFSR-51 × MGC-137 showed adaptability to poor environment for early tasseling as they had inferior mean estimate than population mean coupled with regression coefficient lesser than unity and non-significant minimum deviation from S^2di value.While the hybrids BML-11 × PFSR-46 and KNMH 4010131(check) recorded mean value on par with population mean and showed stable performance under poor environment (**Table 4 and Table 7**). These results are in accordance to the findings of Sowmya *et al.* (2018), Nirmal raj *et al.* (2019), Boreddy *et al.* (2020) and Ismail *et al.* (2023).

For days to 50% silking, three hybrids MGC-90 × PFSR-95, BML-11 × PFSR-151 and BML-11 × MGC-137 were found to exhibit wider adaptability and stable performance for early silking over the three environments. Since the above hybrids possessed regression coefficient (bi) nearer to unity and non-significant (S^2di), lesser mean performance than population mean. Eight hybrids *viz*., GP-111 × PFSR-95, GP-111 × PFSR-151, GP-111 × PFSR-46, BML-20 × PFSR-95, BML-11 × PFSR-95, PFSR-51 × MGC-137, BML-11 × PFSR-46 andKNMH4010131(check) showed less sensitive to environmental changes and adaptability to poor environment for early silking. Five hybrids (GP-35 × MGC-137, GP-35 × PFSR-46, MGC-90 × PFSR-151, BML-20 × MGC-137 and BML-11 × PFSR-129) recorded lesser mean estimate than population mean and stable performance under good environment for early silking. While the hybrids GP-35 × PFSR-46 and MGC-90 × PFSR-151 exhibited mean value statistically on par with the population mean along with regression coefficient greater than unity and non-significant minimum deviation from S^2di value, indicating its adaptability to favourable environment for early silking (**Table 4 and Table 7**). Similar results were reported by Nirmal raj *et al.* (2019) and Arun kumar *et al.* (2020).

The hybrids namely MGC-90 × PFSR-95, BML-11 × MGC-137 and KNMH-4010131(check) exhibited stable performance for days to maturity over the tested environments since it showed lesser mean estimates than population mean, regression coefficient (bi) nearer to unity and non-significant (S^2di). The hybrids GP-35 × MGC-137, BML-20 × MGC-137 and PFSR-51 × PFSR-95 showed lesser mean estimate than population mean along with non-significant S^2di and regression coefficient greater than unity, indicating its adaptability to favourable environment for earliness. While the hybrid BML-11 × PFSR-129 recorded mean value statistically on par with the population mean and stable performance under better environment. Seven hybrids (GP-111 × PFSR-95, GP-111 × PFSR-151, GP-111 × PFSR-46, BML-20 × PFSR-95, BML-11 × PFSR-95, BML-11 × PFSR-46 and PFSR-51 × MGC-137) were found to exhibit less sensitivity to environmental changes and adaptability to poor environment for earliness (**Table 4 and Table 7**). Similar findings were obtained by Sowmya *et al*. (2018) and Arun kumar *et al.* (2020).

Table 2. Pooled ANOVA of maize hybrids across the three environments

Source	df	Days to 50% tasseling	Days to 50% silking	Days to maturity	Plantheight	Ear height	Ear length	Ear girth	Numberof kernel rows per ear	Number of kernels per row	100 seed weight	Grain yield
Hybrids	41	2.42*	2.40*	6.72**	613.88**	104.51**	4.16*	7.42**	8.51*	114.56**	28.15**	25743475.90**
Env.+(Hybrids.*Env)	82	203.30*	202.99**	222.98**	3163.35**	541.49**	89.46**	0.87*	1.08*	2.51*	292.26**	365799.51**
Environments	2	1.57*	1.55*	5.75*	112.64*	37.84*	0.86*	16.15*	18.86**	11.86*	5.85**	2512718.26**
Hybrids.*Env.	80	10.35**	10.11**	15.19**	245.28**	59.74*	4.71**	0.58*	0.73*	2.33*	18.30**	324512.61*
Environments(Lin.)	1	402.99**	402.85**	447.85**	6328.70*	1084.97**	179.58**	32.31*	37.73*	23.72**	585.51**	5025436.53*
Hybrids.*Env.(Lin.)	40	1.02*	1.00*	2.05*	149.32*	49.62*	0.26*	0.56*	0.72 *	2.07*	2.26*	452030.65**
Pooled Deviation	41	2.05*	2.00*	9.11**	72.57*	24.83*	1.37*	0.59*	0.71*	2.54*	8.99*	193277.69**
Pooled Error	120	0.79	0.75	2.15	131.56	48.35**	0.32	0.14	0.33	0.63	4.79	13151.67

*,**Significant at 5% and 1 % level of probability respectively.

Table 3. Environmental indices for eleven quantitative traits in maize

Characters	E_1(Rajendranagar)	E_2(Karimnagar)	E_3(Madhira)
Days to 50% tasseling	0.12	-0.34	0.22
Days to 50%silking	0.15	-0.37	0.21
Days to maturity	0.64	-0.35	-0.29
Plant height	1.16	-0.88	-0.28
Ear height	-0.06	-0.01	0.07
Ear length	0.68	0.30	-0.97
Ear girth	0.46	0.15	-0.61
Number of kernel rows per ear	0.12	0.52	-0.64
Number of kernels per row	-0.02	0.49	-0.46
100 seed weight	0.80	-0.01	-0.78
Grain yield	191.45	45.40	-236.86

Table 4 . Estimation of stability parameters for days to 50% tasseling, days to 50% silking, days to maturity and plant height

S.No.	Hybrids	Days to 50% tasseling			Days to 50% silking			Days to maturity			Plant height		
		μ	bi	s²di	μ	bi	s²di	μ	bi	s²di	μ	bi	s²di
1	GP-35× PFSR-95	53	1.88	2.42**	55	1.88	2.42**	100	1.20	0.87*	166.17	0.87*	-6.41
2	GP-35× PFSR-151	55	0.40	-0.81	57	0.39	-0.80	103	0.02	-3.43	182.83	0.55	21.10**
3	GP-35×MGC-15	55	-0.86	2.83**	57	-0.84	2.82**	102	-2.47	3.14**	163.67	-0.48	7.53**
4	GP-35×MGC-137	48	1.97	-0.62	50	1.95	-0.61	86	3.18	-1.61	176.17	3.18*	25.23**
5	GP-35×PFSR-46	54	2.14	0.27	56	2.12	-0.25	106	1.93	-3.33	169.17	0.87	-6.41
6	GP-35×PFSR-129	56	0.40	-0.81	58	0.39	-0.80	98	0.06	-2.10	164.67	-0.03	-7.46
7	GP-111×PFSR-95	51	-0.71	-1.19	53	-0.69	-1.18	88	-0.71	-2.19	168.17	-0.92	-9.47
8	GP-111 ×PFSR-151	51	0.11	-0.89	53	0.10	-0.88	87	0.29	-3.20	185.33	-1.43	-6.85
9	GP-111×MGC-15	58	-1.06	1.43*	60	-1.04	1.42*	104	-3.52	-2.10	167.67	-1.35	-1.92
10	GP-111×MGC-137	54	-0.57	7.09**	56	-0.56	7.05**	98	1.00	34.72**	174.33	-1.47	42.54**
11	GP-111×PFSR-46	51	-0.71	-1.19	53	-0.69	-1.15	87	-0.08	-0.94	170.33	0.22	32.23**
12	GP-111 ×PFSR-129	58	0.11	-0.89	60	0.10	-0.87	105	0.29	-3.20	167.00	0.12	-10.22
13	MGC-90×PFSR-95	52	1.26	-0.31	54	1.25	-0.30	91	1.09	-1.81	154.5	1.14	-11.06
14	MGC-90×PFSR-151	54	1.74	-1.09	56	1.73	-1.08	102	1.12	5.41**	187.83	1.40	7.72**
15	MGC-90 × MGC-15	56	2.06**	-1.33	58	2.04**	-1.32	104	2.63**	-3.15	172.83	1.18	-10.10
16	MGC-90 × MGC-137	55	-0.80	0.89*	57	-0.80	0.89**	98	-0.77	2.20*	185.67	-1.20	3.65**
17	MGC-90 × PFSR-46	57	1.74	-1.09	59	1.71	-1.05	100	0.31	-3.55	164.17	0.81	-9.23
18	MGC-90 × PFSR-129	57	1.63*	0.14	59	1.61*	0.13	101	-0.14	11.55**	166.83	1.20	3.65*
19	BML-20 × PFSR-95	49	-5.14	-1.11	51	-5.12	-1.10	87	-0.29	-3.20	194.5	1.09	6.12**
20	BML-20 × PFSR-151	55	3.71*	-1.26	57	3.69*	-1.24	106	2.93*	-3.60	182.5	4.66	-12.08
21	BML-20 × MGC-15	53	3.37*	1.74	55	3.32*	1.72	99	4.72	8.01**	162.5	2.01	-6.96
22	BML-20 × MGC-137	50	1.66	-1.08	52	1.64	-1.05	86	1.89	-1.81	168.67	0.55	-9.89
23	BML-20 × PFSR-46	58	0.91*	-0.73	60	0.90*	-0.71	101	2.04	0.11*	182.17	0.70	-7.16
24	BML-20 × PFSR-129	58	3.71*	-1.26	60	3.69**	-1.24	102	4.60**	-2.68	179.33	3.57	-11.93
25	BML-11 × PFSR-95	48	-0.83	-1.30	50	-0.81	-1.29	85	-1.38	-1.18	183.33	-1.01	-10.64
26	BML-11 × PFSR-151	53	1.23	-1.15	55	1.21	-1.14	99	4.23**	-3.6	187.33	2.76	-6.52
27	BML-11×MGC-15	58	0.71	-1.19	60	0.70	-1.17	100	0.31	-3.55	159.00	0.69	-10.91
28	BML-11×MGC-137	52	1.06	-1.08	54	1.04	-1.06	91	0.65	-3.60	173.33	1.31	-12.12
29	BML-11×PFSR-46	54	-0.83	-1.30	56	-0.82	-1.29	93	-1.30	-3.59	184.00	-1.12	-9.82
30	BML-11×PFSR-129	53	1.77	-0.18	55	1.75	0.17	95	2.89	-2.99	186.67	2.13	-4.64
31	PFSR-51 ×PFSR-95	50	6.51**	0.82	52	6.49**	0.81	90	6.17	-3.57	177.67	3.88	112.02**
32	PFSR-51×PFSR-151	53	2.85	1.56*	55	2.82	1.53*	95	2.08	3.92*	163.67	3.05	25.73**
33	PFSR-51×MGC-15	55	1.66	-1.08	57	1.65	-1.07	102	2.59	-3.57	144.00	1.59	-10.58
34	PFSR-51×MGC-137	50	-0.83	-1.30	52	-0.82	-1.29	85	-0.94	-3.15	170.83	-1.28	-10.09
35	PFSR-51 ×PFSR-46	55	4.97**	1.30	57	4.89**	1.29	97	6.48	-3.46	193.50	5.30	5.00**
36	PFSR-51×PFSR-129	56	2.45	-0.45	58	2.41	-0.45	98	2.08	3.92	160.17	2.10	-2.80
	Checks												
1	DHM117	52	-1.06	1.43*	54	-1.05	1.42*	85	-1.85	1.03	170.83	-1.39	16.52**
2	DHM121	55	-1.06	1.43*	57	-1.05	1.42*	95	-1.85	1.03	167.83	-1.06	7.74**
3	Bio9544	62	1.74	-1.09	64	1.72	-1.05	102	2.01	-2.36	171.00	1.81	-8.92
4	NK6240	60	4.51*	-0.01	62	4.51*	-0.01	105	4.72	8.01**	174.17	3.83	-3.23
5	KNMH4010131	54	0.31	-1.27	56	0.30	-1.26	94	0.63	-3.40	165.83	0.37	-11.87
	Mean	54			56			95			164.55		
	SE	0.84			0.83			1.56			2.8		

For plant height, three hybrids MGC-90 × PFSR-95, MGC-90 × PFSR-46 and BML-11 × MGC-15 recorded regression coefficient nearer to unity and non-significant minimum deviation from the regression coefficient (S^2di) and mean performance lesser than population mean, indicating its wider adaptability and stable performance over the three environments. While the hybrids BML-20 × MGC-15, PFSR-51 × MGC-15 and PFSR-51 × PFSR-129 exhibited sensitive to environmental changes and adaptability to favourable environment as they had non-significant deviation from regression and regression coefficient greater than unity with inferior mean estimate than population mean for plant height. The hybrid GP-35 × PFSR-129 showed adaptability to poor environment for plant height (**Table 4 and Table 7**). These results are similar to the findings documented by Arun kumar *et al*. (2020) and Karimizadeh *et al*. (2023).

For ear height, the hybrids GP-35 × PFSR-46, MGC-90 × PFSR-95, MGC-90 × PFSR-46, MGC-90 × PFSR-129, BML-11 × MGC-15 and KNMH 4010131 (check) showed non-significant deviation from regression and 'bi' nearly equal to unity indicating its average stability. The hybrid GP-35 × PFSR-129 exhibited stable performance under poor environments for ear height. While non-significant deviation from regression and 'bi' greater than unity along with inferior mean estimate than the population mean was exhibited by the hybrids PFSR-51 × MGC-15 and PFSR-51 × PFSR-129, indicating its stable performance under good environments for ear height (**Table 5 and Table 7**). Similar results were reported by Arun kumar *et al.* (2020) and Patil *et al*. (2020).

The hybrids namely MGC-90 × PFSR-46, MGC-90 × PFSR-129, BML-20 × PFSR-46, BML-11 × PFSR-46, PFSR-51 × MGC-137 and Bio 9544 (check) exhibited superior mean estimate than population mean and average stability for ear length. While the hybrid PFSR-51 × MGC-15 recorded mean estimate on par with the population mean and wider adaptability for ear length. Ten hybrids (GP-35 × MGC-137, BML-20 × PFSR-151, BML-20 × MGC-137, BML-20 × PFSR-129, BML-11 × PFSR-151, BML-11 × MGC-137, BML-11 × PFSR-129, PFSR-51 × PFSR-95, PFSR-51 × PFSR-46 and NK 6240 (check) were found to exhibit adaptability to favourable environment as they had superior mean estimate than population mean with regression coefficient (bi) greater than unity and non-significant minimum deviation from the regression coefficient (S^2di). Six hybrids (GP- 35 × PFSR-151, GP-35 × MGC-15, GP-111 × MGC-15, MGC-90 × MGC-15, BML-11 × PFSR-95 and DHM 117(check)) showed advanced mean estimate than population mean with regression coefficient less than unity and non-significant minimum deviation from the regression, which indicates its adaptability to poor environment for ear length (**Table 5 and Table 7**). These results are in accordance with the findings reported by Sowmya *et al*. (2018) and Kumawat *et al.* (2023).

For ear girth, the hybrids *viz*., MGC-90 × PFSR-151, MGC-90 × MGC-15, BML-20 × PFSR-95, BML-20 × PFSR-151 and BML-20 × MGC-137 recorded advanced mean estimates than population mean with regression coefficient greater than unity and non-significant minimum deviation from S^2di indicating their adaptability to favourable environment for ear girth. While the hybrid GP-111 × MGC-137 showed mean estimate on par with the population mean and stable performance under better environment for ear girth. The hybrid Bio 9544 (check) recorded average stability for ear girth. The hybrid BML-11 × MGC-15 was found to exhibit adaptability to poor environment for ear girth (**Table 5 and Table 7**). These findings were in confirmation with the results of Kumawat *et al.* (2023) and Swapnil *et al*. (2024). For number of kernel rows per ear, the hybrids *viz.,* GP-35 × MGC-137, BML-20 × MGC-15, BML-20 × MGC-137, BML-11 × PFSR-95, BML-11 × MGC-137, BML-11 × PFSR-129, PFSR-51 × PFSR-46, PFSR-51 × PFSR-129, Bio 9544 (check) and NK 6240 (check) exhibited superior mean estimate than population mean coupled with regression coefficient greater than unity and non-significant minimum deviation from the regression coefficient (S^2di) indicating its better adaptability to favourable environment, while the hybrids BML-11 × PFSR-151 recorded mean estimate on par with the population mean and stable performance under good environmental conditions. The hybrids GP-35 × MGC-15, GP-111 × PFSR-151, GP-111 × MGC-15, GP-111 × MGC- 137, MGC-90 × MGC-15, MGC-90 × MGC-137, DHM-117(check), DHM-121(check) and KNMH-4010131(check) showed stable performance under poor environment for this trait. While the hybrids PFSR-51 × MGC-15, BML-11 × PFSR-46 and PFSR-51 × MGC-137 recorded stable performance over the three environments. (**Table 5 and Table 7**) These results were in conformity with the research findings of Matin *et al*. (2017), Patil *et al*. (2020) and Swapnil *et al*. (2024).

For number of kernels per row, the hybrids GP-35 × PFSR-151, GP-111 × PFSR-151, PFSR-51 × MGC-15, BML-11 × PFSR-46 and PFSR-51 × MGC-137 showed wider adaptability and stable performance across the tested environments. Eight hybrids MGC-90 × PFSR-151, BML-20 × PFSR-151, BML-20 × MGC-15, PFSR-51 × PFSR-95, PFSR-51 × PFSR-151, PFSR-51 × PFSR-46, Bio-9544 (check) and NK 6240 (check) were found to exhibit higher mean estimate than population mean with regression coefficient greater than unity and non-significant minimum deviation from the regression coefficient (S^2di) indicating their adaptability to favourable environment for this trait.The hybrids MGC-90 × MGC-137, BML-20 × PFSR-95, BML-20 × PFSR-46, BML-11 × PFSR-151, DHM 121(check) and KNMH 4010131(check) presented stable performance under poor environment for this trait (**Table 6 and Table 7**). These results are similar to the findings reported by Pramitha *et al*. (2022), Kumawat *et al.*(2023) and Swapnil *et al.* (2024).

Table 5 . Estimation of stability parameters for ear height, ear length, ear girth and number of kernel rows per ear

S.No.	Hybrids	Ear height			Ear length			Ear girth			Number of kernel rows per ear		
		μ	bi	s²di	μ	bi	s²di	μ	bi	s²di	μ	bi	s²di
1	GP-35× PFSR-95	78.33	1.94	0.69*	15.17	2.32**	0.07	13.33	0.72	0.48	14	0.00**	-0.14
2	GP-35× PFSR-151	89.67	0.22	4.03**	18.00	0.00	-0.20	15.67	1.43	2.40	15	0.00	-0.14
3	GP-35×MGC-15	73.33	-0.94	0.55	17.67	-1.16	-0.14	15.83	-1.43	2.40	14	-5.63	0.31
4	GP-35×MGC-137	84.83	4.69	7.43**	21.17	2.32	0.07	17.67	-0.17	3.35*	16	2.92	0.33
5	GP-35×PFSR-46	78.17	1.19	-2.57	16.00	0.00**	-0.20	13.33	2.70	1.60	13	0.00**	-0.14
6	GP-35×PFSR-129	75.17	0.17	-2.44	16.33	0.26	-0.04	13.50	1.08	1.28	13	0.00	-0.14
7	GP-111 ×PFSR-95	85.33	-0.81	-2.67	14.83	1.16	-0.14	13.33	-1.43	2.40	15	0.00	-0.14
8	GP-111 ×PFSR-151	89.83	-0.17	-2.44	20.00	0.00**	-0.20	16.00	-2.15	5.58*	16	-1.46	-0.02
9	GP-111×MGC-15	87.17	-4.88	12.26**	18.67	-1.16	-0.14	15.00	-1.99	0.12	15	-0.21	0.36
10	GP-111×MGC-137	90.17	0.19	27.05**	17.50	1.80	1.56*	14.17	3.25	-0.09	14	-2.50	0.38
11	GP-111 ×PFSR-46	89.83	-0.81	-2.67	15.50	-1.67	0.09	13.67	-0.72	0.48	14	0.00	-0.14
12	GP-111 ×PFSR-129	82.33	0.28	-3.00	15.00	0.00**	-0.20	13.67	-0.72	0.48	15	0.00**	-0.14
13	MGC-90×PFSR-95	70.50	0.83	-2.38	14.00	3.47**	0.41	12.83	2.70	1.60	13	1.25	-0.01
14	MGC-90×PFSR-151	92.17	2.33*	-0.76	17.33	4.50**	0.48	14.67	3.25	-0.09	14	0.00	-0.14
15	MGC-90×MGC-15	86.50	0.83	-2.38	18.83	0.26	-0.04	15.33	1.63	-0.14	14	-1.46	-0.02
16	MGC-90×MGC-137	85.67	-1.42	0.75	19.33	-0.51	0.44*	14.83	2.70	1.60	15	-1.25	-0.01
17	MGC-90×PFSR-46	75.67	0.55	-2.77	18.83	1.16	-0.14	13.17	3.42	4.35*	13	0.00	-0.14
18	MGC-90×PFSR-129	74.17	1.06	0.29	18.17	1.42	-0.18	14.00	2.15	5.58*	14	0.00	-0.14
19	BML-20×PFSR-95	93.83	0.97	-1.01	18.67	0.51	0.44*	14.50	1.99	0.12	15	0.00**	-0.14
20	BML-20×PFSR-151	90.67	4.44*	-2.93	19.00	5.15	-0.15	15.50	4.88	-0.01	13	3.96	0.00**
21	BML-20×MGC-15	75.83	3.77	0.95*	18.83	1.93	0.69*	14.83	1.46	2.89	15	5.43	-0.14
22	BML-20×MGC-137	79.83	0.28	-3.00	20.17	2.32	0.07	16.17	3.25	-0.09	16	2.92	0.33
23	BML-20×PFSR-46	81.33	0.53	-2.23	17.17	1.42	-0.18	16.00	2.15	5.58*	14	0.00**	-0.14
24	BML-20×PFSR-129	85.33	4.36**	-3.08	20.17	3.99	-0.20	16.83	4.69	3.26*	13	5.43	-0.14
25	BML-11×PFSR-95	92.00	-1.28	-2.98	18.67	-1.16	-0.14	14.17	-2.70	1.60	15	1.25	-0.01
26	BML-11×PFSR-151	92.67	2.47**	-2.03	18.67	3.99	-0.20	14.33	-0.52	5.00**	14	4.17	-0.04
27	BML-11×MGC-15	70.50	0.64	-3.05	15.00	0.00*	-0.20	14.00	0.00	-0.15	13	0.00**	-0.14
28	BML-11×MGC-137	83.17	1.83	-2.32	20.17	2.32	0.07	16.83	4.69	3.26*	16	4.17	-0.04
29	BML-11×PFSR-46	85.83	-1.19	-2.57	21.17	1.16	-0.14	16.83	-4.49	10.86**	18	1.01	-0.14
30	BML-11×PFSR-129	89.33	2.39*	-1.06	21.83	2.83	-0.13	16.33	-0.69	16.99**	18	2.92	0.33
31	PFSR-51×PFSR-95	84.17	2.22*	1.84	16.83	3.73	-0.06	13.50	3.97	0.95	13	4.17	-0.04
32	PFSR-51×PFSR-151	80.33	2.05	0.16	15.83	0.26	-0.04	14.17	3.42	4.35*	16	10.85**	-0.14
33	PFSR-51×MGC-15	67.00	1.91	-2.86	16.67	1.12	-0.18	15.17	5.40	6.85*	14	1.17	-0.04
34	PFSR-51×MGC-137	82.33	-1.19	-2.57	22.17	1.16	-0.14	17.67	-5.21	16.80**	18	1.26	-0.02
35	PFSR-51×PFSR-46	95.67	6.30*	0.77	19.00	5.15	-0.15	13.83	3.45	1.34	15	8.35	0.28
36	PFSR-51×PFSR-129	76.17	2.33	-0.76	16.17	1.42*	-0.18	15.00	6.12	11.71**	15	2.71	-0.14
	Checks												
1	DHM117	80.67	-1.50	2.97**	18.83	-2.32	0.07	17.17	-4.69	3.26*	16	-2.92	0.33
2	DHM121	77.33	-0.94	0.55	16.00	-0.90	0.24	17.00	0.17	3.35*	15	-0.21	0.36
3	Bio9544	85.00	2.16	-2.55	20.17	1.42	-0.18	17.67	1.10	-4.44	18	2.71	-0.14
4	NK6240	79.00	4.14*	1.45	18.00	4.25	-0.03	15.83	2.37	5.69	15	5.43	-0.14
5	KNMH4010131	75.17	0.55	-2.77	16.00	0.00	-0.20	14.67	1.43	2.40	14	0.00	-0.14
	Mean	79.25			16.62			14.28			14		
	SE	1.27			0.33			**1.27**			**0.28**		

Table 6 . Estimation of stability parameters for number of kernels per row, 100 seed weight and grain yield

S.No.	Hybrids	Number of kernels per row			100 seed weight			Grain yield		
		μ	bi	s²di	μ	bi	s²di	μ	bi	s²di
1	GP-35×PFSR-95	24	1.07	0.14	27.17	1.65**	-0.07	6333	0.40	-46263
2	GP-35×PFSR-151	30	0.65	-0.27	28.50	-0.49	0.05	8398	2.43	113672**
3	GP-35×MGC-15	30	0.24	1.60	30.17	-1.31	0.54*	10133	-0.42	69995**
4	GP-35×MGC-137	34	3.44	0.21	35.67	3.64	0.20	12053	2.27	-116810
5	GP-35×PFSR-46	26	1.07	0.14	26.00	2.48**	0.37	7285	3.47*	-44052
6	GP-35×PFSR-129	27	0.00**	-0.39	28.33	0.34	-0.27	6800	0.29	-52141
7	GP-111×PFSR-95	24	0.00**	-0.39	26.50	-0.49	0.05	6501	0.46	106886**
8	GP-111×PFSR-151	36	1.07	0.14	35.50	0.49	0.05	10268	-0.10	-52374
9	GP-111×MGC-15	32	-0.41	0.76*	33.50	-2.97	2.06*	9290	-3.69	38598
10	GP-111×MGC-137	28	-0.24	1.60	28.00	0.97	1.47*	8600	-4.99	141750**
11	GP-111×PFSR-46	31	0.00**	-0.39	29.83	-1.16	-0.41	8239	-0.88	-57231
12	GP-111×PFSR-129	30	0.00**	-0.39	30.33	0.83	-0.33	7798	1.98	8294
13	MGC-90×PFSR-95	24	1.72	-0.24	26.00	0.49	0.05	5717	-1.27	-55279
14	MGC-90×PFSR-151	28	2.49	0.04	28.50	3.49	-0.34	8288	2.65*	8921
15	MGC-90 ×MGC-15	34	5.64	2.36	34.17	1.16	-0.41	8255	0.33	14641*
16	MGC-90 ×MGC-137	32	-0.12	0.11	34.33	-2.18	1.19*	7148	0.26	- 36162
17	MGC-90×PFSR-46	26	1.72	-0.24	26.83	0.83	-0.33	6455	1.55	171758**
18	MGC-90×PFSR-129	26	2.49	0.04	25.83	1.84	0.35	6440	4.69	-56566
19	BML-20×PFSR-95	28	-1.31	0.08	31.67	0.68	0.19	8167	0.88	-53870
20	BML-20×PFSR-151	32	3.03	-0.30	34.00	3.01	0.53*	8544	4.48	262322**
21	BML-20×MGC-15	32	4.87	-0.02	34.17	6.65	-0.39	7956	0.92	-56750
22	BML-20×MGC-137	33	1.60	0.81	35.33	3.30	0.98*	10249	0.97	-29885
23	BML-20×PFSR-46	29	-1.19	-0.39	32.00	0.00**	-0.42	9605	1.04	-52125
24	BML-20×PFSR-129	34	3.44	0.21	34.33	6.31	-0.38	9738	3.70	15682
25	BML-11×PFSR-95	35	-1.07	0.14*	35.33	-1.16	-0.41	6933	1.64	49019*
26	BML-11×PFSR-151	29	-0.65	-0.27	31.83	2.82	-0.18	7982	-0.60	-54627
27	BML-11×MGC-15	25	0.00	-0.39	28.00	0.00**	-0.42	5933	2.58	-28323
28	BML-11×MGC-137	34	0.41	0.76*	35.17	1.15	-0.07	10838	1.02	-2925
29	BML-11×PFSR-46	35	1.07	-0.14	35.83	1.15	-0.07	11690	1.08	-38009
30	BML-11×PFSR-129	35	3.44	0.21	36.33	2.82	-0.18	11559	1.94	-16828
31	PFSR-51×PFSR-95	28	3.56	-0.38	27.33	3.83	0.04	7272	0.17	23607*
32	PFSR-51×PFSR-151	27	3.68	0.01	28.33	-0.15	0.74*	7790	4.39	78873*
33	PFSR-51×MGC-15	28	1.19	-0.39	29.17	1.14	-0.20	8432	1.47	-33545
34	PFSR-51×MGC-137	35	1.07	-0.14	36.33	1.16	-0.41	12582	1.30	-26235
35	PFSR-51×PFSR-46	32	3.56	-0.38	34.83	6.80	0.38*	8302	3.79	94854*
36	PFSR-51×PFSR-129	25	0.65	-0.27	26.33	2.33	-0.38	6692	4.07	73375**
	Checks									
1	DHM117	32	0.24	1.6	34.00	-0.97	1.47*	9753	-0.41	60490**
2	DHM121	31	-0.53	-0.26	30.33	-1.65	-0.07	9145	-0.25	14351*
3	Bio 9544	34	2.37	-0.39	34.83	2.33	-0.38	10085	2.31	-57801
4	NK6240	31	4.75	-0.38	31.67	6.16	0.34	9560	4.59	-57251
5	KNMH4010131	28	0.00	-0.39	27.00	0.00	-0.42	8136	4.36	293430**
	Mean	27			28.28			7330		
	SE	0.47			0.51			179.9		

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Table 7 . Nature of stability exhibited by maize hybrids over the three environments.

Characters	Average stability	Above average stability	Below average stability
	bi=1,S^2di=0	bi>1,S^2di=0	bi<1,S^2di =0
Days to 50% tasseling	MGC-90 × PFSR-95, BML-11× PFSR-151and BML-11 × MGC-137	GP-35 × MGC-137,GP-35 ×PFSR-46,MGC-90 × PFSR-151, BML-20 × MGC-137 and BML-11× PFSR-129	GP-111 × PFSR-95, GP-111 × PFSR-151,GP-111×PFSR-46,BML-20×PFSR-95,BML-11×PFSR-95,PFSR-51 ×MGC-137,BML-11×PFSR-46 and KNMH4010131
Days to 50 % silking	MGC-90 × PFSR-95, BML-11 × PFSR-151 and BML-11 × MGC-137	GP-35× MGC-137,GP-35× PFSR-46, MGC-90 × PFSR-151, BML-20 × MGC-137 and BML-11× PFSR-129	GP-111 × PFSR-95, GP-111 × PFSR-151, GP-111×PFSR-46, BML-20×PFSR-95, BML-11 × PFSR-95, PFSR-51 × MGC-137, BML-11× PFSR-46 and KNMH4010131
Days to maturity	MGC-90 × PFSR-95, BML-11× MGC-137 and KNMH4010131	GP-35× MGC-137, BML-20 × MGC-137, PFSR-51 × PFSR-95 and BML-11 × PFSR-129	GP-111 × PFSR-95, GP-111× PFSR-151,GP-111× PFSR-46,BML-20 × PFSR-95, BML-11× PFSR-95, BML-11 × PFSR-46 and PFSR-51 × MGC-137
Plant height	MGC-90 × PFSR-95, MGC-90 × PFSR-46 and BML-11 × MGC-15	BML-20 × MGC-15,PFSR-51× MGC-15 and PFSR-51× PFSR-129	GP-35 × PFSR-129
Ear height	GP-35 × PFSR-46, MGC-90 × PFSR-95, MGC-90 × PFSR-46, MGC-90 × PFSR-129, BML-11 × MGC-15 and KNMH4010131	PFSR-51 × MGC-15 and PFSR-51 × PFSR-129	GP-35 × PFSR-129
Ear length	MGC-90 × PFSR-46, MGC-90 × PFSR-129, BML-11× PFSR-46, BML-20 × PFSR-46, PFSR-51 × MGC-15, PFSR-51 × MGC-137 and Bio 9544 (check)	GP-35 × MGC-137, BML-20 × PFSR-151, BML-20 × MGC-137, BML-20 × PFSR-129, BML-11 × PFSR-151, BML-11 × MGC-137, BML-11 × PFSR-129, PFSR-51 × PFSR-95, PFSR-51 × PFSR-46 and NK6240	GP-35 × PFSR-151, GP-35 × MGC-15, GP-111 × MGC-15, MGC-90 × MGC-15, BML-11 × PFSR-95 and DHM117
Ear girth	Bio 9544	GP-111 × MGC-137, MGC-90 × PFSR-151, MGC-90 × MGC-15, BML-20 × PFSR-95, BML-20 × PFSR-151, BML-20 × MGC-137.	BML-11×MGC-15
Number of kernel rows per ear	PFSR-51 × MGC-15, BML-11× PFSR-46 and PFSR-51 × MGC-137	GP-35 × MGC-137, BML-20 × MGC-15, BML-20×MGC-137, BML-11×PFSR-95, BML-11 × PFSR-151, BML-11 × MGC-137, BML-11×PFSR-129, PFSR-51 × PFSR-46, PFSR-51× PFSR-129, Bio 9544 And NK6240	GP-35 × MGC-15,GP 111 × PFSR-151, GP-111 × MGC-15, GP-111 × MGC-137, MGC-90 ×MGC-15, MGC-90 × MGC-137, DHM-117, DHM-121 and KNMH4010131
Number of kernels per row	GP-35 × PFSR-151, GP-111 × PFSR-151, PFSR-51 × MGC-15, BML-11 × PFSR-46 and PFSR-51×MGC-137	MGC-90 × PFSR-151, BML-20 × PFSR-151, BML-20 × MGC-15, PFSR-51 × PFSR-95, PFSR-51 × PFSR-151, PFSR-51 × PFSR-46, Bio9544 and NK6240	MGC-90 × MGC-137, BML-20 × PFSR-95, BML-20 × PFSR-46, BML-11 × PFSR-151, DHM-121 and KNMH4010131
100 seed weight	GP-111× PFSR-129, MGC-90 × MGC-15, BML-20 × PFSR-95, BML-11 × MGC-137, BML-11 × PFSR-46, PFSR-51 × MGC-15 and PFSR-51 × MGC-137	GP-35 × MGC-137,MGC-90 × PFSR-151, BML-20 × MGC-15, BML-20 × PFSR-129, BML-11 × PFSR-151, BML-11 × PFSR-129, Bio9544 and NK6240	GP-35 × PFSR-151, GP-35 × PFSR-129, GP-111 × PFSR-151, GP-111 × PFSR-46, BML-11 × PFSR-95 and DHM121
Grain yield	BML-20 × PFSR-95, BML-20 × MGC-15, BML-20 × PFSR-46, BML-20 × MGC-137, BML-11 × MGC-137, BML-11 × PFSR-46, PFSR-51 ×MGC-15 and PFSR-51 × MGC-137	GP-35 × MGC-137, BML-11 × PFSR-129,Bio9544 and NK6240	GP-111 × PFSR-151,GP-111× PFSR-46 and BML-11 × PFSR-151

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For 100 seed weight, Seven hybrids GP-111 × PFSR-129, MGC-90 × MGC-15, BML-20 × PFSR-95, BML-11 × MGC-137, BML-11 × PFSR-46, PFSR-51 × MGC-15 and PFSR-51 × MGC-137 recorded superior mean estimate than population mean with regression coefficient nearer to unity and non-significant minimum deviation from the regression coefficient (S^2di) indicating their stable performance across the tested environments for this trait.Non-significant S^2di and regression coefficient higher than unity along with advanced mean estimates than the population mean was exhibited by 8 hybrids (GP-35 × MGC-137, MGC-90 × PFSR-151, BML-20 × MGC-15, BML-20 × PFSR-129, BML-11 × PFSR-151, BML-11 × PFSR-129, Bio 9544 (check) and NK 6240 (check) indicating their stable performance under favourable environment. Whereas the hybrids GP-35 × PFSR-151, GP-35 × PFSR-129, GP-111 × PFSR-151, GP-111 × PFSR-46, BML-11 × PFSR-95 and DHM 121(check) showed less sensitivity to environmental conditions and adaptability to poor environment for this trait (**Table 6 and Table 7**). Similar findings were reported by Nirmal raj *et al*. 2019 and Arun kumar *et al*. (2020).

For grain yield, the hybrids BML-20 × PFSR-95, BML-20 × MGC-15, BML-20 × PFSR-46, BML- 20 × MGC-137, BML-11 × MGC-137, BML-11 × PFSR-46, PFSR-51 × MGC-15 and PFSR-51 × MGC-137 exhibited wider adaptability and stable performance for this trait, while the hybrids GP-35 × MGC-137, BML-11 × PFSR-129, Bio 9544 (check) and NK 6240 (check) showed adaptability to favourable environment for this trait. The hybrids GP-111 × PFSR- 151, GP-111 × PFSR-46 and BML-11 × PFSR-151 recorded non-significant S^2di and regression coefficient lesser than unity along with advanced mean estimates than the population mean, indicating their adaptability to poor environment for this trait (**Table 6 and Table 7**). Similar results for grain yield stability were documented by Boreddy *et al.* (2020) and Ismail *et al.* (2023) Kebede, *et al*. 2023 and Engida *et al*. (2024).

From the stability data determined for 36 maize hybrids across the three locations (**Table 7**), it was observed that for maturity determining traits (days to 50 % tasseling, days to 50 % silking and days to maturity), two hybrids (MGC-90 × PFSR-95 and BML-11 × MGC-137) exhibited earliness and stable performance over the three locations. For yield and its attributing traits, two promising hybrids (BML-11 × PFSR-46 and PFSR- 51 × MGC-137) showed wider adaptability, whereas two hybrids (GP-35 × MGC-137 and BML-11 × PFSR-129) exhibited stable performance under good environment conditions and one cross combination (GP-111 × PFSR-151) showed stable performance under poor environment conditions over the best check for their respective characters. However, these hybrids have to be further evaluated over the seasons and years to confirm their stable performance for their respective characters before their commercial exploitation.

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