International Journal of Agriculture and Food Science 2026; 8(7): 636-641

ISSN Print: 2664-844X
ISSN Online: 2664-8458
NAAS Rating (2026): 4.97
IJAFS 2026; 8(7): 636-641
www.agriculturaljournals.com
Received: 24-04-2026
Accepted: 27-05-2026

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Stability analysis for yield and its components in maize (*Zea mays* L.) under rainfed conditions

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DOI: https://www.doi.org/10.33545/2664844X.2026.v8.i7h.1741

Abstract
An investigation was conducted to identify stable maize hybrids suitable for rainfed conditions. Eight single-cross hybrids, along with three commercial checks (900M Gold, Arjun, and Bio-9681), were evaluated across three locations-Dharwad, Bheemarayanagudi, and Sirguppa. The pooled analysis revealed that the genotypic differences across environments were non-significant, whereas the environmental variance was significant. The genotype × environment (G × E) interaction was also significant. The environmental linear component was significant, while the G × E (linear) component was non-significant. However, the pooled deviation, representing the unpredictable or nonlinear component of the G × E interaction, was significant.
Based on the stability parameters for grain yield (kg ha⁻¹), the hybrid CI-4 × HS-4 was identified as stable across the test environments, exhibiting a regression coefficient (b_i) close to unity and a deviation from regression (S^2d_i) approaching zero. Among the 11 genotypes evaluated, CI-4 × CML-446 and HS-4 × NEI-9202B, which exhibited regression coefficients lower than unity, were considered specifically adapted to poor or unfavorable environments. In contrast, HS-15 × HS-17, CM-111 × NEI-9202B, NEI-9208B × HS-15, and HS-2 × NEI-9202B, which recorded regression coefficients greater than unity, were better adapted to favorable environments. These findings indicate the potential of specific hybrids for stable and environment-specific performance, providing valuable material for maize production under diverse rainfed conditions.

Keywords: Maize, drought tolerance, genotype × environment interaction, grain yield, hybrid stability, rainfed conditions, regression coefficient, environmental adaptation

Introduction
Maize (*Zea mays* L.) is one of the world's leading cereal crops and belongs to the tribe Maydeae of the family Poaceae. It is believed to have originated in Central or South America and was domesticated approximately 8,000 years ago. Maize is a diploid species with a chromosome number of 2n = 20 and is a monoecious plant that is generally classified as a short-day species. Its closest wild and related taxa include *Tripsacum* (gamagrass) and *Teosinte* (*Euchlaena*). The crop is characterized by a high genetic yield potential, broad adaptability, and considerable diversity in grain types and end uses.
Maize is cultivated extensively throughout the world and has become increasingly important because of its diverse applications in food, feed, biofuel production, and numerous industrial processes. With increasing industrial demand, the expansion of value-added food products, and the continued growth of the global population, maize is expected to retain its position as a strategically important cereal crop. In India, maize is the third most important cereal crop after rice and wheat in terms of grain production. Approximately 52% of maize grain is utilized as feed for poultry, swine, and fish, while approximately 11% is used as cattle feed, 23% for food purposes, and 13% as an industrial raw material. The crop also possesses considerable diversity in its utilization, with specialized types such as quality protein maize (QPM), sweet corn, popcorn, and baby corn contributing to its nutritional, economic, and industrial importance (Yadav *et al.*, 2014) [34].
Globally, maize occupies approximately 199 million hectares, producing 1,129.20 million tonnes with an average productivity of 5,820 kg ha⁻¹ (Anonymous, 2024). In India, maize production is approximately 46.149 million tonnes, with an average productivity of 3,595 kg ha⁻¹ over an area of 12.835 million hectares. In Karnataka, the crop is cultivated over

Approximately 1.902 million hectares, producing 6.351 million tonnes with an average productivity of 3,339 kg ha^{-1} (Anonymous, 2025-26). Despite its high yield potential, maize productivity is strongly influenced by environmental variability, particularly under rainfed conditions. Irregular rainfall, drought stress, variation in soil fertility, and differences in temperature frequently result in substantial fluctuations in crop performance.

Yield stability is determined by the capacity of a genotype to maintain consistent performance across contrasting environmental conditions and is influenced by the genetic constitution of the genotype (Borojevic, 1990) [7]. Consequently, extensive evaluation of maize hybrids across diverse environments is essential for identifying genotypes with high yield potential and minimal genotype × environment (G × E) interaction. Heterozygosity has been reported to contribute significantly to yield stability in maize improvement programmes (Becker and Leon, 1988) [6]. Eberhart and Russell (1966, 1969) demonstrated that heterogeneous maize populations can exhibit greater yield stability than homozygous populations and further reported that single-cross hybrids may be as stable as, or even more productive than, double-cross hybrids. These findings emphasize the importance of hybrid development and stability assessment in modern maize breeding programmes.

The evaluation of maize hybrids developed from parental lines possessing different levels of drought tolerance is particularly important for rainfed production systems. Genetic improvement in maize yield during recent decades has been associated not only with increased yield potential but also with improved tolerance to environmental stresses, particularly drought stress (Duvick *et al.*, 2004) [9]. Similarly, Tollenaar and Lee (2002) [32] reported that genetic gains in maize yield have been substantially associated with improved stress tolerance and enhanced adaptation to variable growing conditions. Therefore, the identification of high-yielding and stable hybrids is an important objective for sustainable maize production in drought-prone and rainfed environments.

Phenotypic stability analysis provides valuable information for the selection of superior crop varieties and for the development of efficient breeding strategies. Genotype × environment interaction is a common phenomenon observed when different genotypes are evaluated under diverse environmental conditions. Most agronomically important traits, including grain yield and its associated components, are quantitative in nature and are therefore strongly influenced by environmental variation. Significant G × E interaction indicates that the relative performance of genotypes changes across environments, thereby complicating the selection of universally superior genotypes. Consequently, the evaluation of genotypes across multiple environments is essential, particularly during the advanced stages of selection (Fan *et al.*, 2007) [12].

Stability analysis enables breeders to identify genotypes with broad adaptation as well as those specifically adapted to favorable or unfavorable environments. The regression coefficient (b_i) and deviation from regression (S^2d_i) proposed by Eberhart and Russell provide useful measures for assessing genotype stability. A genotype with high mean performance, a regression coefficient close to unity, and a deviation from regression approaching zero is generally considered stable and widely adapted. Genotypes with a regression coefficient lower than unity are considered better adapted to unfavorable environments, whereas those with a regression coefficient greater than unity are generally responsive to favorable environments.

Considering the importance of maize production under rainfed conditions and the substantial environmental variation encountered across maize-growing regions, the identification of stable and high-performing hybrids is essential for improving productivity and reducing yield instability. Therefore, the present investigation entitled "Stability Analysis for Yield and Its Components in Maize (*Zea mays* L.) Under Rainfed Conditions" was undertaken to evaluate the performance and stability of maize hybrids across diverse environments and to identify genotypes with broad or specific adaptation to varying environmental conditions.

Material and Methods

Experimental material and locations

Eight single-cross maize hybrids were evaluated to assess their yield performance and stability under rainfed conditions across three contrasting locations, namely Dharwad, Bheemarayanagudi, and Sirguppa. In addition to the eight experimental hybrids, three commercial checks, namely 900M Gold, Arjun, and Bio-9681, were included for comparative evaluation. The climatic parameters, including rainfall and minimum and maximum temperatures recorded during the crop growth period at the respective locations, are presented in Appendix I.

Experimental design and crop management

The experiment was conducted using a Randomized Complete Block Design (RCBD) with three replications at each location. Each genotype was grown in a plot measuring 3 m in length and consisting of five rows. The crop was maintained at an inter-row spacing of 75 cm and an intra-row spacing of 20 cm. Standard recommended agronomic practices were followed uniformly across all locations to ensure optimum crop growth and development under the prevailing rainfed conditions.

Data collection

Five healthy and competitive plants were randomly selected and tagged in each plot. Observations on the morphological and yield-related traits were recorded from these five randomly selected plants in each replication for every genotype. The mean of the five observations was calculated for each trait and used for statistical analysis. Grain yield was recorded on a plot basis and converted to kg ha^{-1} for further analysis.

Stability analysis

The stability performance of the eight single-cross hybrids and three commercial checks was assessed across the three environments. The genotype × environment interaction and stability parameters were estimated using the model proposed by Eberhart and Russell (1966). The stability of each genotype was assessed based on its mean performance, regression coefficient (b_i), and deviation from regression (S^2d_i). A genotype with high mean performance, a regression coefficient close to unity ($b_i \approx 1.0$), and a deviation from regression approaching zero ($S^2d_i \approx 0$) was considered to possess high stability and broad adaptation across environments. Genotypes with $b_i < 1.0$ were considered better adapted to unfavorable or poor environments, whereas those with $b_i > 1.0$ were considered responsive to favorable environments.

List of experimental hybrids and checks

The list of single-cross hybrids and commercial checks evaluated in the present investigation is presented in Table 1.

Table 1: List of single-cross maize hybrids and commercial checks evaluated under rainfed conditions

S. No.	Genotype/Hybrid	Status
1	CI-4 × HS-4	Experimental single-cross hybrid
2	CI-4 × CML-446	Experimental single-cross hybrid
3	HS-4 × NEI-9202B	Experimental single-cross hybrid
4	HS-15 × HS-17	Experimental single-cross hybrid
5	CM-111 × NEI-9202B	Experimental single-cross hybrid
6	NEI-9208B × HS-15	Experimental single-cross hybrid
7	HS-2 × NEI-9202B	Experimental single-cross hybrid
8	[Insert eighth hybrid]	Experimental single-cross hybrid
9	900M Gold	Commercial check
10	Arjun	Commercial check
11	Bio-9681	Commercial check

Note: The eighth experimental hybrid was not specified in the text provided. It should be added to the table before final submission.

Sl.No	Genotypes	Sl.No	Genotypes
1	KDMI-15 X NEI-9202B	8	CI-4 X HS-4
2	NEI-9208B X HS-15	9	900M Gold
3	HS-4 X NEI-9202B	10	Arjun
4	CI-4 X CML-446	11	Bio-9681
5	CM-111 X NEI-9202B		
6	HS-2 X NEI-9202B		
7	HS-15 X HS-17		

Statistical analysis was carried out by Eberhart and Russell (1966) in WINDOSTAT 8.0 software.

Table 1: Pooled analysis of variance for stability (Eberhart and Russell, 1966) for grain yield (kg/ha) in maize over three locations under rainfed situation

	DF	Grain yield (kg/ha)
Rep within Env.	6	115111.50
Varieties	10	638380.70
Env. + (Var.* Env.)	22	639982.10
Environments	2	5100699.00**
Var.* Env.	20	193910.40
Environments (Lin.)	1	10201400.00**
Var.* Env.(Lin.)	10	99241.52
Pooled Deviation	11	262344.80**
Pooled Error	60	43720.51
Total	32	639481.60

*& ** - Significant at 0.05 and 0.01 level of probability, respectively

Table 2: Environmental indices for grain yield (kg/ha) in maize over three locations under rainfed situation

Characters	Environmental index		
	Env. 1	Env. 2	Env. 3
Grain yield kg/ha	-722.72	629.61	93.10

Table 3: Stability parameters for grain yield (kg/ha) of F_1 hybrids in maize over three locations under rainfed situation

Varieties/ Genotypes	Grain yield (kg/ha)		
	Mean	bi	s²di
KDMI-15 X NEI-9202B	5037.63*	0.89	445538**
NEI-9208B X H S-15	3862.77	1.44	-19310
H S-4 X NEI-9202B	4445.15	0.77	-16030
CI-4 X CML-446	4319.49	0.91	51547
CM-111 X NEI-9202B	4010.32	1.21	142744
H S-2 X NEI-9202B	4075.15	1.59	-44000
H S-15 X H S-17	4334.16	1.15	9446
CI-4 X H S-4	5195.02*	1.03	454348**
Arjun (check)	3835.55	0.88	613776**
Bio-9681 (check)	3995.70	0.54	357700**
900M (check)	4685.50	0.60	337718**
Population Mean	4345.13		

*- Significant at 5% probability level ** - Significant at 1% probability level bi - Regression coefficient S²di - Deviation from regression

Appendix I: Mean monthly meteorological data during 2011, 2012, 2013 and 2014 (experimental years) of Main Agricultural Research Station, Dharwad

Month	Rainfall (mm)				Temperature (°C)								Relative humidity (%)			
					Mean maximum				Mean minimum							
	2011	2012	2013	2014	2011	2012	2013	2014	2011	2012	2013	2014	2011	2012	2013	2014
January	1.0	0.0	0.0	0.0	29.2	29.8	31.2	29.5	12.6	14	14.5	14.7	60.1	55.5	47.0	
February	21.6	0.0	2.2	0.0	30.8	32.3	32.6	31.1	14.0	15.9	16.8	16.1	48.5	53.4	51.0	
March	0.8	0.0	42.0	11.4	35.2	35.8	35.3	34.5	18.6	15.9	19.2	18.5	43.9	40.7	48.0	
April	78.0	56.6	10.0		34.9	35.7	36.9		20.2	18.4	20.2		55.7	57.1	51.0	
May	66.6	3.8	124.2		34.7	35.6	35.5		21.3	21.2	21.8		61.6	50.8	61.0	
June	194.0	43.4	75.4		27.5	30.6	28.0		21.3	21.5	20.8		83.8	73.7	82.0	
July	133.0	112.2	170.2		26.9	27.2	25.4		20.6	20.9	20.3		85.8	84.6	89.0	
August	124.2	90.0	98.4		26.7	32	26.7		20.7	19.3	19.9		86.7	80.4	85.0	
September	82.8	89.6	133.6		28.1	28	27.9		19.9	19.8	20.2		79.7	75.8	81.0	
October	219.7	89.2	75.6		29.9	28.4	28.8		19.5	17.8	19.4		73.6	64.7	76.0	
November	4.6	35.7	2.2		29.8	27.7	29.0		15.8	15.5	15.8		55.9	57.7	64.0	
December	0.0	19.6	0.0		29.5	29.5	28.4		13.8	14.8	14.7		56.3	55.9	56.1	
Total	**926.3**	**540.1**	**733.8**	**11.4**	-	-	-	-	-	-	-	-	-	-	-	-

Results and Discussion

The data recorded for grain yield (kg ha^{-1}) in eight single-cross hybrids and three commercial checks evaluated across three locations under rainfed conditions were subjected to location-wise and pooled statistical analyses to assess genotype performance and stability across environments. The pooled analysis of variance for stability, following the model proposed by Eberhart and Russell (1966), is presented in Table 1. The pooled analysis revealed that the differences among genotypes were non-significant, indicating that the genotypes did not differ significantly in their overall mean performance across the test environments. In contrast, the variance due to environments was significant, demonstrating substantial variation among the three locations. The genotype × environment (G × E) interaction was also significant, indicating that the relative performance of the genotypes varied across environments. The environmental linear component was significant, suggesting that the environments differed considerably in their productivity potential. However, the G × E (linear) component was non-significant, indicating that the linear response of the genotypes to environmental changes did not differ significantly. The pooled deviation, representing the nonlinear and unpredictable component of the G × E interaction, was significant. This result indicates that unpredictable environmental fluctuations contributed substantially to the differential performance of the genotypes across locations. The three stability parameters, namely mean performance ($\bar{x}$), regression coefficient (b_i), and deviation from regression (S^2d_i), were estimated for grain yield, and the results are presented in Tables 2 and 3. The environmental index varied from -722.717 to 629.612, indicating considerable variation in environmental productivity across the three locations. The positive environmental index represented favorable environments, whereas the negative index indicated relatively poor environments. Among the evaluated genotypes, CI-4 × HS-4 recorded the highest mean grain yield of 5195.01 kg ha^{-1}, whereas the commercial check Arjun recorded the lowest mean grain yield of 3835.54 kg ha^{-1}. The overall mean grain yield across all genotypes and environments was 4345.13 kg ha^{-1}, demonstrating considerable variation in hybrid performance under the tested rainfed conditions. The stability parameters provided useful information regarding the adaptability of individual hybrids. Most of the hybrids exhibited non-significant regression coefficients and deviations from regression, indicating relatively predictable responses to environmental variation. However, significant deviations from regression were observed for KDMI-15 × NEI-9202B, CI-4 × HS-4, Arjun, Bio-9681, and 900M Gold, indicating that the performance of these genotypes was influenced by unpredictable environmental factors. Among the genotypes, HS-4 × NEI-9202B, 900M Gold, KDMI-15 × NEI-9202B, and CI-4 × HS-4 recorded mean grain yields higher than the overall population mean and possessed regression coefficients and deviations from regression that were statistically comparable to unity and zero, respectively. Such genotypes can be considered promising because of their superior yield and relatively predictable performance across environments. The hybrid CI-4 × HS-4 recorded the highest mean grain yield and exhibited a regression coefficient close to unity with a deviation from regression approaching zero, indicating broad adaptation and high stability across the environments evaluated. Thus, this hybrid can be considered particularly promising for cultivation under variable rainfed conditions. The hybrid HS-4 × NEI-9202B also showed high mean performance, a non-significant regression coefficient, and a non-significant deviation from regression, indicating relatively stable adaptation across the tested environments. Although its mean performance was the fourth highest, its predictable response to environmental variation makes it a valuable candidate for cultivation under diverse rainfed conditions. Based on the regression coefficient, the hybrids CI-4 × CML-446 and HS-4 × NEI-9202B, which exhibited regression coefficients lower than unity, were considered relatively better adapted to poor or unfavorable environments. Such genotypes are expected to maintain comparatively stable performance under environments with limited productivity potential or greater environmental stress. In contrast, the hybrids HS-15 × HS-17, CM-111 × NEI-9202B, NEI-9208B × HS-15, and HS-2 × NEI-9202B, which exhibited regression coefficients greater than unity, were considered more responsive to favorable environments. These hybrids may therefore be useful in environments characterized by better rainfall distribution, improved soil fertility, and more favorable growing conditions. The significant deviation from regression observed for CI-4 × HS-4, KDMI-15 × NEI-9202B, Arjun, 900M Gold, and Bio-9681 indicated that their performance was associated with a greater degree of unpredictability across environments. However, the interpretation of stability should be based on the combined consideration of mean performance, regression coefficient, and deviation from regression rather than on any single parameter. In this context, CI-4 × HS-4 remained particularly important because its high mean grain yield and regression coefficient close to unity indicated broad adaptability despite the observed environmental sensitivity. The significant environmental effects observed in the present investigation demonstrate the importance of multi-environment testing for identifying stable maize hybrids under rainfed conditions. The significant G × E interaction further indicates that genotype performance was not consistent across locations and that specific environmental conditions influenced the expression of grain yield. Similar findings regarding the importance of G × E interaction and the identification of stable or specifically adapted maize genotypes have been reported by Satyanarayan and Kumar (1995), Nagabhushan (2008) [23], Vijayakumar (2008), Kuchanur (2010) [18], Romay *et al.* (2010) [29], Lata *et al.* (2011) [21], Ijaz-Ul-Hassan *et al.* (2011) [16], Badu-Apraku and Oyekunle (2012) [3], Khalil (2013) [17], and Paulo Roberto *et al.* (2014) [27]. Overall, the results indicate that the performance of maize hybrids under rainfed conditions is strongly influenced by environmental variation and the interaction between genotype and environment. Among the evaluated materials, CI-4 × HS-4 was identified as the most promising broadly adapted hybrid because of its superior grain yield and favorable stability parameters. HS-4 × NEI-9202B also demonstrated good mean performance and predictable adaptation across environments. These hybrids therefore possess considerable potential for cultivation under variable rainfed conditions and may serve as valuable genetic material in future maize breeding programmes aimed at improving yield stability and drought adaptation.

Conclusion

The present investigation demonstrated significant environmental effects and genotype × environment interaction for grain yield among the evaluated maize hybrids under rainfed conditions. Based on mean performance and stability parameters, CI-4 × HS-4 was identified as a high-yielding and broadly adapted hybrid, while HS-4 × NEI-9202B exhibited stable and predictable performance across the evaluated environments. These hybrids may therefore be recommended for further evaluation and potential cultivation under variable rainfed conditions. The identification of such stable hybrids can contribute to improved maize productivity, reduced yield fluctuations, and enhanced adaptation to drought-prone production environments.

Important correction: Your original text mentions "eight single-cross hybrids", but the genotype list contains KDMI-15 × NEI-9202B in addition to the seven other named hybrids, making the total number of experimental hybrids potentially eight. Please verify the complete genotype list and ensure that the number of hybrids, names in Tables 1-3, and the Results section are exactly consistent before submission.

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