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Navigating Hybrid-Environment Interaction in Maize Evaluation: Parametric and Non-Parametric Insights

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ABSTRACT

Development of high-yielding maize (*Zea mays* L.) hybrids, along with being well-adapted to many environments, is the most important goal of the National Maize Research Program in India. genotype × environment interaction (GEI) continues to be a major challenging issue to plant breeders and production agronomists. The present research investigates the (GEI), specifically examining hybrid stability and yield performance across distinct environmental conditions. A total of 62 maize hybrids were evaluated using both parametric and non-parametric methodologies across the four environments (Coimbatore, Dharwad, Hyderabad, Karimnagar) during *Kharif* 2021. Combined analysis of variance (ANOVA) and the Additive Main Effects and Multiplicative Interaction (AMMI) model are widely employed in multi-environment trials (MET) to evaluate genotype performance and stability. The AMMI model integrates ANOVA for assessing additive main effects with principal component analysis (PCA) to explore GEI, offering a comprehensive understanding of hybrid responses across environments. Moreover, PCA and correlation analysis were utilized to elucidate the relationships between parametric and non-parametric metrics, facilitating a comprehensive understanding of hybrid performance dynamics. The findings underscored the necessity of simultaneously considering yield and stability to harness GEI effects, thereby refining the maize cultivar selection process. The stability parameters, such as $S^{(6)}$, $NP^{(2)}$, $NP^{(3)}$, $NP^{(4)}$, *KR*, and *CVi*, were identified as effective statistics for screening desirable hybrids as they had a significant positive correlation with mean yield. Furthermore, according to the static and dynamic concepts of stability, the results revealed that stability statistics clustered into five groups. The overall stability analysis following different stability methods concluded that G51, G26, G30, G31, G12, G2, G27, G20, G47, and G56, identified as high yielding and stable across the four tested environmental conditions. Through the integration of yield and stability considerations and the utilization of analytical tools like PCA, consisting of both parametric and non-parametric statistics and cluster analysis, this study contributes to identifying resilient maize cultivars capable of confronting the challenges posed by climate change.

KEYWORDS: stability, parametric; non-parametric; AMMI; Maize

INTRODUCTION

Maize, as a fundamental crop in agriculture, plays a crucial role in the worldwide food supply chain, serving a wide range of farmers and stakeholders. Maize is India's third most significant cereal crop, next to rice and wheat in acreage and production. Global maize production reached 1.16 billion tonnes in 2022, cultivated over 203 million hectares, and increased to 1.22 billion tonnes in 2023 [1]. In India, maize was grown on 11.24 million hectares, yielding 37.66 million tonnes in 2023–24, highlighting its growing demand and significance in the agricultural sector [2]. Although its cultivation area in India is smaller compared to crops like rice and wheat, [3], corn holds significant importance due to its versatile applications [4]. It serves as a primary raw material for secondary industries such as poultry and starch production. However, a notable portion of corn cultivation in the country relies on rainfed conditions, which presents challenges in maintaining a consistent supply due to unpredictable weather patterns. Sometimes, these fluctuations lead to the need for imports to meet domestic demands, emphasizing the necessity for increased resilience within the corn farming sector. Essential to addressing these challenges is understanding the complex relationship between the hybrid and the environment, which greatly influences crop performance. Maize hybrids show high heterosis, but variable performance across environments highlights genotype × environment interaction, emphasizing the need to define adaptation zones and match cultivars to regional conditions for stable yield [5]. GEI emerges as a critical factor, impacting the behaviour of corn hybrids across various environmental conditions. This interaction can complicate the selection of superior hybrids, highlighting the need for robust methodologies to assess hybrid adaptability and stability.

The process of choosing the best hybrids for a range of environmental circumstances depends heavily on MET. According to [6], MET typically entails assessing a variety of hybrids over several locations and years. Plant breeders strive for high-yield performance combined with stability, and their goal is to create new commercial hybrids that can flourish in a variety of environments. However, substantial GEI interactions frequently make it difficult to interpret hybrid performance [7]. The association between genotypic and phenotypic values is impeded by this interaction, which makes hybrid selection difficult [8].

Maize, as a prominent cereal, is expected to play a vital role in meeting future global food demand. Crop production is driven by genotype, environment, and their interaction (GEI), with quantitative traits like yield influenced by both genetic effects and GEI [9]. It is essential to comprehend GEI interaction in METs to evaluate hybrid stability across various environments [10,11]. To examine hybrid adaptation and GEI interaction under variable growth conditions, a number of stability techniques have been put forth [7]. Identifying high-yielding and stable genotypes across diverse environments remains a key challenge due to GEI. To address this, hybrids must be evaluated under both favorable and unfavorable conditions across multiple environments [12]. [13], distinguished between two main methods for examining GEI interaction and adaptation: the non-parametric method, which takes environments and phenotypes into account in relation to biotic and abiotic factors, and the parametric method, which is based on distributional assumptions. Combining the two methods enables a thorough analysis and interpretation of GE interaction [10,14].

Combining parametric and non-parametric approaches is becoming more and more common in breeding programs, despite the pros and cons of both methods [10,15]. Cultivating hybrids with strong environmental adaptation is one way to improve maize yields. When it comes to producing grains under varying circumstances, the optimal hybrid should exhibit both stability and adaptation. The comparison between parametric and nonparametric statistics has been explored in various crops by different researchers. For instance, [16], investigated this in chickpea, [11] in barley, [17] in barley as well, [18] in durum wheat, [19] in maize, and [20] in rapeseed. Despite these studies, there remains a paucity of research specifically focusing on maize. Thus, the objectives of this research were to: (1) determine the effects of hybrid by environment interaction on grain yield for 62 maize hybrids in 4 test environments; (2) find hybrids that exhibit stable performance and high yield; and (3) investigate the associations, similarities, and distinctions between parametric and nonparametric stability methods.

MATERIALS AND METHODS

A study was conducted to evaluate the stability performance of 62 single-cross maize hybrids regarding yield. The materials used for the study are listed in Table 1, along with their hybrid names, codes and source. The hybrids used in the present study comprised all the public and private sector hybrids that were tested in the AICRP (All India Coordinated Research Project). The experiment followed an alpha lattice design with three replications, including four standard checks-NK 6240, CMH 08-287, CMH 08-282, and BIO 9682 (Table 1). It was executed across four diverse environments: Coimbatore (Tamil Nadu) with latitude 11.0168° N and longitude 76.9558° E, Dharwad (Karnataka) with latitude 15.4589° N and longitude 75.0078° E, Hyderabad (Telangana) with latitude 17.4065° N and longitude 78.4772° E, and Karimnagar (Telangana) with latitude 18.4386° N and longitude 79.1288° E during the *Kharif* season of 2021, with detailed climatic conditions outlined in (Supplementary Materials Table S1). In each environment, 58 single-cross hybrids alongside the four checks were evaluated. The experiment was laid out with rows 4 meters long, maintaining 60 cm inter-row and 20 cm intra-row spacing. Each hybrid was sown in two rows. At all test locations, crop management followed recommended practices suited to the respective agro-ecological conditions. Harvesting was done at physiological maturity, marked by the black layer formation in the kernel. Grain yield for each hybrid was recorded on a plot basis and converted to kg ha^{-1}.

Various parametric and non-parametric methods were employed in the present study to assess hybrid stability and adaptability. Parametric methods included regression coefficient (b_i), deviation from regression (s^2_{di}), Wricke's ecovalence (W_i^2), Shukla's stability variance (σ^2_i), and Francis and Kannenberg's Coefficient of Variability (CVi). Furthermore, non-parametric methods such as Nassar and Huehn's statistics ($S^{(1)}$, $S^{(2)}$, $S^{(3)}$, $S^{(6)}$), Thennarasu's statistics ($NP^{(1)}$, $NP^{(2)}$, $NP^{(3)}$, $NP^{(4)}$) and Kang's rank-sum (KR).

Table 1. Details of the 62 maize hybrids used in the present study, including their codes, source, and names.

Code	Hybrid	Source	Code	Hybrid	Source
G1	ADV 7132	Private	G32	JKMH1581	Private
G2	AH 1625	Public	G33	KMH-005	Public
G3	AH 8087	Public	G34	KMH-1 (CAH1612)	Private
G4	AH 8323	Public	G35	KNMH-4185	Public
G5	BH416112	Public	G36	KNMH-4187	Public
G6	BIO 534	Private	G37	MAH-14-138	Public
G7	BIO 536	Private	G38	MAH-14-239	Public
G8	BIO 9682 ©	Private	G39	MFH18-14	Public
G9	BLH135	Private	G40	MM2033	Private
G10	BLH137	Private	G41	MM2828	Private
G11	BRMH-16039	Public	G42	MM9207	Private
G12	CMH 08-282 ©	Public	G43	NK 6240 ©	Private
G13	CMH 08-287 ©	Public	G44	OMH 17-2	Public
G14	CMH14-716	Public	G45	PHM1801 (CAH1801)	Private
G15	CMH14-722	Public	G46	PM18101L	Private
G16	CP808 SUPER	Private	G47	PM18102L	Private
G17	DH-315	Public	G48	PM18103L	Private
G18	FAUJI	Private	G49	PM18104L	Private
G19	DHM-117	Public	G50	PM18105L	Private
G20	GK3124	Public	G51	PM18106L	Private
G21	GK3164	Public	G52	QMH 1590	Public
G22	HKH-366	Public	G53	QMH1571	Public
G23	HT18007	Private	G54	Rasi 4992	Private
G24	IMHSB-17K-08	Public	G55	Rasi 70197	Private
G25	IMHVS-005	Public	G56	STARX-5	Private
G26	JH 15002	Public	G57	SUPER-4050	Private
G27	JH 16026	Public	G58	SYN816514	Private
G28	JH 16224	Public	G59	TS2505	Private
G29	JH 17014	Public	G60	TS2601	Private
G30	JH 17026	Public	G61	X5826	Private
G31	JH 17029	Public	G62	X5873	Private

STATISTICAL ANALYSIS

A combined analysis was conducted using AMMI to assess the impacts of Hybrid (G), Environment (E), and their interaction (GE) employing Windostat version 9.30 software (Indosat services, Hyderabad, India). Various stability metrics, both parametric and non-parametric, were computed, including regression coefficient (b_i), deviation from regression (s^2_{di}), Wricks's ecovalance (W_i^2), Shukla's stability variance (σ^2_i), Francis and Kannenberg's Coefficient of Variability (CVi), and Nassar and Huehn's ($S^{(i)}$), Kang's rank-sum (*KR*), and Thennarasu ($NP^{(i)}$), detailed information of stability parametres are given in Supplementary Materials Table S2)

These metrics were derived from established formulas proposed by [13,21–27], respectively, utilizing the Stability Soft software. Spearman's rank correlation was employed to examine the associations among these metrics using Windostat version 9.30 software. To further comprehend the interrelations among the stability metrics, a PCA based on the ranks of stability parameters was executed using XL Stat 2023 (Addinsoft, a French company). For line clustering, a hierarchical cluster analysis was performed based on mean yield and stability measures. The Ward's clustering method [28], utilizing Euclidean distance as the dissimilarity measure, was adopted, and the discriminant analysis test was employed to ascertain the optimal number of clusters.

RESULTS AND DISCUSSION

Analysis of Variance and Partitioning of the GE Interactions

The combined ANOVA analysis revealed significant disparities among different hybrids (G) in grain yield, suggesting considerable diversity across the hybrids. Similarly, there were notable differences observed among environmental conditions (E). The interaction between hybrid and environment (G + GE) was highly significant, indicating varied responses of hybrids to different environmental conditions, influenced by both linear and non-linear components affecting grain yield. AMMI analysis showed that environmental factors (E) contributed the most (69.24%) to the total variation, followed by hybrid effects (G) at 16.55%, and G + GE interaction at 9.84%. The significant influence of the non-linear component within the GE interaction underscores its importance in selecting stable hybrids. The large contribution of GE interaction was mainly due to a non-linear component, which is crucial for identifying stable hybrids. Further analysis of this interaction into two principal component axes (PCAs) revealed that PCA I explained 52.27% of interaction variation, while PCA II explained 29.38% (Table 2).

Table 2. Analysis of variance for combined and AMMI analysis for 62 maize hybrids and portion of sum of squares attributed to environment, hybrids, and hybrid × environment as a percentage of the total sum of squares (TSS).

Sources	DF	Sum of Squares	Mean Squares	F Ratio	Probability	TSS%	% G × E
Rep within Env.	8	1,158,029.08	144,753.64	0.16	1.00×10^{0}	-	-
Hybrid (G)	61	276,342,157.80	4,530,199.31	4.89	$<1.00 \times 10^{-5}$ ***	-	-
E.+ (G * E.)	186	1,320,265,040.00	7,098,199.14	7.66	$<1.00 \times 10^{-5}$ ***	-	-
Environments	3	1,155,973,537.00	385,324,512.40	415.60	$<1.00 \times 10^{-5}$ ***	-	-
G.* E.	183	164,291,502.80	897,767.77	0.97	5.80×10^{-1}	-	-
Environments (Lin.)	1	1,155,973,537.00	1,155,973,537.00	1246.79	1.00×10^{-5} ***	-	-
G.* E. (Lin.)	61	49,323,212.51	808,577.25	0.87	7.20×10^{-1}	-	-
Pooled Deviation	124	114,968,290.20	927,163.63	6.31	$<1.00 \times 10^{-5}$ ***	-	-
Pooled Error	488	71,717,712.92	146,962.53	-	-	-	-
AMMI Analysis							
Treatment	247	1,596,607,232.00	6,463,996.89	7.20	$<1.00 \times 10^{-5}$ ***	95.63	-
Hybrids	61	276,342,168.60	4,530,199.49	5.05	$<1.00 \times 10^{-5}$ ***	16.55	-
Environments	3	1,155,973,245.00	385,324,414.90	429.20	$<1.00 \times 10^{-5}$ ***	69.24	-
G * E Interaction	183	164,291,818.70	897,769.50	-	-	9.84	-
PCA I	63	85,878,267.10	1,363,147.10	9.28	$<1.00 \times 10^{-5}$ ***	5.14	52.27%
PCA II	61	48,271,605.33	791,337.79	5.39	$<1.00 \times 10^{-5}$ ***	2.89	29.38%
Residual	59	30,141,946.28	510,880.45	3.48	$<1.00 \times 10^{-5}$ ***	1.81	18.35%

*** Significant at the 0.001 probability levels.

Parametric Measures

The parametric statistics of stability for grain yield among 62 maize hybrids, as regression coefficient (b_i), deviation from regression (s^2_{di}), Wricks's ecovalance (W_i^2), Shukla's stability variance (σ^2_i), Francis and Kannenberg's Coefficient of Variability (*CVi*) outlined are detailed in Tables 3 and 4. In terms of parametric measures, considering the significant main effect of hybrids on grain yield, mean yield was prioritized as the primary parameter for evaluating the hybrids. Among the hybrids tested across four environments, G46, G48, G54, G10, and G49 exhibited the highest mean yields, whereas G22, G38, G11, G53, and G17 showed the lowest. Hybrids with regression coefficients (b_i) greater than 1, such as G46, G49, G6, G32, G2, G61, G4, G8, and G7, demonstrated above-average yield performance and adaptation to favourable environments. Conversely, hybrids with b_i less than 1, including G22, G11, G17, G52, G37, G42, G24, G19, G15, G34, G16, G56, G3, G5, and G18, exhibited poor adaptation to the environments, possibly favouring harsh conditions. Notably, G26, G30, G2, and G20 among these hybrids showed relatively better yield performance, with b_i values close to 1 and low s^2_{di}, suggesting suitability even in adverse conditions [29]. Using Wricke's ecovalance (W_i^2) and Shukla's stability variation (σ^2_i), G2, G52, G29, G31, G26, and G56 were identified as the most stable hybrids, given their lowest values in these parameters. Additionally, based on the Coefficient of Variation stability statistic (*CVi*), hybrids G5, G54, G36, and G39 were considered desirable and stable due to their low values.

Table 3. Mean yield and estimates of stability parameters for 62 maize hybrids tested in 4 environments.

Hybrid	Y	$S^{(1)}$	$S^{(2)}$	$S^{(3)}$	$S^{(6)}$	$NP^{(1)}$	$NP^{(2)}$	$NP^{(3)}$	$NP^{(4)}$	W_i^2	σ^2_i	b_i	s^2_{di}	*CVi*	*KR*
G1	9439.9	13.0	118.0	8.2	0.7	15.3	0.4	0.4	0.3	2,894,446.1	981,883.3	1.2	309,432.7	32.9	55.0
G2	9187.0	3.7	8.3	0.6	0.2	5.0	0.2	0.2	0.1	132,181.8	30,436.7	1.0	17,444.1	27.8	24.0
G3	8266.7	16.8	170.9	21.1	1.7	13.0	0.4	0.6	0.7	1,262,746.1	419,853.3	0.9	166,116.8	28.9	60.0
G4	9000.6	12.5	98.3	8.4	0.9	12.0	0.3	0.4	0.4	1,907,286.2	641,861.6	1.0	265,837.7	30.3	58.0
G5	8409.0	29.5	559.6	53.7	2.4	23.5	0.5	0.8	0.9	9,593,962.7	3,289,494.6	0.4	382,485.1	16.1	100.0
G6	9713.9	18.3	203.0	13.7	1.0	18.3	0.4	0.5	0.4	3,996,839.9	1,361,596.7	1.1	560,950.9	29.7	59.0
G7	8749.8	19.2	264.9	28.6	1.7	17.0	0.5	0.8	0.7	5,239,280.0	1,789,548.3	1.1	724,838.4	34.5	92.0
G8	8864.5	19.7	241.0	21.0	1.3	17.8	0.3	0.6	0.6	3,320,106.0	1,128,499.5	1.0	468,701.4	31.7	74.0
G9	9992.3	14.2	120.9	7.5	0.7	18.8	0.3	0.4	0.3	2,118,364.3	714,566.3	0.8	237,965.7	22.3	40.0
G10	10,206.5	8.8	52.9	3.0	0.4	18.0	0.3	0.4	0.2	2,527,711.4	855,563.6	1.2	278,226.9	29.8	42.0
G11	6551.4	6.0	22.7	11.3	2.7	20.5	4.4	3.7	1.0	4,246,416.3	1,447,562.0	0.6	210,239.7	25.7	110.0
G12	9187.7	11.5	81.6	6.7	0.7	10.5	0.2	0.4	0.3	895,943.1	293,510.0	1.2	50,933.9	31.9	35.0
G13	10,076.6	15.7	174.3	10.6	0.8	22.8	0.3	0.5	0.3	4,484,086.6	1,529,426.1	1.0	634,761.0	26.5	60.0
G14	9708.4	19.0	234.0	14.6	0.9	22.5	0.3	0.5	0.4	3,759,603.1	1,279,881.8	1.1	496,773.8	30.9	58.0
G15	8089.1	11.5	89.6	13.3	1.3	11.8	0.7	0.7	0.6	1,016,878.6	335,165.6	0.8	78,341.5	26.4	62.0
G16	8137.1	11.8	90.9	12.8	1.4	15.5	0.6	0.8	0.6	2,215,303.4	747,956.4	0.8	201,828.4	25.7	79.0
G17	6894.1	10.7	100.7	33.6	3.3	19.8	4.3	2.3	1.2	4,265,201.4	1,454,032.4	0.7	385,277.4	29.1	109.0
G18	8710.5	26.3	512.7	40.5	1.7	15.8	0.3	0.6	0.7	12,090,827.1	4,149,525.7	0.7	1,478,816.0	29.1	97.0
G19	8048.6	10.0	63.0	9.7	1.1	10.5	0.7	0.7	0.5	547,078.6	173,345.6	0.8	3318.5	25.8	57.0
G20	8897.3	6.8	28.3	2.5	0.5	9.5	0.1	0.3	0.2	406,555.7	124,943.3	1.0	57,300.1	27.8	38.0
G21	8966.1	15.2	156.9	12.5	0.9	12.3	0.2	0.4	0.4	1,633,473.7	547,548.4	1.0	230,743.9	28.1	57.0
G22	6072.8	1.2	0.9	1.0	1.1	15.8	12.5	6.0	0.4	1,632,483.9	547,207.5	0.9	196,903.5	37.9	88.0
G23	7650.7	10.2	66.9	14.1	1.5	14.8	1.5	1.2	0.7	1,523,555.6	509,687.7	1.1	200,524.9	36.3	77.0
G24	7970.5	11.7	104.7	16.5	1.6	8.3	0.7	0.7	0.6	810,969.7	264,241.5	0.9	58,893.6	27.1	60.0
G25	9035.4	24.8	370.3	29.8	1.6	17.5	0.4	0.6	0.7	4,435,554.9	1,512,709.7	1.3	431,648.5	36.9	80.0
G26	9660.7	8.0	40.0	2.6	0.4	7.0	0.3	0.2	0.2	322,416.5	95,962.0	0.9	30,011.2	23.9	19.0

Table 3. *Cont.*

Hybrid	Y	$S^{(1)}$	$S^{(2)}$	$S^{(3)}$	$S^{(6)}$	$NP^{(1)}$	$NP^{(2)}$	$NP^{(3)}$	$NP^{(4)}$	W_i^2	σ^2_i	b_i	s^2_{di}	CVi	KR
G27	9082.0	10.7	90.0	6.9	0.7	12.0	0.2	0.4	0.3	919,617.3	301,664.5	1.1	79,342.4	31.6	40.0
G28	9850.2	18.7	249.7	15.8	0.9	17.5	0.3	0.4	0.4	3,783,301.7	1,288,044.7	0.8	426,576.7	22.5	55.0
G29	7887.4	9.2	50.9	9.4	1.3	6.8	0.9	0.5	0.6	244,585.2	69,153.4	1.1	21,679.2	33.9	55.0
G30	9539.1	11.8	84.3	5.8	0.7	10.5	0.3	0.3	0.3	539,137.7	170,610.4	0.9	64,512.0	24.7	23.0
G31	9199.6	6.5	26.3	2.0	0.4	7.5	0.2	0.2	0.2	305,140.6	90,011.4	1.1	5454.0	30.3	25.0
G32	9220.7	21.3	289.7	25.2	1.5	20.3	0.5	0.6	0.6	4,927,410.5	1,682,126.6	1.1	687,230.6	32.2	75.0
G33	9806.9	12.8	100.9	6.3	0.6	17.3	0.3	0.4	0.3	2,042,449.7	688,417.9	1.3	103.9	33.8	42.0
G34	8129.3	19.5	281.6	37.1	2.1	17.0	0.8	0.8	0.9	3,437,804.6	1,169,040.1	0.8	341,411.9	25.8	89.0
G35	7350.4	9.3	60.7	16.5	2.0	12.3	2.1	1.3	0.8	1,366,855.8	455,713.3	1.1	163,474.8	38.5	74.0
G36	9182.5	16.8	182.3	13.8	0.9	12.5	0.3	0.4	0.4	1,194,024.9	396,182.7	0.8	22,151.5	20.9	40.0
G37	7556.5	6.2	26.3	6.2	1.1	10.5	1.9	1.1	0.5	1,375,497.3	458,689.8	0.8	134,946.9	28.9	74.0
G38	6433.0	4.2	10.9	7.7	2.6	18.8	6.6	4.6	1.0	2,266,942.0	765,743.0	1.1	300,888.2	44.3	96.0
G39	6971.2	10.8	80.9	22.6	2.9	25.8	1.9	2.4	1.0	5,144,936.5	1,757,052.3	0.5	158,159.5	21.0	112.0
G40	9252.1	24.5	381.6	30.7	1.7	22.8	0.4	0.6	0.7	5,673,096.1	1,938,973.9	1.4	432,248.9	38.6	77.0
G41	8331.0	23.3	329.7	38.8	2.2	16.5	0.6	0.8	0.9	4,311,394.0	1,469,943.2	1.3	341,123.4	40.9	92.0
G42	7942.8	15.3	148.3	20.7	1.9	16.3	0.7	0.9	0.7	2,938,079.5	996,912.6	0.7	252,515.7	25.4	90.0
G43	9153.5	18.0	219.0	17.1	1.0	12.8	0.3	0.4	0.5	1,923,911.5	647,588.1	0.8	147,030.9	22.2	55.0
G44	8514.6	19.2	224.9	26.7	1.9	16.5	0.5	0.7	0.8	2,384,736.0	806,316.5	1.3	167,251.9	37.4	73.0
G45	8659.6	15.0	142.0	15.2	1.4	15.5	0.4	0.6	0.5	1,261,051.4	419,269.6	1.0	179,354.2	30.2	53.0
G46	10,707.7	3.2	8.3	0.4	0.1	9.0	0.6	0.2	0.1	1,884,288.4	633,940.1	1.1	248,491.2	26.3	29.0
G47	8824.9	10.2	70.9	6.5	0.7	9.8	0.2	0.4	0.3	745,877.3	241,820.7	1.1	76,554.8	31.6	43.0
G48	10,591.8	5.5	20.9	1.1	0.2	12.5	0.7	0.3	0.1	3,690,759.6	1,256,169.1	1.2	439,968.9	29.4	46.0
G49	10,122.1	16.5	167.6	10.3	0.8	15.5	0.6	0.4	0.3	7,502,587.2	2,569,131.9	1.0	1,066,452.5	30.1	65.0
G50	8497.9	15.3	174.7	20.2	1.5	14.3	0.3	0.6	0.6	1,501,973.6	502,253.9	1.3	11,822.0	37.5	61.0
G51	9856.5	5.7	19.3	1.1	0.3	8.3	0.2	0.3	0.1	841,907.5	274,897.8	1.2	35,507.0	29.9	20.0
G52	6901.2	3.8	8.9	4.0	1.3	5.3	3.2	0.9	0.6	154,844.3	38,242.7	0.9	3524.9	33.1	59.0
G53	6849.6	5.7	23.3	8.8	1.8	21.3	3.4	2.9	0.7	4,221,459.9	1,438,965.9	1.0	601,175.4	41.1	108.0
G54	10,387.5	14.5	176.3	9.8	0.7	21.0	0.3	0.4	0.3	4,052,953.0	1,380,924.6	0.7	295,631.6	18.0	51.0
G55	8323.5	14.5	146.3	19.7	1.6	13.8	0.5	0.7	0.7	1,486,002.7	496,752.8	1.1	153,435.5	35.1	63.0
G56	8141.2	5.3	17.3	2.5	0.6	6.3	0.7	0.4	0.3	366,366.9	111,100.5	0.9	33,416.6	28.2	50.0
G57	9221.1	23.0	320.7	25.3	1.5	18.8	0.4	0.5	0.6	3,283,483.2	1,115,885.0	1.1	442,532.5	31.7	60.0
G58	9299.5	25.5	432.9	35.8	1.8	22.8	0.4	0.6	0.7	5,194,891.0	1,774,258.8	1.5	140,503.0	40.0	74.0
G59	8143.0	13.2	136.9	19.8	1.7	10.0	0.6	0.8	0.6	1,540,600.9	515,558.8	1.2	120,423.4	37.1	68.0
G60	7910.7	10.3	70.3	11.4	1.2	12.3	1.0	0.9	0.6	1,478,584.0	494,197.5	1.1	191,929.9	35.2	72.0
G61	9024.1	18.8	253.6	19.9	1.4	19.8	0.4	0.5	0.5	2,474,271.3	837,156.4	1.0	349,966.9	30.3	65.0
G62	9715.2	13.2	125.6	7.6	0.7	15.0	0.3	0.3	0.3	1,976,212.7	665,602.9	1.0	279,703.9	26.2	42.0

Table 4. Ranks of Mean yield and estimates of stability parameters for 62 maize hybrids tested in 4 environments.

Hybrid	Y	$S^{(1)}$	$S^{(2)}$	$S^{(3)}$	$S^{(6)}$	$NP^{(1)}$	$NP^{(2)}$	$NP^{(3)}$	$NP^{(4)}$	W_i^2	σ^2_i	b_i	s^2_{di}	CVi	KR
G1	16	32	32	21	13	31	31	23	16	20	39	39	44	43	44
G2	23	3	3	2	2	1	6	1	2	4	1	1	3	6	21
G3	42	44	41	49	48	26	32	34	49	30	18	18	15	26	25
G4	29	30	28	22	21	18	17	21	21	26	29	29	11	38	36
G5	39	62	62	62	58	61	38	48	58	58	61	61	62	47	1
G6	12	47	46	34	26	47	30	27	25	28	47	47	12	56	29
G7	34	51	53	54	47	40	37	45	47	54	58	58	24	60	48
G8	32	54	50	48	33	45	19	33	38	42	42	42	8	54	40
G9	7	35	33	18	16	48	12	18	15	9	33	33	35	35	6
G10	4	15	16	10	5	46	15	15	5	12	38	38	39	39	30
G11	60	10	9	29	60	54	60	60	60	61	50	50	59	33	11
G12	22	25	23	16	17	13	7	12	18	7	13	13	38	12	42
G13	6	42	42	28	19	58	22	25	19	30	54	54	10	58	18
G14	13	50	49	37	23	57	24	26	23	26	45	45	30	55	37
G15	47	25	25	33	33	17	47	42	36	35	15	15	36	17	17
G16	45	28	27	32	36	32	39	47	33	49	34	34	46	32	12
G17	58	22	29	57	62	51	59	57	62	60	51	51	53	48	26
G18	35	61	61	61	50	35	21	35	48	57	62	62	54	62	27
G19	48	18	18	25	29	13	46	40	31	24	9	9	37	2	13

Table 4. *Cont.*

Hybrid	Y	$S^{(1)}$	$S^{(2)}$	$S^{(3)}$	$S^{(6)}$	$NP^{(1)}$	$NP^{(2)}$	$NP^{(3)}$	$NP^{(4)}$	W_i^2	$\sigma^2{}_i$	b_i	$S^2{}_{di}$	CVi	KR
G20	31	13	13	8	8	10	1	7	8	8	7	7	2	13	20
G21	30	39	39	31	24	20	5	14	24	24	27	27	5	34	22
G22	62	1	1	3	28	35	62	62	27	51	26	26	28	30	56
G23	53	19	19	36	40	29	53	55	53	47	24	24	17	31	51
G24	49	27	31	40	44	7	49	41	41	30	11	11	32	14	19
G25	27	59	58	55	45	43	33	32	46	50	53	53	51	50	52
G26	14	14	14	9	6	5	11	2	7	1	5	5	16	9	8
G27	26	22	26	17	15	18	4	10	13	9	14	14	31	18	39
G28	9	48	51	39	25	43	20	19	22	20	46	46	45	49	7
G29	52	16	15	24	32	4	51	28	35	20	3	3	14	7	47
G30	15	28	24	12	12	13	10	6	14	3	8	8	13	15	9
G31	21	12	11	6	7	6	3	3	6	5	4	4	29	4	35
G32	20	55	55	51	42	53	34	38	42	46	55	55	18	59	43
G33	10	31	30	14	10	42	18	17	10	12	32	32	57	1	46
G34	46	53	54	59	56	40	50	50	56	52	43	43	41	45	14
G35	55	17	17	41	55	20	56	56	55	42	19	19	27	25	57
G36	24	44	45	35	22	23	9	16	26	9	16	16	48	8	3
G37	54	11	11	13	30	13	54	54	29	42	20	20	34	20	24
G38	61	5	5	20	59	48	61	61	59	56	35	35	23	42	62
G39	56	24	22	50	61	62	55	58	61	62	56	56	60	24	4
G40	18	58	59	56	49	58	28	36	45	47	59	59	58	51	58
G41	40	57	57	60	57	38	41	49	57	54	52	52	55	44	60
G42	50	40	38	47	53	37	48	51	52	53	40	40	49	37	10
G43	25	46	47	42	27	25	14	22	28	20	30	30	47	22	5
G44	37	51	48	53	54	38	35	43	54	41	36	36	50	27	54
G45	36	38	36	38	37	32	25	31	32	19	17	17	1	28	33
G46	1	2	2	1	1	9	43	4	1	6	28	28	22	36	16
G47	33	19	21	15	14	11	2	13	17	15	10	10	26	16	38
G48	2	7	8	4	3	23	45	9	3	16	44	44	42	52	28
G49	5	43	40	27	20	32	42	24	20	37	60	60	9	61	32
G50	38	40	43	46	39	28	23	37	39	34	23	23	52	5	55
G51	8	8	7	5	4	7	8	5	4	2	12	12	40	11	31
G52	57	4	4	11	33	2	57	53	36	28	2	2	20	3	45
G53	59	8	10	23	51	56	58	59	51	59	49	49	4	57	61
G54	3	36	44	26	18	55	16	20	12	18	48	48	56	41	2
G55	41	36	37	43	43	27	36	44	44	36	22	22	33	23	49
G56	44	6	6	7	9	3	44	11	9	17	6	6	21	10	23
G57	19	56	56	52	40	48	27	30	40	30	41	41	25	53	41
G58	17	60	60	58	52	58	29	39	50	42	57	57	61	21	59
G59	43	33	35	44	46	12	40	46	43	39	25	25	43	19	53
G60	51	21	20	30	31	20	52	52	34	40	21	21	19	29	50
G61	28	49	52	45	38	51	26	29	30	37	37	37	7	46	34
G62	11	33	34	19	11	30	13	8	11	12	31	31	6	40	15

Non-Parametric Measures

The non-parametric statistics of stability for grain yield among 62 maize hybrids, as outlined by Nassar and Huehn ($S^{(1)}$, $S^{(2)}$, $S^{(3)}$, $S^{(6)}$), Thennarasu ($NP^{(1)}$, $NP^{(2)}$, $NP^{(3)}$, $NP^{(4)}$) and Kang (KR), are detailed in Tables 3 and 4. Among these hybrids, G22, G46, G2, G52, and G38 exhibited the lowest values in $S^{(1)}$ and $S^{(2)}$, designating them as desirable, whereas G5, G18, G58, G25, and G40 displayed the highest values, rendering them unstable. Moreover, in $S^{(3)}$, G46, G2, G22, G48, and G51 were found to have the most stable characteristics due to their lowest values, contrasting with the less stable nature observed in G5, G18, G41, G34, and G58. Furthermore, in $S^{(6)}$, G46, G2, G48, G51, and G10 were identified as stable, while G17, G39, G11, G38, and G5 exhibited the highest values, indicating their instability. Lower values in stability statistics signify greater stability. Comparatively, in $NP^{(1)}$, G2 was identified as the most stable, followed by G52, G56, G29, and G26, while G39, G5, G58, and G40 were labelled as unstable due to their higher values. For $NP^{(2)}$, G20 had the lowest values, followed by G47, G31, G27, and G21, suggesting greater stability, whereas G22, G38, G11, G17, and G53 were deemed less stable. Similarly, in $NP^{(3)}$, G22, G38, G11, G53, and G39 exhibited the lowest values, indicating stability, while G6, G18, G10, G12, and G3 were less stable with higher values. $NP^{(4)}$, highlighted G46, G2, G48, G51, and G10 as the most stable, in contrast to G17, G39, G11, and G38, which showed relatively higher values indicating lower stability [30], rank-sum stability measure identified G26, G51, G30, G2, and G31 as stable, whereas G39, G11, G17, G53, and G5 were labelled as unstable based on higher value.

Interrelationship among Parametric and Non-Parametric Methods

The study investigates the relationship between mean yield and a variety of stability metrics, categorized into parametric (W_i^2, σ^2_i, b_i, s^2_{di}, CVi) and non-parametric indicators ($S^{(1)}$, $S^{(2)}$, $S^{(3)}$, $S^{(6)}$, $NP^{(1)}$, $NP^{(2)}$, $NP^{(3)}$, $NP^{(4)}$, KR), as outlined in (Table 5). Our analysis reveals a significant positive correlation between mean yield and several stability measures ($S^{(6)}$, $NP^{(2)}$, $NP^{(3)}$, $NP^{(4)}$, KR) at a stringent significance level of $p < 0.01$. Additionally, a noteworthy positive association was found between $S^{(3)}$ and CVi at $p < 0.05$. Conversely, we observed a pronounced, significant negative relationship with $S^{(1)}$, $S^{(2)}$ at $p < 0.01$, and with W_i^2, σ^2_i, s^2_{di} at $p < 0.05$. Similar findings have been reported by [17] in barley, [31] in durum wheat, and [11], who observed a positive and significant association between mean yield and stability metrics such as $S^{(3)}$, $S^{(6)}$, $NP^{(2)}$, $NP^{(3)}$ and $NP^{(4)}$. Likewise, [32], in their study on grass pea, reported a significant negative correlation between mean yield and $S^{(1)}$ and $S^{(2)}$

Intriguingly, $S^{(1)}$ and $S^{(2)}$ not only exhibit a significant positive inter-correlation but also maintain a positive linkage with other stability metrics ($S^{(3)}$, $S^{(6)}$, $NP^{(1)}$, $NP^{(4)}$, KR, W_i^2, σ^2_i, b_i, s^2_{di}), notwithstanding their significant negative correlation with mean yield (Y) and CVi. $S^{(3)}$, emerges as positively correlated with mean yield and all other stability metrics, except for CVi. Moreover, $S^{(6)}$, $NP^{(4)}$, and KR stand out for their significant positive correlation with both mean yield and the entire spectrum of stability metrics under evaluation. $NP^{(2)}$ is distinctively characterized by its negative correlation with $S^{(1)}$ and $S^{(2)}$, while it upholds a positive relationship with the rest of the metrics. $NP^{(3)}$, conversely, aligns positively with all other metrics, except for $S^{(1)}$ and $S^{(2)}$, with which it shows no significant correlation.

From a parametric standpoint, Wricke's ecovalence (W_i^2), Shukla's stability variance (σ^2_i), and deviation from regression (s^2_{di}) are all positively interrelated and also share positive correlations with most stability measures, except CVi, with which they are negatively correlated relative to mean yield. The regression coefficient (b_i) demonstrates a significant positive correlation across all non-parametric and parametric metrics. The coefficient of variation (CVi) uniquely correlates significantly with mean yield, $S^{(6)}$, $NP^{(2)}$, $NP^{(3)}$, and KR, underscoring its relevance in the context of yield stability analysis.

Table 5. Spearman rank correlation between mean yield and stability, parametric and non-parametric statistics for 62 maize hybrids tested in 4 environments.

Variables	Y	$S^{(1)}$	$S^{(2)}$	$S^{(3)}$	$S^{(6)}$	$NP^{(1)}$	$NP^{(2)}$	$NP^{(3)}$	$NP^{(4)}$	KR	W_i^2	σ^2_i	b_i	s^2_{di}	CVi
Y	1	−0.251 **	−0.251 **	0.239 *	0.663 **	−0.085	0.692 **	0.792 **	0.693 **	0.631 **	−0.163 *	−0.163 *	0.043	−0.201 *	0.230 *
$S^{(1)}$	-	1	0.993 **	0.822 **	0.411 **	0.558 **	−0.211 *	0.095	0.381 **	0.326 *	0.611 **	0.611 **	0.274 **	0.505 **	0.026
$S^{(2)}$	-	-	1	0.830 **	0.417 **	0.569 **	−0.207 *	0.100	0.380 **	0.331 **	0.624 **	0.624 **	0.301 **	0.514 **	0.020
$S^{(3)}$	-	-	-	1	0.813 **	0.565 **	0.225 *	0.530 **	0.795 **	0.689 **	0.605 **	0.605 **	0.393 **	0.444 **	0.140
$S^{(6)}$	-	-	-	-	1	0.502 **	0.615 **	0.865 **	0.989 **	0.893 **	0.475 **	0.475 **	0.359 **	0.303 **	0.274 **
$NP^{(1)}$	-	-	-	-	-	1	0.173 *	0.402 **	0.462 **	0.579 *	0.869 **	0.869 **	0.338 **	0.702 **	0.061
$NP^{(2)}$	-	-	-	-	-	-	1	0.825 **	0.633 **	0.706 **	0.220 *	0.220 *	0.148 *	0.174 *	0.239 *
$NP^{(3)}$	-	-	-	-	-	-	-	1	0.874 **	0.898 **	0.352 **	0.352 **	0.273 **	0.225 *	0.328 **
$NP^{(4)}$	-	-	-	-	-	-	-	-	1	0.889 **	0.438 **	0.438 **	0.337 **	0.275 **	0.291 **
KR	-	-	-	-	-	-	-	-	-	1	0.637 **	0.637 **	0.315 **	0.500 **	0.292 **
W_i^2	-	-	-	-	-	-	-	-	-	-	1	0.921 **	0.394 **	0.843 **	0.065
σ^2_i	-	-	-	-	-	-	-	-	-	-	-	1	0.394 **	0.843 **	0.065
b_i	-	-	-	-	-	-	-	-	-	-	-	-	1	−0.03	−0.075
s^2_{di}	-	-	-	-	-	-	-	-	-	-	-	-	-	1	0.082
CVi	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1

* and ** Significant at the 0.05 and 0.01 probability level, respectively.

Studies of Relationships among Stability Parameters and Grouping Hybrids

To explore the connections, distinctions, and parallels between parametric and non-parametric statistics, we conducted PCA utilizing the rank correlation matrix. The initial two principal components elucidated 49.43% and 24.11% of the total variation concerning the ranks of mean grain yield and stability parameters, respectively. The PC1 versus PC2 was used to produce the biplot illustrated in Figure 1. The resulting biplot, depicted in Figure 1, showcases the positioning of variables in the PC1 versus PC2 space. Group I includes mean yield, $S^{(6)}$, $NP^{(2)}$, $NP^{(3)}$, $S^{(6)}$, KR, and CVi, suggesting a preference for selection based on these parameters. This group aligns with the dynamic concept of stability and is associated with genotypic mean yield. In agreement with this finding, [11] observed in their study on barley that the average yield, Kang's rank-sum, two statistics proposed by Nassar and Huehn ($S^{(3)}$ and $S^{(6)}$), along with three of Thennarasu's statistics ($NP^{(2)}$, $NP^{(3)}$, and $NP^{(4)}$), clustered together on the biplot. These parameters were categorized as group III, indicating their joint influence by both mean yield and stability. This group aligns with the dynamic concept of stability and is associated with genotypic mean yield. Group II, positioned between Groups I and III, comprises $S^{(3)}$ and b_i. Notably, $S^{(3)}$ exhibits a significant correlation with mean yield, while bi lacks any discernible relation to mean yield. Group III encompasses the statistics of NP1, W_i^2, σ^2_i, and s^2_{di}, offering insights into stability within the static concept. Significantly, this group demonstrates a notable negative correlation with genotypic mean yield. Similar vein, [29] observed the enduring stability of the NP1 W_i^2, σ^2_i, s^2_{di} parameters in durum wheat MET.

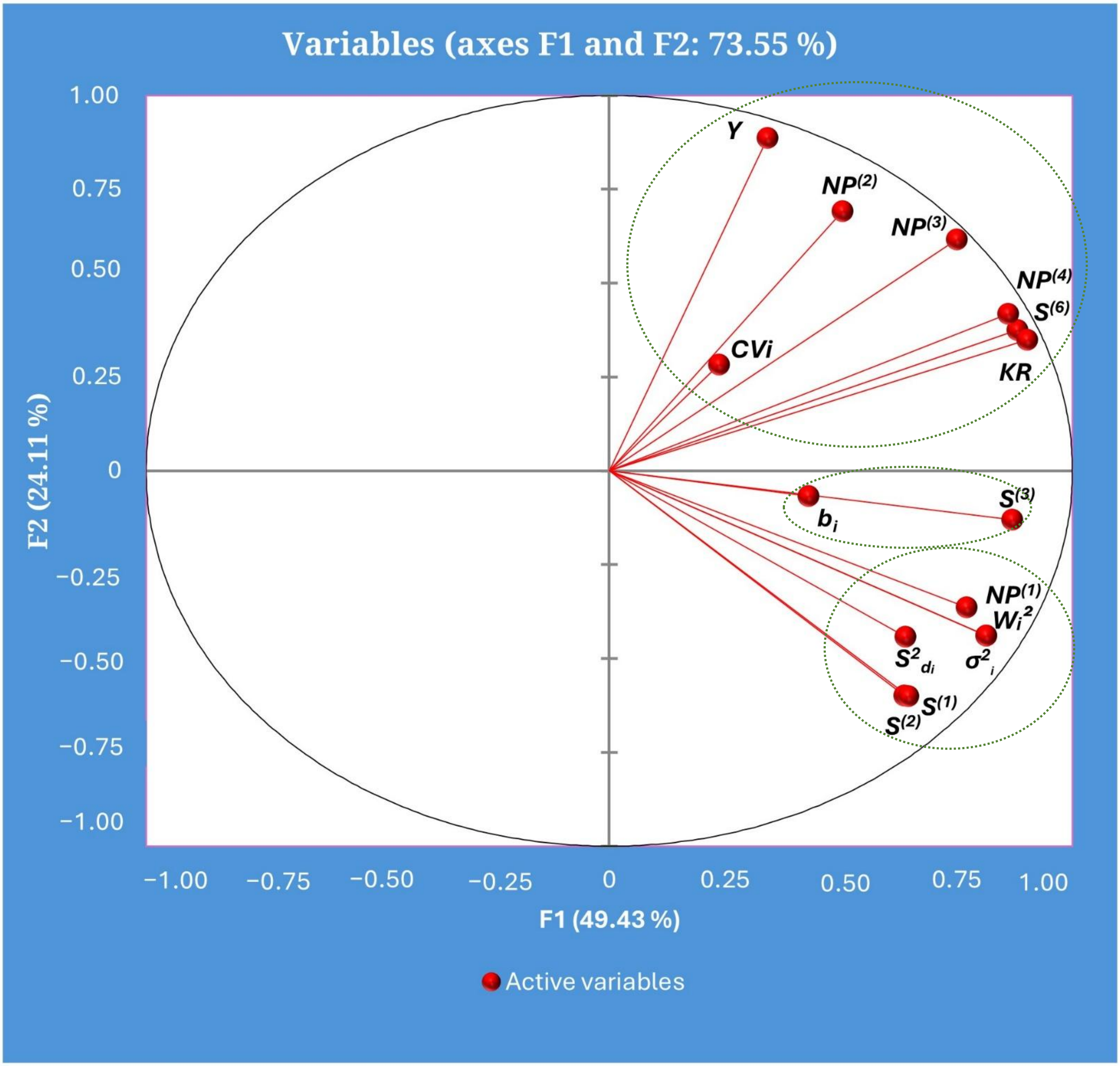

Figure 1. Biplot of PCA1 versus PCA2 for different parametric and non-parametric measures of stability. GY; W_i^2; σ^2_i; b_i; CVi; s^2_{di}; $S^{(1)}$, $S^{(2)}$, $S^{(3)}$, $S^{(6)}$; $NP^{(1)}$, $NP^{(2)}$, $NP^{(3)}$, $NP^{(4)}$; KR: Mean Grain Yield; Wricks's ecovalance; Shukla's stability variance; regression coefficient of Eberhart and Russell; Francis and Kannenberg's Coefficient of Variability; deviation from regression (Eberhart and Russell); Nassar and Huehn's nonparametric stability statistics; Thennarasu's Non-Parametric stability statistics and Kang's rank-sum respectively.

The methods employed in our investigation to assess stability did not offer a comprehensive insight into how individual hybrids respond to varying environmental conditions. Certain hybrids exhibited stability according to certain parameters while showing instability according to others. This issue aligns with findings from prior studies on hybrid-environment interaction [17,33]. A novel strategy to address the inherent variability in hybrid responses was the categorization of hybrids into distinct, qualitatively similar stability groups via cluster analysis, a method supported by [15,33]. This approach facilitated a more structured understanding of hybrid performance across varying conditions. In this vein, the analysis successfully classified 62 maize hybrids into five distinct clusters as shown in (Figure 2, Supplementary Material Table S3). Significantly, Cluster I emerged as a group of high-yielding hybrids, characterized by moderately stable performance across environments (with stability parameter sum ranks between 200 and 444). This suggests a potential for specific environmental adaptations among these hybrids. Notably, hybrids G46, G48, and G10, which are among the top performers in terms of grain yield (ranked 1, 2, and 4, respectively), were grouped within this cluster, indicating their robustness in certain conditions.

Conversely, Cluster V encapsulated high-yielding hybrids G49, G13, and G28 (ranked 5, 6, and 9, respectively, in mean yield) but with a propensity towards instability, as indicated by higher values in both parametric and non-parametric stability statistics (sum ranks spanning 443 to 710). This suggests these hybrids are less consistent across different environmental conditions. Clusters III and IV consisted of lower-yielding hybrids, yet they exhibited higher stability statistic values (with sum ranks of 351–654 for Cluster III and 526–778 for Cluster IV), suggesting a complex relationship between yield performance and stability across environments.

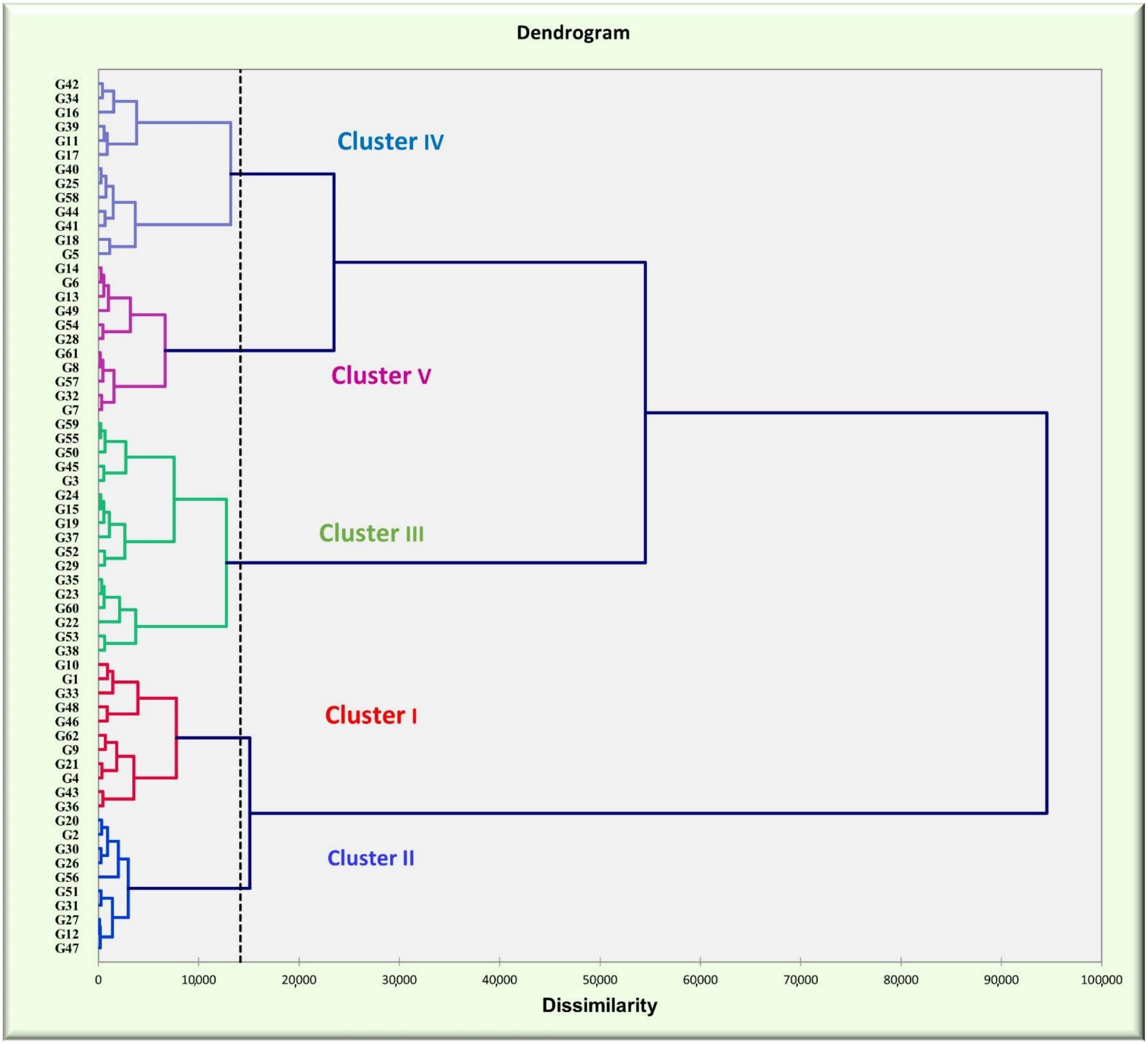

Figure 2. Dendrogram showing hierarchical classification of 62 maize hybrids based on ranks of mean yields and parametric and non-parametric statistics.

Cluster II distinguished itself by assembling a selection of hybrids that span intermediate to high yield potentials (G51, G26, G30, G31, G12, G2, G27, G20, G47, and G56), which are ranked 8, 14, 15, 21, 22, 23, 26, 31, 33 and 44 respectively in terms of mean yield. Despite this rank, they also exhibited lower stability statistic values (sum ranks between 79 and 362), signalling a robust level of stability across varied environments. This trait earmarks these hybrids as invaluable resources for bolstering adaptability within maize breeding endeavours, highlighting their potential to contribute significantly to the development of more resilient and versatile maize varieties.

CONCLUSIONS

Our investigation elucidates the intricate relationship between parametric and non-parametric statistics in maize cultivation, employing PCA and cluster analysis. Our findings underscore the critical role of parameters, such as mean yield, $NP^{(2)}$, $NP^{(3)}$, $NP^{(4)}$, $S^{(6)}$, *KR*, and *CVi*, in hybrid selection due to their association with dynamic stability and mean yield. Notably, hybrids G51, G26, G30, G31, G12, G2, G27, G20, G47, and G56, characterized by their high yield potential and low stability statistic values, are indicative of consistent stability across various environmental conditions.

SUPPLEMENTARY MATERIALS

The following supplementary materials are available online, Table S1: Agro-climatic characteristics of environments in yields stability experiments for 62 maize hybrids. Table S2: Details of Parametric and non-parametric methods. Table S3: Sum Ranks of Stability parameters, Rank of Grain yield, Genotypic Code according to dendogram of 62 maize hybrids.

DATA AVAILABILITY

All data generated from the study are available in the manuscript or supplementary files.

AUTHOR CONTRIBUTIONS

Conceptualization, SN and JB; methodology, JB; software, JB; validation, SN and JB; formal analysis, DA and JB; investigation, SN, JB, NKMV, BD, VK, RMK, SD and RKP; resources, SN; data curation, SN and JB; writing—original draft preparation, JB and SN; writing—review and editing, SN, JB, NKMV, BD, VK, RMK, SD and RKP; visualization, SN, JB; supervision, SN; project administration, SN; funding acquisition, SN. All authors have read and agreed to the published version of the manuscript

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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