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YIELD STABILITY IN MAIZE (*ZEA MAYS* L.) USING GGE BIPLOT AND SELECTION INDICES UNDER IRRIGATED AND DROUGHT-STRESS CONDITIONS

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SUMMARY

Drought stress is a major constraint in maize (*Zea mays* L.) production that significantly affects grain yield. Maize hybrids with broad adaptation and environment-specific potential related to water stress will ensure sustainable maize production. The presented study aimed to evaluate the grain yield performance of eight hybrids and two commercial check cultivars of maize under irrigated and drought-stress conditions and the correlation among tolerance indices and identify the stable and high-yielding hybrids. The study was conducted in four different environments, with two each under irrigated and drought-stress conditions, using a randomized complete block design with three replications. Maize genotypes, environments, and genotype-by-environment interactions (GEI) significantly ($P < 0.01$) affected grain yield. Hybrids experienced a 42.4% yield reduction under drought compared with irrigated conditions. The tolerance indices mean productivity (MP), harmonic mean (HM), geometric mean productivity (GMP), stress tolerance index (STI), yield index (YI), and modified stress tolerance index (K1STI and K2STI) showed significant correlations with grain yield under both environments. Based on the tolerance indices, the drought-tolerant hybrids that included G05 (R0641), G03 (R0211), and G08 (R0020) performed better. GGE biplot analysis identified two mega-environments, where the G06 emerged superior under irrigated conditions and G03 under drought stress, while G05 was stable under both environments.

Keywords: Maize (*Z. mays* L.), drought stress, genotype-by-environment interaction, hybrid selection, multi-environment trial, tolerance indices

Key findings: Drought stress significantly reduced the grain yield of maize (*Z. mays* L.) and can worsen with increased drought intensity, highlighting the critical need for drought-tolerant hybrids in tropical agriculture. Tolerance indices and GGE biplot can explain the strengths and weaknesses in identifying the drought-tolerant maize hybrids.

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INTRODUCTION

Maize (*Zea mays* L.) is an important cereal crop used in food, feed, and various industries (Panikkai *et al*., 2017; Erenstein *et al*., 2022). In Indonesia, 75% of maize production comprised animal feed, with the remainder used for food (BPS, 2023). However, the challenges, such as climate change and biotic and abiotic stress factors, threaten the stability of maize production and national food security (Bushero *et al*., 2021). In overcoming these problems, researchers have focused on developing high-yielding and stress-resistant cultivars through conventional and molecular plant breeding.

Climate change is a major global constraint in maize production, with drought stress and high-temperature conditions being the main hindrances (Kim and Lee, 2023). Drought is a crucial abiotic stress that inhibits production stability, reducing the potential yield as high as 76%, depending on the intensity and growth stage in maize (Khatibi *et al*., 2022). Drought stress causes considerable yield reduction if it occurs during the flowering and early seed-filling stages (Ao *et al*., 2020). Addressing these issues led researchers to use various selection indices to identify the promising genotypes and develop drought-tolerant cultivars through conventional and molecular breeding in maize (Kim and Lee, 2023).

Maize’s drought tolerance has been assessed by using various stress tolerance indices that include the stress tolerance index (STI), stress susceptibility index (SSI), geometric mean productivity (GMP), and harmonic mean (HM) (Moussa *et al*., 2023). These stress indices’ calculations relied on grain yield under irrigated and drought-stress conditions. The STI, GMP, and HM are very effective in differentiating drought-tolerant genotypes (Moussa *et al*., 2023). Past studies have successfully identified the drought-tolerant maize hybrids using these indices and yield traits (El-Moula, 2023). Such findings can better help breeders to develop maize cultivars adapted to irrigated and drought-stress conditions.

High-yielding cultivars across various environments are insufficient for selection; thus, stability analysis, including genotype-by-environment interactions (GEI) and physiological assessments, is also crucial (Regmi *et al*., 2021). GGE biplot analysis is a widely used tool in breeding to evaluate yield stability and G × E interactions within stress conditions, including drought in maize (Badu-Apraku *et al.*, 2020). This method can effectively identify the stable and high-yielding maize hybrids across diverse environments (Kumar *et al.*, 2023) and serves as a valuable tool for breeders in hybrid selection in maize (Zhao *et al.*, 2019). The following study aimed to evaluate the genotype stability under irrigated and drought-stress conditions, examine the tolerance indices correlation, and identify high-yielding and stable maize hybrids.

MATERIALS AND METHODS

The study evaluated eight single-cross maize hybrids and two commercial check cultivars (Table 1). The trials were conducted at four locations under irrigated and drought-stress conditions from April to August 2024. Set up of drought-stress trials commenced in the locations of Bandarkedungmulyo, Jombang, and Plosoklaten-Kediri, while managed irrigated trials were at Ngronggot, Nganjuk, and Banguntapan-Bantul, Indonesia. All experimental sites had locations at 55–220 masl, with varied soil types, including alluvial, grumusol, and andosol. Drought test locations featured clay loam and sandy loam textures (Table 2). The study used a randomized complete block design layout with three replications. Each plot consisted of four rows, 5 m in length (14 m²), spaced at 0.75 m apart and 0.20 m within rows.

Each planting hole entailed sowing with two seeds before thinning to one plant per hole 15 days after planting (DAP). Fertilization occurred twice, at 10–14 DAP and 30–35 DAP, using 400 kg ha^{-1} NPK (15% N, 15% P, and 15% K) and 350 kg ha^{-1} urea (46% N). Keeping all trials weed-free employed herbicides and manual weeding, carrying out

Table 1. Genetic material and pedigree of the maize hybrids.

No.	Code	Hybrid	Female parent	Male parent
1	G1	R0105	1028	0704
2	G2	R0118	1045	0704
3	G3	R0211	1045	0906
4	G4	R0498	1053	1028
5	G5	R0641	1045	1053
6	G6	R0654	1037	1053
7	G7	R0016	0704	0903
8	G8	R0020	0906	0704
9	G9	RSA002	Commercial hybrid, Indonesia	
10	G10	NK7328	Commercial hybrid, Indonesia	

Table 2. Environments used for hybrid evaluation.

No.	Locations	Condition	Soil Type	Soil Texture	Altitude (masl)	Temperature (°C)	
						Minimum	Maximum
1	Ngronggot, Nganjuk, East Java	Irrigated	Alluvial	Sandy loam	55	20.89	32.40
2	Banguntapan, Bantul, Yogyakarta	Irrigated	Grumusol	Clay loam	220	22.58	31.67
3	Bandar Kedungmulyo, Jombang, East Java	Drought	Alluvial	Sandy loam	148	23.62	32.26
4	Plosoklaten, Kediri, East Java	Drought	Andosol	Sandy loam	70	24.63	32.90

manual weeding at 20 DAP and 50 DAP. Other treatments, including weed removal and pesticide application, followed the recommended maize cultivation guidelines (MacRobert *et al.*, 2014). Technical irrigation application continued until the soil reached flooding to a height of 5 cm. Drought-stress experiments followed the test guidelines of CIMMYT (International Maize and Wheat Improvement Center), applying drought stress from 40 to 80 DAP (Zaidi *et al.*, 2016). Irrigation ran every 10 days under drought-stress conditions. The last irrigation performed was at 40 DAP, ensuring drought stress lasted from 50 to 80 DAP. Harvesting took place when the plants were physiologically mature, as marked by a dried cobber, no milk line, and a black layer appearing on the kernel. The grain yield (GY) with 15% moisture content was the main characteristic observed using the following formula:

$$Yield\ t\ ha^{-1} = \frac{10000}{PS}\ x\ \frac{100 - MC}{100 - 15}\ x\ \frac{EW}{1000}\ x\ SP$$

Where PS = the plot size (m^2), MC = the actual moisture content at harvest, EW = the ear weight per plot (kg), and SP = the ratio of kernel to cob weight.

A joint analysis of variance (ANOVA) ensued to assess the genotype-by-environment interaction effects on grain yield, considering three factors: genotypes (hybrids), environments, and replications, using a linear model with interaction effects. Tolerance indices (Table 3) gained interpretations based on standard ideotypes (high values were desirable except for TOL and SSI), with the GGE biplot used to determine the appropriate decision for selecting promising genotypes. Applying Pearson’s correlation sought to clarify the relationship between the grain yield under different environments and the tolerance indices. Genotypes’ stability and superiority to specific environments incurred assessment using the GGE biplot analysis (Yan and Kang, 2003). The GGE biplot (discriminativeness vs. representativeness, mean vs. stability, genotype ranking, and which-won-where) served to assess and select the stable high-yielding genotypes under various environmental conditions and tolerant to drought stress conditions. The GGE biplot analysis followed the standard methodology of

Table 3. Stress tolerance indices based on the grain yield.

Index	Formula	References
Tolerance index (TOL)	$Y_s - Y_p$	(Rosielle and Hamblin, 1981)
Mean productivity (MP)	$(Y_s + Y_p)/2$	(Rosielle and Hamblin, 1981)
Harmonic mean (HM)	$(2*Y_s \times Y_p)/ Y_s + Y_p$	(Schneider *et al*., 1997)
Geometric mean productivity (GMP)	$\sqrt{(Y_p \times Y_s)}$	(Fernandez, 1992)
Stress susceptibility index (SSI)	$(1-(Ys-Yp))/(1-\bar{Ys}/\bar{Yp}))$	(Fischer and Maurer, 1978)
Stress tolerance index (STI)	$(Y_s \times Y_p) / \bar{Y}^2_p$	(Fernandez, 1992)
Yield index (YI)	$Ys/ \bar{Y}s$	(Gavuzzi *et al*., 1997)
Yield stability index (YSI)	Ys/ Yp	(Bouslama and Schapaugh, 1984)
Modified stress tolerance index 1 (K_1STI)	$Y^2_p/\bar{Y}^2_p$	(Farshadfar and Sutka, 2002)
Modified stress tolerance index 2 (K_2STI)	$Y^2_s/\bar{Y}^2_s$	(Farshadfar and Sutka, 2002)

Yp = yield productivity under normal conditions; Ys = yield productivity under drought conditions; $\bar{Yp}$ = average yield productivity of all genotypes under irrigated conditions; $\bar{Ys}$ = average yield productivity of all genotypes under drought conditions.

Table 4. Joint analysis of variance for grain yield under irrigated and drought conditions.

Source of Variation	d.f.	Irrigated conditions	Drought conditions
		MS	MS
Environments (E)	1	0.11	0.49
Block/Environments	4	0.77	0.80
Genotype (G)	9	8.91**	7.07*
G x E	9	0.59	1.48**
Error	36	0.46	0.47
CV (%)	6.61		12.03

Yan and Kang (2003) as implemented in the ‘metan’ package.

All statistical analyses engaged R Software 4.4.2 using the package 'metan' (Olivoto and Lúcio, 2020) for joint ANOVA, GGE biplot, GT biplot, and Spearman's rank correlation of tolerance indices. Using Microsoft Excel helped to calculate the tolerance indices. The development of violin plots utilized the 'ggplot' package.

RESULTS

Analysis of variance revealed significant maize genotype effects on grain yield under irrigated and drought stress conditions (Table 4). The combined ANOVA showed the environments (E) remarkably influenced grain yield (Table 5), with genotypes (G) also being significant, reflecting varying hybrid responses. The interactions between the genotypes and environments were noteworthy, emphasizing the impact of environmental factors on grain yield performance. Average yields under drought-stress conditions were approximately 42.4% lower than under optimal irrigation conditions. The grain yield’s response, presented in a violin plot (Figure 1a), showed that maize hybrids G06, G08, and G05 had the highest yield potential and stability under irrigation, while the hybrids G04, G09, and G10 showed narrower distribution and drought sensitivity. Environments N2, N1, D2, and D1 had the ultimate yield potential, with N2 and N1 exhibiting greater variability in maize grain yield (Figure 1b).

The D2 environment exhibited a higher yield distribution than D1, suggesting a lower stress level favors plant growth under drought stress conditions. Hybrids G06 and G08 performed well in N2 and N1 environments, making them the best genotypes for optimal

Table 5. Joint analysis of variance for grain yield under all environments.

Source of Variation	d.f.	MS
Environments (E)	3	189.41
Block/Environments	8	0.98
Genotype (G)	9	14.31*
G x E	27	1.42**
Error	72	0.40
CV (%)	7.92	-

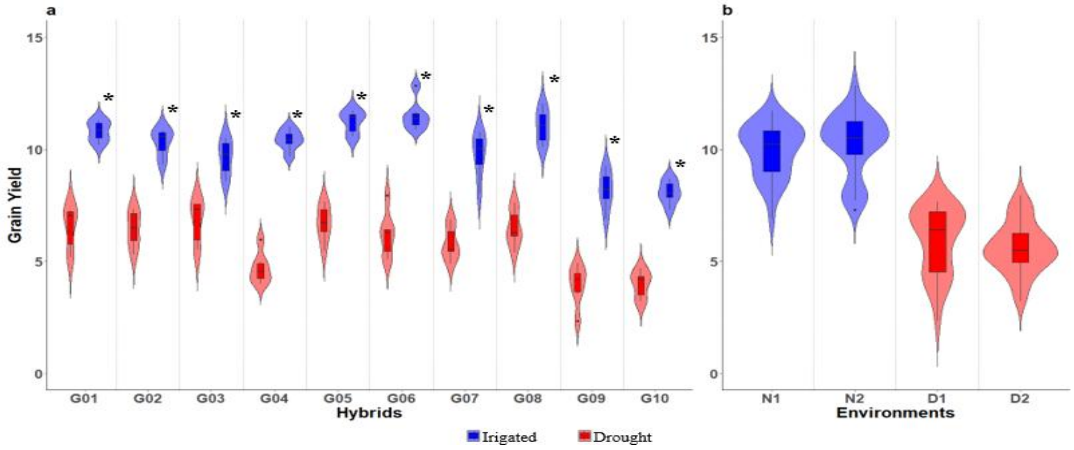

Figure 1. Grain yield performance. Violin plot of hybrids (a) and environments (b) showing the distribution of grain yield.

irrigation conditions, while hybrids G04, G09, and G10 showed lower performance under drought environments, indicating poor adaptation to drought-stress conditions. The grain yield performance of 10 maize hybrids (G01-G10) under irrigated (Yp) and drought-stress (Ys) conditions appears in Table 6. The promising hybrids under irrigated conditions were G06 (11.53), G05 (11.23), and G08 (11.04), while under drought conditions, the hybrids G03 (6.81), G05 (6.71), and G01 (6.52) showed the best performance.

The TOL index indicated maize hybrids G03 (2.84) and G02 (3.86) had relatively small yield losses, suggesting better drought tolerance than hybrids G06 (5.33) and G04 (5.11). The GMP index showed consistent performance for the hybrids G05 (8.68), G08 (8.47), and G06 (8.46) under both environments. Similar trends were evident for the MP and HM indices. The STI index identified the hybrids G05 (1.08), G08 (1.03), and G06 (1.02) as drought-tolerant genotypes with higher grain yield. Additionally, hybrid G03 had the lowest SSI value (7.78), authenticating it as one of the most stable maize genotypes under drought-stress conditions.

Overall, the maize hybrids G05, G03, and G08 emerged as superior genotypes based on the various selection indices. Hybrid G05 consistently exhibited the higher grain yield and drought tolerance across all the indices, making it an ideal candidate genotype for future breeding programs. Hybrid G03 excelled in yield stability with low losses under drought-stress conditions, whereas hybrid G08 showed a better balance of adaptation under irrigated and drought-stress conditions. These hybrids emerged as highly recommended to improve maize productivity in environments with variable water availability.

Yp and Ys showed a significant correlation ($P < 0.05$) (0.88) in maize hybrids (Table 5). The Yp also exhibited substantial ($P < 0.05$) correlation with all the tolerance

Table 6. Yield performance of maize genotypes under irrigated (Yp) and drought-stress (Ys) conditions and their values for various selection indices calculated using Yp and Ys.

Hybrids	Yp	Ys	TOL	MP	HM	GMP	SSI	STI	YI	YSI	K1STI	K2STI
G01	10.81	6.52	4.29	8.67	8.14	8.40	10.49	1.01	0.81	0.60	1.69	0.67
G02	10.32	6.45	3.86	8.39	7.94	8.16	9.90	0.95	0.80	0.63	1.45	0.62
G03	9.65	6.81	2.84	8.23	7.98	8.10	7.78	0.94	0.85	0.71	1.25	0.67
G04	10.19	5.08	5.11	7.64	6.78	7.20	13.26	0.74	0.63	0.50	1.10	0.30
G05	11.23	6.71	4.52	8.97	8.40	8.68	10.65	1.08	0.83	0.60	1.95	0.75
G06	11.53	6.20	5.33	8.87	8.07	8.46	12.22	1.02	0.77	0.54	1.95	0.61
G07	9.76	5.81	3.95	7.78	7.28	7.53	10.71	0.81	0.72	0.59	1.11	0.42
G08	11.04	6.50	4.54	8.77	8.18	8.47	10.87	1.03	0.81	0.59	1.79	0.67
G09	8.20	3.94	4.25	6.07	5.32	5.68	13.73	0.46	0.49	0.48	0.45	0.11
G10	8.08	3.98	4.09	6.03	5.34	5.67	13.41	0.46	0.50	0.49	0.43	0.11
Means	10.08	5.80	4.28	7.94	7.34	7.64	11.30	0.85	0.72	0.57	1.32	0.49
Selected hybrids	G06, G05, G08	G03, G05, G01	G03, G02, G07	G05, G06, G08	G05, G08, G01	G05, G08, G06	G03, G02, G01	G05, G08, G06	G03, G05, G01	G03, G06, G08	G05, G06, G08	G05, G03, G08
Ranking summary	G05, G03, G08											

YP = yield under optimum conditions; YS = yield under drought-stress conditions; TOL = tolerance index; MP = mean productivity; HM = harmonic mean; GMP = geometric mean productivity; SSI = stress susceptibility index; and STI = stress tolerance index.

indices, except for TOL, YSI, and SSI, while Ys revealed no meaningful correlation only with TOL. The Yp values had a considerable positive correlation with the indices GMP (0.93), MP (0.99), HM (0.91), and STI (0.85), indicating these indices effectively represented the maize genotypes with grain yield performance under optimum conditions.

Similarly, Ys demonstrated strong correlation with GMP (0.97), MP (0.93), HM (0.94), STI (0.97), and YI (0.99), indicating these indices were effective in evaluating the genotypes' drought tolerance (Figure 2). The indices GMP, MP, and HM occurred as highly correlated (≥0.97), suggesting these indices provide similar information regarding the average performance of genotypes under both environments. Additionally, STI showed a notable correlation with Yp (0.85) and Ys (0.97), making it an ideal index for assessing the high-yielding maize genotypes under optimal and drought-stress conditions.

Polygon diagrams showed the relationship between the maize hybrids and stress tolerance indices. Figure 3a presents the vector view of the GT biplot, which illustrates the correlations among the tolerance indices and their associations with the genotypes. Figure 3a detailed the tolerance indices GMP, MP, HM, STI, Yi, K1STI, and K2STI appeared as positively correlated with Yp and Ys. These indices exhibited long vectors and clustered closely, indicating strong discriminative ability and consistent identification of high-yielding genotypes under both optimal and drought-stress conditions. In contrast, TOL and SSI formed wider angles, positioning farther from the high-yield cluster, reflecting their tendency to identify stress-sensitive genotypes.

Figure 3b displays the which-won-where (polygon) view of the GT biplot, identifying the genotypes that performed best for specific tolerance indices. Genotypes G05, G06, and G08 displayed close locations to the indices GMP, MP, HM, STI, and Ys, indicating these genotypes have the higher grain yield and better drought tolerance. The polygon pattern confirms these genotypes dominate the sectors defined by high-yield-related indices, making them the top performers within stress. Maize hybrid G03 was closer to the YSI index, showing better grain yield stability under drought-stress conditions. Hybrids G04, G09, and G10 occurred close to indices TOL and SSI,

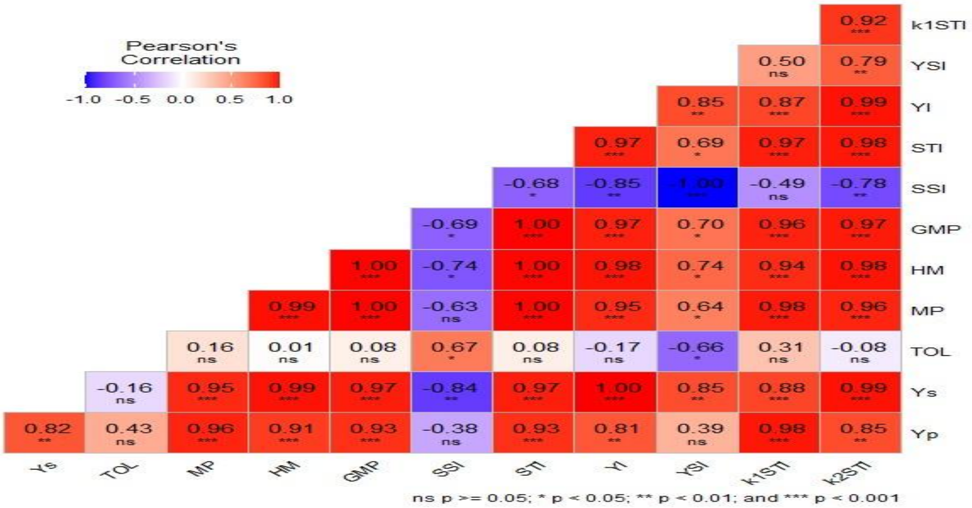

Figure 2. Pearson correlation between tolerance indices, evaluated under irrigated and drought-stress conditions.

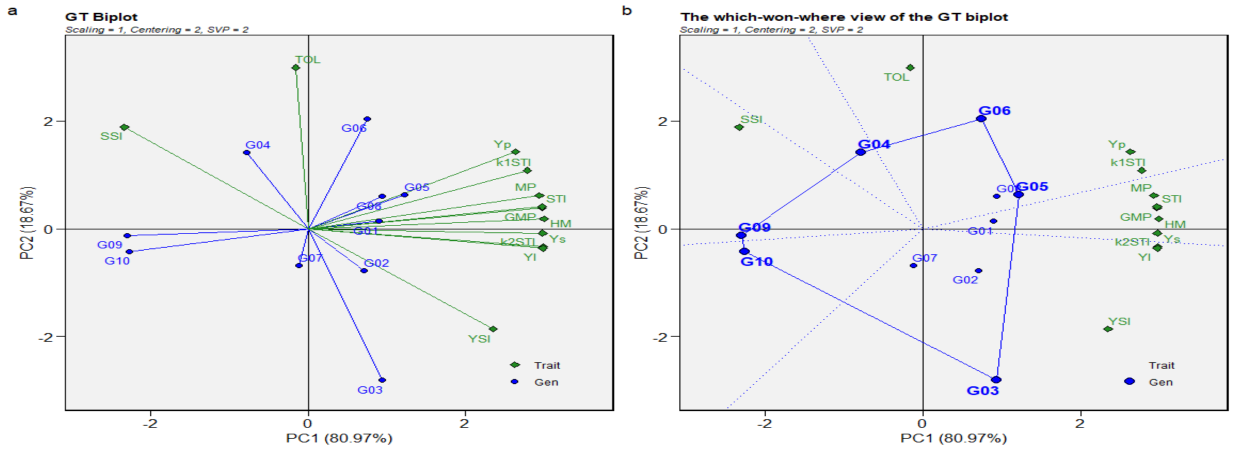

Figure 3. Polygon diagram of maize genotypes to tolerance indices studied under drought conditions.

signifying their alignment with indices associated with higher drought sensitivity and greater yield reduction.

GGE biplots on grain yield of the 10 hybrids are visible in Figure 4, with principal component 1 (PC1) and PC2 values used to generate the graphs. This study applied four types of GGE biplot analyses: discriminativeness vs. representativeness, mean vs. stability, genotype ranking, and which-won-where (Figure 4). The length of the vector line from the biplot origin reflects the strength of discrimination, with longer lines indicating stronger discrimination. The representativity of an environment succeeded in its determination by the angle between the vector line and the average environment coordinate (AEC) axis, where the smaller angles signify greater representativity. Environments N1, N2, and D2 exhibited vector lines extending beyond concentric circles, indicating a high discriminating power. The acute angles formed with the AEC axis in environments N1, N2, D1, and D2 further confirm their representativity.

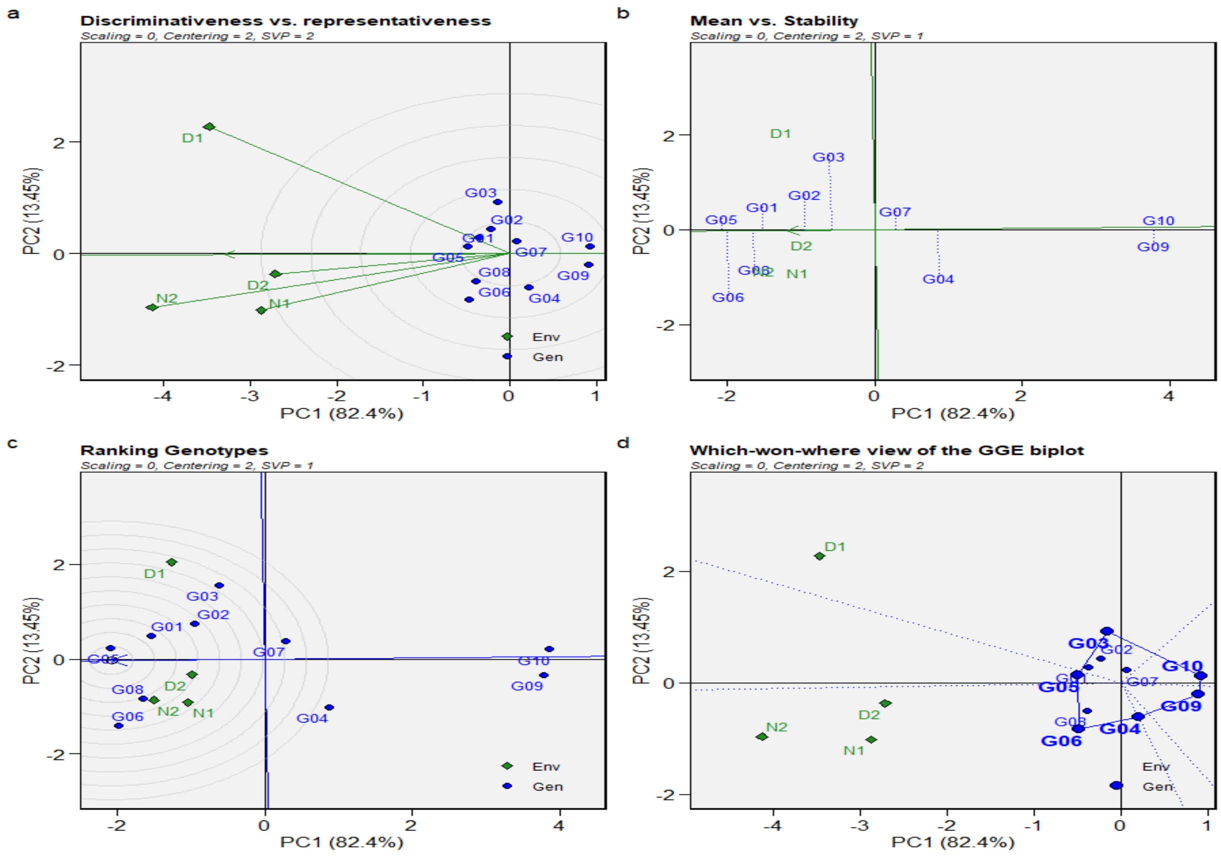

Figure 4. Genotype + genotype × environment (GGE) biplot. (a) Mean vs. stability; (b) Which-won-where view of the GGE biplot; (c) Discriminativeness vs. representativeness; and (d) Ranking genotypes for mean grain yield of 10 maize hybrids influenced by genotype × environment interactions under irrigated and drought-stress conditions.

The mean vs. stability of the hybrids revealed where hybrids reached positions near the average environment coordinate (AEC) axis, exhibiting higher stability (Figure 4b). The vertical distance from the AEC axis indicates the magnitude of genotypes' influence based on the environments. The ranking of hybrids from highest to lowest yield was G05 > G06 > G08 > G01 > G02 > G03 > G07 > G04 > G09 > G10 (Figure 4c). Maize hybrids with minimal vertical distance from the AEC axis demonstrate a reduced influence of the genotype-by-environment interactions (GEI). Notably, the maize hybrids G05 and G01, as positioned close to the AEC axis, suggest their high stability across the diverse environments.

DISCUSSION

Drought-stress conditions cause considerable reduction in maize productivity. In this study, the grain yield under drought-stress conditions was 42.44% lower than those under irrigated conditions. Ertiro *et al.* (2017) reported a reduction of up to 50% under drought-stress conditions in maize. The yield reduction under drought-stress conditions was within the range reported by other researchers in maize (Akaogu *et al.*, 2017). Yield-related traits under drought-stress conditions were considerably effective for obtaining drought-tolerant maize genotypes (Bänziger *et al.*, 2000). In tropical countries, most of the arable areas are prevalent on the drylands with greater potential for drought. The development of drought-tolerant cultivars is one of the main objectives of tropical breeding programs. Evaluating genotypes under optimum and drought-stress conditions is vital for selecting the tolerant and stable crop genotypes.

Joint analysis of variance for grain yield of 10 hybrids tested in four environments showed significant ($P < 0.01$) differences among the genotypes (G), environments (E), and GEI effects. The environmental component developed more variation than the genotypes and GEI, indicating the highest variability among the tested environments (Belay, 2022; Liu *et al*., 2022). In this experiment, the irrigated and drought-stress conditions resulted in high variability among environments and the grain yield performance of hybrids. The highest variability indicates the opportunity to select the promising genotypes with environment-specific adaptation (Kumar *et al*., 2023).

The maize genotypes' performance under irrigated and drought-stress situations often differs; therefore, the use of tolerance indices helped assess hybrid performance under irrigated and drought-stress conditions. The stress tolerance indices MP, GMP, HM, STI, YI, YSI, K1STI and K2STI have been applicable in various studies to identify the drought stress-tolerant maize genotypes (Khatibi *et al*., 2022). Lower TOL and SSI values indicate more tolerant genotypes and vice versa. Tolerance levels increased with decreasing values of TOL and SSI; however, the results could still not distinguish the maize genotypes with higher productivity (Moussa *et al*., 2023).

Kumar *et al.* (2023) reported HM, GMP, and STI were the selection indices for irrigated and drought-stress conditions, with YI being more suitable under drought environments. Based on these findings, hybrid G05 excelled under both environments based on the indices MP, HM, GMP, STI, K1STI, and K2STI, whereas hybrid G03 excelled under drought conditions based on the indices TOL, SSI, YI, and YSI. According to Zendrato *et al.* (2024), selecting maize genotypes depended on the ranking of tolerance index values, with hybrids consistently ranked at the top declared as stress tolerant. As a result, the maize hybrids G05, G03, and G08 performed best as drought-tolerant hybrids.

The highest correlation between Yp and Ys signified the potential of drought-tolerant genotypes. All the tolerance indices exhibited positive correlations with Yp, except for TOL, SSI, and YSI. However, Ys had no correlation with TOL. The tolerance indices displayed noteworthy correlatedness with Yp and Ys and were effectively beneficial to identify the tolerant maize genotypes (Khatibi *et al*., 2022). Integrating selection indices and biplot studies helps select genotypes that perform best under specific conditions, thus aiding the selection of drought-tolerant genotypes.

The GGE biplot is an effective tool used for analyzing genotype-by-environment interaction (GEI) effects by including the main effects of the genotype (G) and G × E interactions. The GGE biplots can decompose GEIs and identify the widely adapted and promising genotypes in specific environments (Yan and Kang, 2003). Its ability to recognize genotypes with broad and site-specific adaptations makes it useful for screening abiotic stress-tolerant genotypes. The presented results were also in line with several previous studies on maize screening for drought tolerance (Ertiro *et al*., 2017; Regmi *et al*., 2021).

In this study, four types of biplot analyses were successful: discriminativeness vs. representativeness, mean vs. stability, ranking genotypes, and which-won-where. In the discriminativeness vs. representativeness polygon, environments with long vector arms showed a high degree of discrimination; thus, they provide detailed information about genotype performance (Yan *et al*., 2007). Environments with an acute angle with the AEC were more representative than an environment with an obtuse angle (Dube *et al*., 2024). Figure 4a on discriminativeness vs. representativeness showed environments N1 and N2 with D1 forming a right angle.

In the biplot, the angle between two environment vectors, the graph illustrates their relationship (Yan and Kang, 2003). An acute angle indicates similarity in hybrid performance among the environments, a right angle reflects zero correlation, and an obtuse angle suggests a negative relationship in the maize hybrids performance (Makumbi *et al*., 2011). Based on these results, irrigated and drought-stress environments had no correlation, and genotypes that excel in irrigated environments may not necessarily lead under drought-stress environments. These results align with this study's findings; hybrid G06, with the best grain yield potential under optimum conditions, was not promising under drought-stress conditions. However, a positive correlation was also evident in N1 and N2 environments, which were the irrigated conditions.

In the 'mean vs. stability' polygon, the direction of the AEC appears in Figure 4b, from the right of the biplot toward the left, indicating the genotypes on the left side have better performance. Genotype stability based on the GGE biplot was identifiable by the vertical distance of the hybrids from the AEC axis. Hybrids with the smallest distance to the AEC axis were considerably stable across environmental conditions, and if the genotypes were far from the AEC axis, then they emerged as site-specific superior maize hybrids (Ahmed *et al*., 2020). According to stability, the maize hybrids G05, G01, G07, G09, and G10 were reliable due to their proximity to AEC. G5 and G6 were also superior to the other hybrids based on the grain yield performance. Hybrid G03 has a high vertical line toward the D1 drought condition environment, meaning the G03 was a putative drought-tolerant hybrid.

The 'which-won-where' polygon illustrates the genotype-by-environment interaction, environmental differentiation, and specific adaptation patterns. The biplot entailed dividing into several quadrants using dotted lines (Yan *et al*., 2007). This biplot divides environments into mega-environments and groups the hybrids that were adaptive to specific environments in the same sector. In this study, hybrid G06 had a wide adaptation in N1, N2, and D2, whereas G03 excelled under the G1 drought condition. The hybrids G05 and G01 had their location in sectors that do not contain environments but were between the mega-environments of irrigated and drought-stress conditions. This means hybrid G05 does not excel in specific environments but has better stability under irrigated and drought-stress conditions.

CONCLUSIONS

Maize genotypes, environments, and genotype-by-environment interactions emerged as significant for grain yield under irrigated and drought-stress conditions. Based on the tolerance index, the maize hybrids G05, G03, and G08 were the best options as drought-tolerant genotypes and proved superior under normal conditions. Significant correlation was evident among the tolerance indices MP, HM, GMP, STI, YI, K1STI, and K2STI under both environments. Based on GGE biplot analysis, hybrids G06 and G08 performed superiorly under irrigated conditions, while hybrids G03 and G02 were superior under drought-stress conditions, and hybrids G05 and G01 were outstanding under both environments.

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