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MAIZE HYBRIDS' RESPONSE TO OPTIMUM AND SUBOPTIMUM ABIOTIC ENVIRONMENTAL CONDITIONS USING GENOTYPE BY ENVIRONMENT INTERACTION ANALYSIS

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SUMMARY

Breeding maize (*Zea mays* L.) for stable production and adaptability poses a significant challenge because of the vital role of genotype and environment interactions. The presented study aimed to elucidate the maize hybrids' response, estimating the genetic parameters and trait associations, to identify the stable hybrids under optimum and suboptimum conditions. The conducted experiment used an augmented randomized complete block design, where check varieties had three replications across three blocks. The combined analysis of variance revealed that genotype-by-environment interactions significantly affected the grain yield and most of the traits. The average grain yield under the suboptimum environment was lower than the optimum environment. Genetic variability belonged to the high category, whereas the heritability was in the range of moderate to high for most traits. Grain yield appeared notably correlated with plant and ear height, stay green, kernels per row, and anthesis-silking interval. The maize hybrids G02, G06, G07, G08, G09, and G10 emerged as stable based on stability statistics, while hybrids G06, G08, G09, and G10 were also considered stable based on the GGE analysis. The identified genetic variability, trait association, and stable maize hybrids could be beneficial in future maize breeding programs for further improvement in grain yield.

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Keywords: Maize (*Z. mays* L.), optimum and suboptimum abiotic conditions, G × E interactions, hybrids' response, genetic variability, traits association, yield-related traits

Key findings: Information on genotype by environment interaction effects, heritability, and trait association may be useful for selecting promising maize (*Z. mays* L.) hybrids. Six maize hybrids were identified as stable hybrids based on parametric and non-parametric stability.

INTRODUCTION

Maize (*Zea mays* L.) is a widely cultivated cereal crop with significant potential for high yields, standing third in cereal grains after wheat and rice for global production (FAOSTAT, 2022). Several factors, including utilization of advanced production technology, increased input usage, improved pest management, and implementation of suitable cultivation techniques, could progress to enhance maize productivity to meet the population demand (Assefa *et al*., 2021).

Maize breeding presents a potential solution for improving productivity based on maize genotypes' existing diversity, to select maize genotypes with genetic potential for the highest production (Anand *et al*., 2023). Utilizing the available genetic variability of maize germplasm can enhance the efficiency of plant breeding programs by identifying the selection traits and heritability (Magar *et al*., 2021). The use of selection traits associated with primary quantitative traits, i.e., grain yield, determines the effectiveness of the genetic gain (Alam *et al*., 2022).

Genotype-by-trait interaction biplot proved a highly effective tool in detecting interactions between the genotypes and traits, as well as, their associated relationships (Yan and Rajcan, 2002). The said method can also illustrate the relationship between trait associations and identify the promising genotypes for certain traits, especially selection traits (Shojaei *et al*., 2020). This will help breeders choose the desired genotype with high-yield potential and good agronomic traits.

Further to selecting genotypes based on trait association and heritability information, the breeders must focus on selection based on genotypes' stability and adaptability. The ideal maize genotypes should exhibit a substantial average grain yield with minimal variability across diverse environmental conditions, both geographically and environmentally (Azrai *et al*., 2023). However, the improvement in maize production with stable agronomic performance bears great influences from environmental conditions. Differences in topography, climate, and abiotic conditions in the soil, as well as, planting time, cause significantly varied agronomic performance and grain yield of maize genotypes under diverse environments (Konate *et al*., 2023).

Hybrid maize development requires screening and evaluation over different crop seasons and locations to determine the genotypes' performance and identify the superior maize hybrids (Rezende *et al*., 2020). Therefore, the breeders must evaluate the stability of maize hybrids in the target environment, especially in non-optimal environmental conditions, which is an essential criterion in releasing superior cultivars (Azrai *et al*., 2022, Matongera *et al*., 2023).

Several stability models can serve to explain the complex phenomenon of genotypes under diverse environmental conditions. Hence, the objectives of this study were to a) elucidate the maize hybrids' response under optimum and suboptimum abiotic conditions, b) estimate the genetic variability and traits association that could benefit for improving maize breeding programs, and c) identify the stable maize hybrids under optimum and suboptimum conditions.

MATERIALS AND METHODS

Plant material and experimental sites

The genetic material comprised 11 maize (*Z. mays* L.) hybrids, namely, G01 (L22 × L26), G02 (L22 × Nei), G03 (L26 × L15), G04 (Mr14

Table 1. Description of four environmental conditions.

Parameters	Leuwikopo 2022 (E1)	Cikabayan 2022 (E2)	Ponorogo 2023 (E3)	Leuwikopo 2023 (E4)
Soil type	Alluvial	Alluvial	Latosol	Alluvial
Soil texture	Clay loam	Clay loam	Loam	Clay loam
Year	2022	2022	2023	2023
Altitude (masl)	± 189	± 164	± 101	± 189
Coordinate	6°33′50.8″ S; 106°43′29.7″ E	6°33′05.7″ S; 106°42′55.3″ E	7°52′05.2″ S; 111°27′06.2″ E	6°33′50.8″ S; 106°43′29.7″ E
Rainfall (mm/year)	3505.4	3505.4	1067	3787.9
pH H_2O	5.26	4.28	7.90	5.67
pH KCl	4.80	4.03	7.22	5.37
C-organic (%)	1.88	1.25	2.23	1.74
N-total (%)	0.22	0.17	0.25	0.25
Al-dd (cmol Al/kg)	0.00	2.10	0.11	0.21
H-dd (cmol H/kg)	0.23	0.63	0.19	0.27
P potential (mg P_2O_5/100g)	98.76	69.10	110.86	153.51
K potential (mg K_2O/100g)	32.41	12.57	79.36	45.75

× P10), G05 (Nei × P2), G06 (BISI 18), G07 (JHG02 – L15 × Mr14), G08 (P21), G09 (P27), G10 (NK Perkasa), and G11 (NK Sumo). The G01 to G05 were newly developed maize hybrids, while the G06 to G11 were the existing cultivars. The research progressed from September 2022 - December 2023 in four different environments, i.e., Leuwikopo IPB Experimental Station 2022 (E1), the Cikabayan IPB Experimental Station 2022 (E2), Ponorogo 2023 (E3), and Leuwikopo IPB Experimental Station 2023 (E4). Different abiotic environmental conditions were evident at these experimental locations. The Cikabayan 2022 (E2) belonged to a suboptimum environment, with a low pH and no addition of manure and lime. Leuwikopo 2022 and 2023 (E1 and E4) and Ponorogo (E2) were in the category of an optimum environment, with slightly acidic to neutral pH. Details about the abiotic conditions for each environment are available in Table 1.

Experimental procedure

In the presented study, using an augmented randomized complete block design with six checks (G06 to G11) had replications across three blocks. The minimum plot size was a single row of 4 m. Soil characteristics' measurement included pH in each environment. The cultivation procedures were as follows: In E1, E2, and E4, the planting distance was 75 cm × 25 cm, and the first fertilization was applied 7–10 days after planting (DAP) using urea at 150 kg ha^{-1} (N 46%) and NPK Phonska at 350 kg ha^{-1} (N 15%, P 10%, K 12%, and S 10%); the second fertilization was applied at 28–32 DAP using urea 150 kg ha^{-1} (N 46%). Manure (10 t ha^{-1}) and dolomite lime (1 t ha^{-1}) application ensued in E1 and E4. E3 had a planting distance of 70 cm × 20 cm, with fertilization application using urea only, proceeded three times at 7 DAP (113 kg ha^{-1}), 28 DAP (225 kg ha^{-1}), and 49 DAP (50 kg ha^{-1}). The crop maintenance included weed management, irrigation, and pest and disease controls, as needed. Harvesting succeeded at ±100 DAP.

Data recording and statistical analysis

Ten plants, randomly selected in each subplot, incurred measuring of the following traits: (1) days to 50% anthesis; (2) days to 50% silking; (3) anthesis-silking interval, calculated as the difference between days to silking and days to anthesis; (4) plant height (cm), measured as the distance from the soil surface level to the node bearing the flag leaf; (5) ear height (cm), measured as the distance from the soil surface level to the node bearing the uppermost ear; (6) stem diameter (mm), measured at the first internode above the soil surface; (7) leaf length (cm), measured on the leaf above the uppermost ear, from the leaf collar to the leaf tip; (8) stay green (%), counting the number of plants remaining green at harvest time on a plot basis; (9) moisture content (%); (10) ear length (cm); (11) ear diameter (mm); (12) number of ear rows; (13) number of kernels per row; (14) 1000- kernel weight (g); (15) shelling percentage; and (16) grain yield (t ha^{-1}) at 15% moisture content, calculated using the following equation:

$$Yield\ (kg\ ha^{-1}) = \frac{10000}{PS} \times \frac{100 - MC}{100 - 15} \times EW \times SP$$

Where, MC is the actual moisture content of the harvested grain, PS is the harvested plot size (m^2), EW is the ear yield per plot (kg), and SP is the shelling percentage.

All the recorded data analysis used mixed model analysis of variance on agronomic characters, grain yield, and yield components to elucidate the effects of maize genotype, environments, and genotype by environment interactions. The formulation of the genetic coefficient of variation (GCV), phenotypic coefficients of variation (PCV), and broad-sense heritability (H) on the entry-mean basis occurred for the observed traits. The heritability categories comprised as low (< 20%), moderate (20%–50%), and high (> 50%) (Stansfield, 1991). Trait associations analysis determined the relationship between observed characters using the Pearson correlation, PCA biplot approach, and genotype by trait (GT) biplot method (Yan and Rajcan, 2002).

The grain yield stability evaluation continued when the effect of genotype by environment interaction was significant for grain yield. Yield stability parameters determination utilized several methods, including the coefficient of variation (CV_i) (Francis and Kannenberg, 1978), the regression coefficient of average genotype yield on the environmental index (b_i) (Finlay and Wilkinson, 1963), yield and stability index (YS_i) (Kang 1993), multivariate analysis, including additive main effects and multiplicative interactions-AMMI (Gauch and Zobel, 1988), and genotype-environment interaction (GGE biplot) (Yan *et al*., 2000). All the analyses' applications engaged the SAS on Demand for Academics (welcome.oda.sas.com) for combined analysis of variance and to obtain the adjusted mean values for each trait. Likewise, using Microsoft Excel 2019 analyzed the genetic variability and heritability. GEA-R helped obtain stability parameters and AMMI using the adjusted mean of yields, with the R studio (R version 4.1.2) used for the PCA biplot running the 'factoextra' package (Kassambara, 2020), and GT and GGE Biplot visualization employing the 'metan' package (Olivoto and Lúcio, 2020).

RESULTS AND DISCUSSION

Combined analysis of variance and mean performance

The combined analysis of variance showed environments had a significant ($p < 0.05$) impact on morphological traits, grain yield, and yield component traits in maize (Table 2). The genotypes also affected yield and yield components, except for the moisture content. The interaction effects between the genotypes and environments (G × E) were also remarkable for grain yield and most of the traits, except plant and ear height, ear length and diameter, moisture content, and the 1000-seed weight. The performance of maize genotypes sustained influences from the agroecosystem, agroclimatic, soil, and environmental conditions (Singamsetti *et al*., 2021). This significance of the G × E interaction on yield indicates hybrids with superior yield in one environment may not necessarily show superiority under other environments (Haruna *et al*., 2017).

The Cikabayan environment (E2) had the lowest yield value (3.90 t ha^{-1}) among all target environments (Table 3). This suboptimum environment has the least pH value, being categorized as acidic, with the highest Al-dd value and lack of available nutrients compared with other environments (Table 1). Acidic soil was a notable abiotic stress for maize that can affect and reduce

Table 2. Combined analysis of variance of maize hybrids.

Sources	df	Agronomic traits (p-value)							
		MFA	FFA	ASI	PH	EH	SD	LL	SG
Environments (E)	3	<.0001	<.0001	0.001	0.002	0.001	0.002	0.002	0.018
Block / Environment	8	0.697	0.608	0.048	0.006	0.002	0.008	0.004	0.037
Genotypes (G)	10	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Hybrids (H)	4	0.002	0.004	<.0001	0.002	0.021	0.529	0.001	0.022
Checks (C)	5	0.001	0.001	0.001	0.001	0.002	<.0001	<.0001	0.146
H vs C	1	0.002	0.001	0.001	<.0001	<.0001	0.708	0.007	<.0001
G x E	30	0.002	0.005	0.002	0.472	0.400	0.010	0.016	<.0001
H x E	12	0.001	0.003	0.020	0.321	0.168	0.064	0.047	0.001
C x E	15	0.131	0.176	0.002	0.501	0.638	0.004	0.012	0.147
(H vs C) x L	3	0.031	0.012	0.233	0.643	0.543	0.811	0.746	<.0001
CV (%)		1.67	1.80	37.73	4.22	5.05	3.83	2.38	10.42
Sources	df	Yield and yield components (p-value)							
		EL	ED	ER	KR	SP	MC	W1000	Y
Environments (E)	3	0.002	<.0001	0.026	0.003	<.0001	<.0001	<.0001	0.001
Block / Environment	8	0.058	0.748	0.221	0.326	0.044	0.917	0.942	0.001
Genotypes (G)	10	<.0001	<.0001	<.0001	<.0001	<.0001	0.141	<.0001	<.0001
Hybrids (H)	4	0.004	0.003	<.0001	<.0001	<.0001	0.171	0.008	0.037
Checks (C)	5	<.0001	<.0001	<.0001	<.0001	<.0001	0.253	<.0001	<.0001
H vs C	1	0.002	0.188	0.074	<.0001	<.0001	0.084	0.463	<.0001
G x E	30	0.085	0.145	0.045	0.019	<.0001	0.133	0.121	<.0001
H x E	12	0.035	0.070	0.008	0.011	<.0001	0.436	0.014	<.0001
C x E	15	0.503	0.388	0.844	0.118	0.490	0.536	0.840	<.0001
(H vs C) x L	3	0.077	0.282	0.022	0.186	<.0001	0.002	0.208	0.016
CV (%)		3.02	1.91	2.58	3.05	0.76	2.73	6.01	6.92

MFA = 50% male flowering age; FFA = 50% female flowering age; ASI = anthesis-silking interval; PH = plant height; EH = ear height; SD = stem diameter; LL = leaf length; SG = stay green; EL = ear length; ED = ear diameter; ER = number of ear rows; KR = number of kernels per row; SP = shelling percentage; MC = moisture content; W1000 = thousand kernels weight; Y = grain yield; CV = coefficient of variation; and df = degrees of freedom.

Table 3. Mean grain yield (t ha^{-1}) of maize hybrids under the four different environmental conditions.

Hybrids	Leuwikopo 2022 (E1)	Cikabayan 2022 (E2)	Ponorogo 2023 (E3)	Leuwikopo 2023 (E4)	Means
G01	4.05	2.29	7.41	5.30	4.76
G02	6.70	4.19	8.71	7.66	6.81
G03	7.95	2.75	10.45	2.45	5.90
G04	7.47	3.67	3.09	7.73	5.49
G05	7.65	3.12	3.33	6.42	5.13
G06	8.19	4.65	6.41	7.49	6.69
G07	8.35	3.82	9.19	6.15	6.88
G08	7.95	5.29	7.95	9.26	7.61
G09	9.18	4.74	8.35	10.68	8.24
G10	9.61	5.07	8.56	10.22	8.36
G11	10.01	3.37	6.84	9.77	7.50
Means	7.92	3.90	7.30	7.56	6.67
S.E.	0.81	0.74	1.33	0.76	0.46
$LSD_{0.05}$	1.80	1.65	3.00	1.69	0.93
CV (%)	10.19	19.01	18.16	10.05	6.92
p-value	0.001	0.021	0.028	<.0001	<.0001

SE = standard error; LSD = least significant difference; CV = coefficient of variation.

Table 4. Genetic variability and heritability of maize hybrids.

Traits	GCV (%)		PCV (%)		H	
Days to anthesis (d)	3.88	Low	5.73	Low	0.46	Moderate
Days to silking (d)	4.15	Low	6.14	Low	0.46	Moderate
Anthesis-silking interval (d)	108.78	High	144.70	High	0.57	High
Plant height (cm)	15.60	Moderate	18.63	Moderate	0.70	High
Ear height (cm)	19.23	Moderate	22.77	High	0.71	High
Stem diameter (mm)	9.77	Low	13.68	Moderate	0.51	High
Leaf length (cm)	7.02	Low	9.19	Low	0.58	High
Stay green (%)	21.83	High	26.18	High	0.70	High
Ear length (cm)	8.51	Low	11.27	Moderate	0.57	High
Ear diameter (mm)	5.50	Low	7.20	Low	0.58	High
Number of ear rows	17.03	Moderate	18.18	Moderate	0.88	High
Number of kernels per row	14.24	Moderate	16.12	Moderate	0.78	High
Shelling percentage (%)	1.78	Low	2.82	Low	0.40	Moderate
Moisture content (%)	1.32	Low	6.80	Low	0.04	Low
Thousand kernels weight (g)	16.49	Moderate	22.09	High	0.56	High
Grain yield (t ha^{-1})	24.38	High	30.89	High	0.62	High

GCV = genetic coefficient of variation; PCV = phenotypic coefficient of variation; H = heritability.

grain yield and other agronomic traits. In acidic soils, heavy metals, such as aluminum (Al), iron (Fe), and manganese (Mn), can be harmful to crop plants and interfere with their growth and nutrient absorption. These metals can impede the uptake of essential nutrients and disrupt the root development, photosynthate mobilization, and the binding of nutrients in the soil (Tandzi *et al*., 2018).

The Leuwikopo 2022 (E1) environment had the maximum average grain yield (7.92 t ha^{-1}). This environment provides optimum agricultural cultivation conditions for maize with the addition of ameliorants, such as lime and manure, before planting. The Ponorogo 2023 (E3) and Leuwikopo 2023 (E4) environments gave grain yields of 7.30 and 7.56 t ha^{-1}, respectively. The Ponorogo 2023 environment consisted of rice fields with pH conditions reaching 7.90 (pH H_2O) and 7.22 (pH KCl), which belongs to an alkaline environment category. However, the average grain yield of the maize hybrids was 6.92 t ha^{-1} in the four environments.

Overall, the seven maize hybrids had above-average performance, viz., G02, G06, G07, G08, G09, G10, and G11. The phenotypic performance of the maize genotypes for various plant traits sustained effects from the genotypes and existing environmental conditions and genotype-by-environment interactions. Non-optimum environments with abiotic stress conditions can affect the growth and yield of maize genotypes (Zendrato *et al*., 2024). Among the four environments, variations in environmental factors, such as soil pH and nutrient content, along with the genetic diversity among the studied maize genotypes, had a remarkable impact on the phenotypic performance of maize. Past studies also enunciated that stress factors, including nutrient deficiency and low pH, substantially altered the agronomic performance and grain yield in maize (Haruna *et al*., 2017, Matongera *et al*., 2023).

Genetic parameters and traits association

The genetic parameters of the agronomic traits, grain yield, and yield components of various hybrids under four different abiotic stress conditions appear in Table 4. The genotypic coefficient of variation (GCV) values for all traits were lower than the phenotypic coefficient of variation (PCV), indicating the environments played a vital role and influenced all observed traits in maize. The highest GCV (108.78%) and PCV (144.70%) were evident for the anthesis-silking interval, whereas the lowest values were prominent for shelling percentage (1.78% and 2.82%, respectively). The genetic coefficient of variation can indicate the genetic variability of a trait (Magar *et al*., 2021). Most traits exhibited a large portion of genetic variance, as shown by the heritability values tended to be moderate to high. Traits with high heritability can be an option for selection, as they could produce desired genetic advances (Demeke *et al*., 2023). However, in the latest study, it is crucial to note that heritability means repeatability, which indicates the consistency of the genotypes' ranking, even if repeating the said experiment.

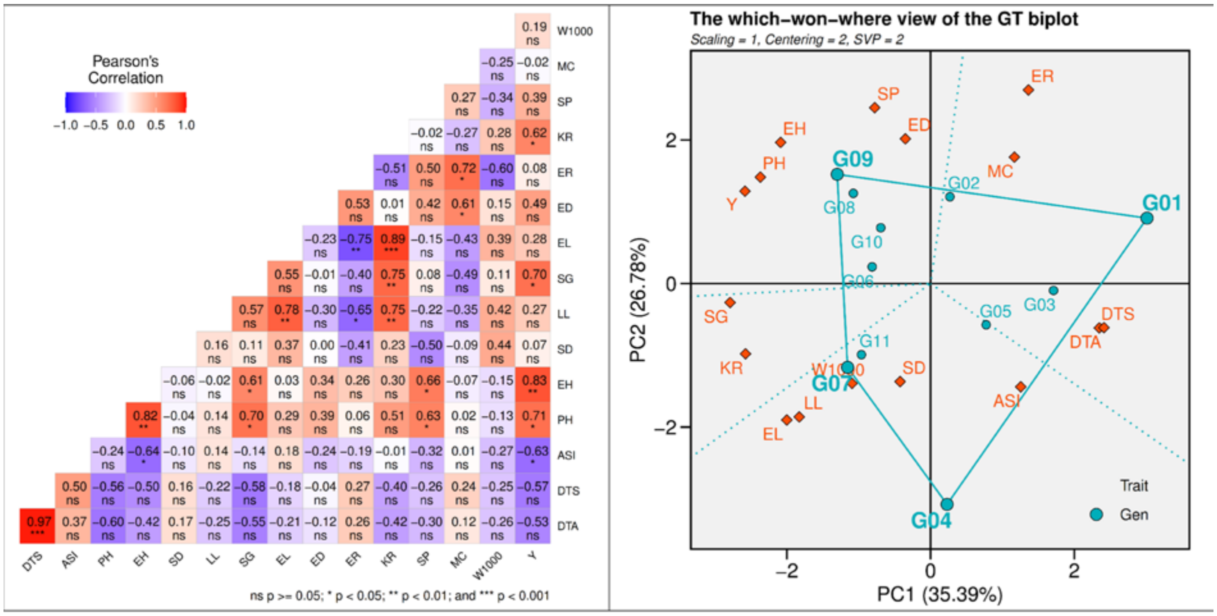
The Pearson correlation among the observed traits is available in Figure 1a. Grain yield, which is an essential quantitative trait in maize, has a significant ($P \leq 0.05$) positive correlation with plant and ear height, stay green, and kernels per row, as well as, a notable negative correlation with the anthesis-silking interval. This suggests these traits could be options as selection criteria for maize breeding efforts in enhancing grain yield (Magar *et al*., 2021). Agronomic and yield component traits showed considerable correlation with grain yield, and further studies for elucidating their direct and indirect effects can be conducted using path analysis (Aman *et al*., 2020).

The genotype by trait (GT) PCA biplot depicts two principal components, namely, PC1 (35.4%) and PC2 (26.8%), explaining a total of 62.2% (Figure 2b). The "which-won-where" view on the GT biplot attained division into four sectors. The traits, plant and ear heights, shelling percentage, and ear diameter were in the same sector as grain yield, indicating a positive association. The anthesis-silking interval (ASI) has the opposite direction from the grain yield, implying a lower ASI value is desired for a higher grain yield. The PCA biplot method may effectively reveal an association between grain yield and its components and agronomic traits (Jahangirlou *et al*., 2021). A similar method of genotype by traits (GT), which is a modified method of the GGE biplot can be a suitable tool for identifying the maize genotypes and their interaction with observed traits (Mousavi *et al*., 2021). The GT biplot approach enables the selection of genotypes with good performance for particular traits. The traits associated with vital quantitative traits, such as grain yield, also make it easier for breeders to determine the direction of future breeding programs.

Stability analysis across environments

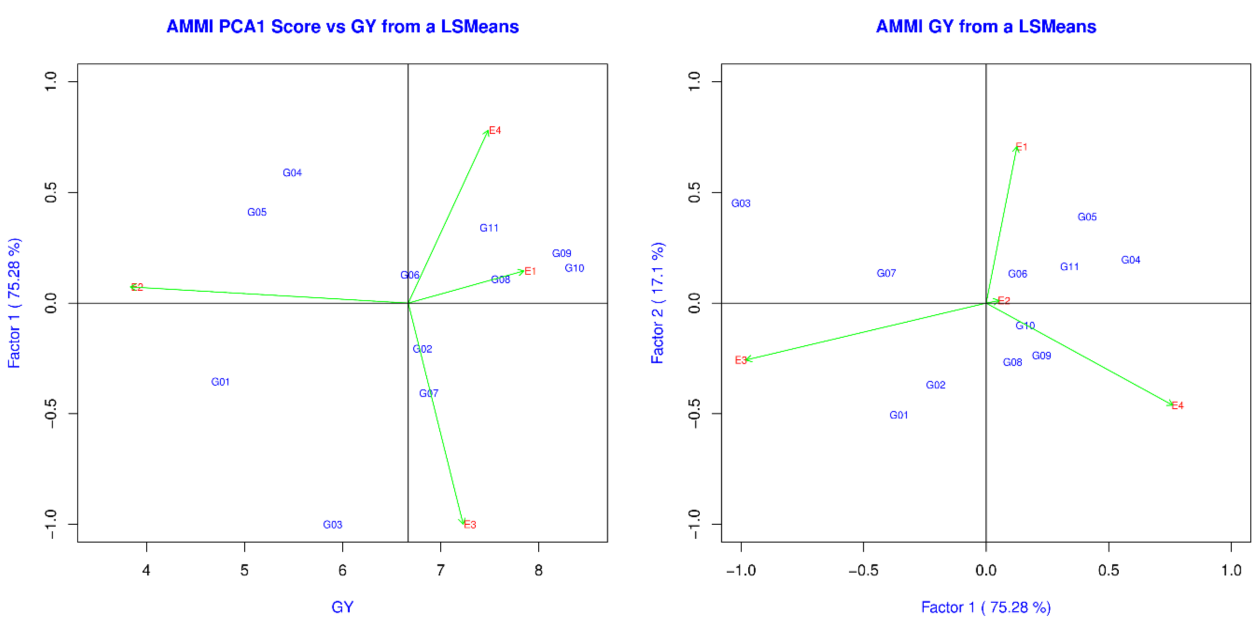
Development of high-yielding and stable genotypes is the major objective of maize breeding programs. A critical aspect to consider is the complex interaction between the genotype and the environment when assessing the stable performance of maize genotypes (Matongera *et al*., 2023). The effects of genotype by environment interactions (GEI) on yield traits and several agronomic traits were highly significant (Table 2). The noteworthy interaction between the genotypes and environments needs further evaluation with stability analyses to explain the response of the hybrids across the test environments. The effects of GEI demonstrate the occurrence of inconsistent performance of the maize genotypes in the studied environments (Azrai *et al*., 2022).

Francis and Kannenberg (1978) used the concept of static stability analysis based on the values of the coefficient of variance (CV_i) and average grain yield (Y_i), wherein the stable and consistent group have $CV_i < \overline{CV}$ and $Y_i > \overline{Y}$. The maize hybrids G02, G06, G07, G08, G09, and G10 appeared as stable based on this parameter. Finlay and Wilkinson (1963) used the concept of stability based on a linear regression coefficient for each genotype (b_i), average grain yield (Y_i), and environmental index. The b_i value of the maize hybrids ranged from 0.77 to 1.56 (Table 5), and those with b_i not significantly different from 1.00 indicated possessing average stability. Hybrids G01 to G10 belonged to the category of the stable genotypes; however, several hybrids (G01, G03, G04, and G05) have lower yields (Y_i) than the average ($\overline{Y}$). The stability component using the Kang yield-stability index (YS_i) indicates the magnitude of the GE interaction of the i^{th} genotype (Kang, 1993). Genotypes, whose YS_i statistical values were higher than the average ($\overline{YS}$), were selected genotypes for the highest and stable grain yields. The maize



a b

Figure 1. a) The Pearson correlations between the observed traits of maize hybrids; b) The "which-won-where" view of the GT biplot; Abbreviations: DTA = days to 50% anthesis; DTS = days to 50% silking; ASI = anthesis-silking interval; PH = plant height; EH = ear height; SD = stem diameter; LL = leaf length; SG = stay green; EL = ear length; ED = ear diameter; ER = number of ear rows; KR = number of kernels per row; SP = shelling percentage; MC = moisture content; W1000 = thousand kernels weight; and Y = grain yield.



a b

Figure 2. a) AMMI I biplot between the first principal component (IPC1) and average grain yield of maize hybrids; b) AMMI II biplot between the first principal component (IPC1) and the second principal component (IPC2).

Table 5. Stability parameters on grain yield for each maize hybrid across different abiotic conditions.

Hybrids	Y_i	CV_i	b_i	YS_i
G01	4.76	45.26	0.78	-10.00
G02	6.81	28.39	0.87	1.00 (+)
G03	5.90	66.91	1.07	-7.00
G04	5.49	44.64	0.77	-8.00
G05	5.13	43.99	0.84	-9.00
G06	6.69	23.04	0.77	0.00 (+)
G07	6.88	35.03	1.07	2.00 (+)
G08	7.61	21.87	0.82	4.00 (+)
G09	8.24	30.64	1.26	5.00 (+)
G10	8.36	27.49	1.20	6.00 (+)
G11	7.50	41.47	1.56	3.00 (+)
Means	6.67	37.16	1.00	-1.18

Y_i = average grain yield; CV_i = coefficient of variation; b_i = regression coefficient of average hybrid yield on environmental index; YS_i = yield and stability index (+: greater than the average of YS).

hybrids G02, G06, G07, G08, G09, G10, and G11 were recognizably high-yielding and stable, as indicated by the positive notation (+) based on Kang's stability.

Multivariate analysis for stability using additive main effects and multiplicative interactions (AMMI) and genotype main effects and genotype-environment effects (GGE) can provide an interpretation of the genotypes in a graphical representation using the principal component analysis (PCA) (Gauch, 2006). The following two stability analysis models offer a comprehensive understanding of the effects of genotype and environment interactions on genotype stability and adaptation in various environment groups (Khan *et al*., 2021). The AMMI-I biplot between the mean grain yield and the first interaction of the principal component (IPC1) showed hybrid G10 had the highest grain yield (8.36 t ha^{-1}), followed by hybrids G09 (8.24 t ha^{-1}) and G08 (7.61 t ha^{-1}), with a PC1 contribution (75.28%) (Figure 2a).

The AMMI-II biplot described the interactions of the 11 maize hybrids and four different environments with IPC1 (75.28%) and IPC2 (17.1%) (Figure 2b). AMMI-II is a useful tool for identifying the well-adapted genotypes to specific environments. A report has stated these biplots can provide valuable information for making informed decisions about crop management and breeding programs (Shojaei *et al*., 2021). Genotypes closer to the center (0.0) were the genotypes exhibiting insensitivity and stability to environmental variations, whereas genotypes that were far away proved sensitive to variations in the environmental conditions and substantial interactions (Azrai *et al*., 2023). The maize hybrids G06 and G10 were regarded as stable hybrids to variations in the target environments based on the analysis carried out through the AMMI-II biplot.

Multivariate analysis using genotypes and genotype-by-environment (GGE) provided a graphical representation of the G × E effects and made it possible to identify the visual pattern, relationship, and outliers in interpreting the results from genotyping (Shojaei *et al*., 2022). Figure 3a displays the GGE biplot “mean vs. stability” of the hybrids based on the direction of the *x*-axis AEA (average environmental axis). Hybrids with locations far away from the center in the direction of the arrow were prominent with a higher grain yield mean value ranking. Meanwhile, determining the level of stability was through the short perpendicular distance to the average environment axis (AEA) (*x*-axis) (Shojaei *et al*., 2021). The maize hybrids G06, G08, G09, and G10 emerged with the shortest perpendicular distance to the AEA, suggesting these hybrids revealed stability in the test environments. However, the hybrids G03 and G04 occurred with the longest distance, implying these hybrids were sensitive to environmental variations.

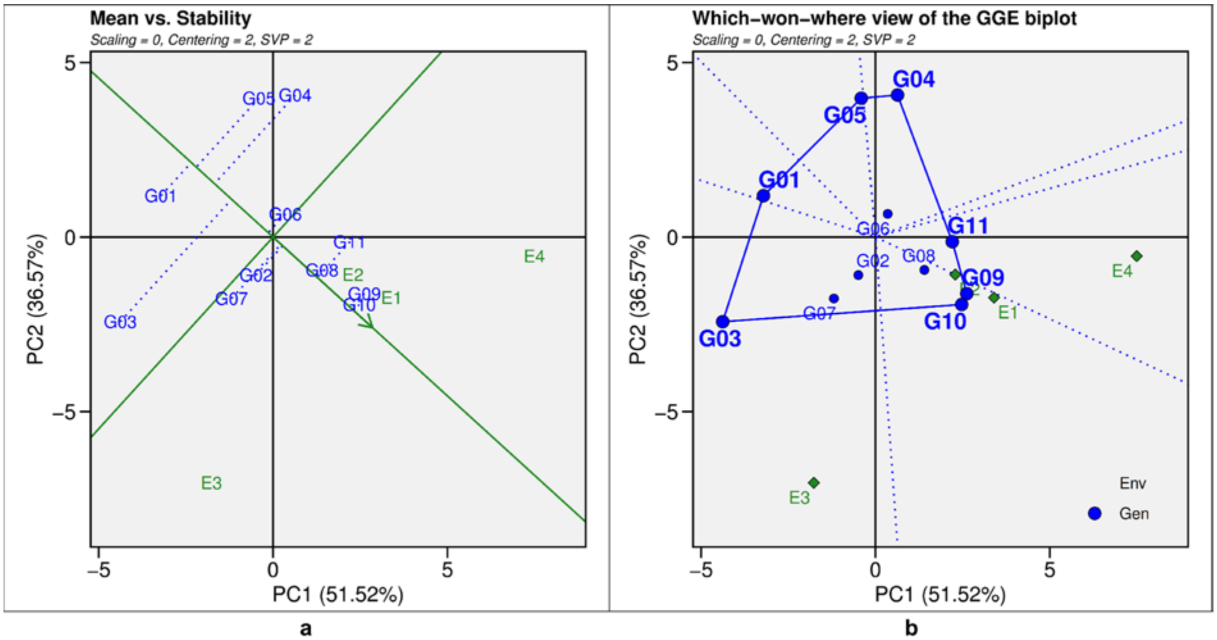


Figure 3. GGE biplot: a) mean vs. stability; b) which-won-where view of maize hybrids on grain yield.

The "which-won-where" view explained the determination of adaptive and superior genotypes and grouped the environments into seven different sectors (Figure 3b). The hybrid G11 demonstrated a specific adaptation to the Leuwikopo 2023 (E4). Hybrids G10, G09, and G08 proved suitable for development in the E1 (Leuwikopo 2022) and E2 (Cikabayan 2022) environments, indicating these three hybrids were adaptable to both optimum and suboptimum environments. The maize hybrids G02, G07, and G03 were well-adapted to the E3 (Ponorogo 2022), while the other maize hybrids showed no relationship to any group of environments. Some hybrids provided compatibility between static and dynamic stability concepts, as well as, between parametric and non-parametric concepts. The hybrids G02, G06, G07, G08, G09, and G10 registered as stable ($CV_i < \overline{CV}$ and $Yi > \overline{Y}$; b_i values were not significantly different from 1.0; and $YS_i > \overline{YS}$). Multivariate analysis of the GGE showed the maize hybrids G06, G08, G09, and G10 were more stable compared with all other genotypes.

Additionally, the hybrid G02 (L22 × Nei) resulting from the IPB and Indonesia Cereal Research Institute (ICERI) maize breeding program, had a higher average grain yield than G06 (BISI 18, a widely grown maize cultivar in Indonesia), and tended to have better yields under optimum environment (E3) conditions (Table 3). The same hybrid G02, as well as, G03 (L26 x L15) and G07 (JHG02) have good adaptability and high grain yields under the optimum environment described in the "which-won-where." The hybrid JHG02 has the potential to be tolerant to waterlogging stress conditions (Azrai *et al.*, 2022). Some maize hybrids were promising candidates for further evaluation and development, particularly under suboptimum environments. Therefore, it is necessary to produce tolerant maize hybrids also stable in non-optimum environments using a selection approach in breeding programs (Ammar *et al.*, 2024; Kthiri *et al.*, 2024).

CONCLUSIONS

Genotype-by-environment interactions significantly affected grain yield, agronomic traits, and yield components. The average grain yield under the suboptimum environment was lower than in the optimum environment. The heritability of the observed traits fell in the moderate to high category. Plant and ear height, stay green, kernels per row, and anthesis-silking interval have a notable positive correlation with grain yield. The maize hybrids G02, G06, G07, G08, G09, and G10 were regarded stable based on parametric and non-parametric stability, while the hybrids G06, G08, G09, and G10 were also considered stable based on the GGE analysis.

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REFERENCES

Alam MA, Rahman M, Ahmed S, Jahan N, Khan MA, Islam MR, Alsuhaibani AM, Gaber A, Hossain A (2022). Genetic variation and genotype by environment interaction for agronomic traits in maize (*Zea mays* L.) hybrids. *Plants* 11: 1–16. https://doi.org/10.3390/ plants11111522.

Aman J, Bantte K, Alamerew S, Sbhatu DB (2020). Correlation and path coefficient analysis of yield and yield components of quality protein maize (*Zea mays* L.) hybrids at Jimma, Western Ethiopia. *Int. J. Agron.* https://doi.org/10.1155/2020/9651537.

Ammar A, Aslam M, Khan MS, Ahmad RM (2024). Exploring the genetic potential of maize (*Zea mays* L.) for high-temperature stress tolerance. *SABRAO J. Breed. Genet.* 56(5): 2004-2014. http://doi.org/10.54910/ sabrao2024.56.5.23.

Anand A, Subramanian M, Kar D (2023). Breeding techniques to dispense higher genetic gains. *Front. Plant Sci.* 13:1076094. https://doi.org/10.3389/fpls.2022.1076094.

Assefa BT, Chamberlin J, Ittersum MK, Reidsma P (2021). Usage and impacts of technologies and management practices in Ethiopian smallholder maize production. *Agriculture* 11: 938. https://doi.org/10.3390/ agriculture11100938.

Azrai M, Aqil M, Efendi R, Andayani NN, Makkulawu AT, Iriany RN, Suarni, Yasin M, Suwardi, Zainuddin B, Salim, Sitaresmi T, Bahtiar, Paesal, Suwarno WB (2023). A comparative study on single and multiple trait selections of equatorial grown maize hybrids. *Front. Sustain. Food Syst*. 6: 1–13. https://doi.org/10.3389/fsufs.2023.1185102.

Azrai M, Efendi R, Muliadi A, Aqil M, Suwarti, Zainuddin B, Syam, Amiruddin S, Junaedi Syah UT, Dermail A, Marwiyah S, Suwarno WB (2022). Genotype by environment interaction on tropical maize hybrids under optimum irrigation and waterlogging conditions. *Front. Sustain. Food Syst*. 6: 1–16. https://doi.org/10.3389/fsufs.2022. 913211.

Demeke B, Dejene T, Abebe D (2023). Genetic variability, heritability, and genetic advance of morphological, yield related and quality traits in upland rice (*Oryza sativa* L.) genotypes at Pawe, Northwestern Ethiopia. *Cogent Food Agric*. 9. https://doi.org/10.1080/23311932.2022.21 57099.

FAOSTAT (2022). Agricultural production statistics 2000–2022 (accessed March 2024).

Finlay KW, Wilkinson GN (1963). The analysis of adaptation in plant breeding program. *Aust. J. Agric. Res*. 13: 742–754. https://doi.org/10.1071/AR9630742.

Francis TR, Kannenberg LW (1978). Yield stability studies in short-season maize. I. a descriptive method for grouping genotypes. *Can. J. Plant Sci.* 58: 1029–1034. https://doi.org/10.4141/cjps78-157.

Gauch HG (2006). Statistical analysis of yield trials by AMMI and GGE. *Crop Sci.* 46: 1488–1500. https://doi.org/10.2135/ cropsci2005.07-0193.

Gauch HG, Zobel RW (1988). Predictive and postdictive success of statistical analysis of yield trial. *Theor. Appl. Genet*. 76: 1–10. https://doi.org/10.1007/BF00288824.

Haruna A, Adu GB, Buah SS, Kanton RAL, Kudzo AI, Seidu AM, Kwadwo O (2017). Analysis of genotype by environment interaction for grain yield of intermediate maturing drought tolerant top-cross maize hybrids under rain-fed conditions. *Cogent Food Agric.* 3. https://doi.org/10.1080/23311932.2017.13 33243.

Jahangirlou M, Akbari GA, Alahdadi I, Soufizadeh S, Kumar U, Parsons D (2021). Phenotypic traits, grain yield and yield components of

maize cultivars under combinations of management practices in semi-arid conditions of Iran. *Int. J. Plant Prod.* 15: 459–471. https://doi.org/10.1007/s42106-021-00151-7.
Kang MS (1993). Simultaneous selection for yield and stability in crop performance trials: Consequences for growers.*Agron J.* 85:754–757. https://doi.org/10.2134/agronj1993.00021962008500030042x.
Kassambara A (2020). Factoextra: Extract and visualize the results of multivariate data analyses. Available at https://cran.r-project.org/web/packages/factoextra/factoextra.pdf (accessed March 2024).
Khan MMH, Rafii MY, Ramlee SI, Jusoh M, Mamun MA (2021). AMMI and GGE biplot analysis for yield performance and stability assessment of selected bambara groundnut (*Vigna subterranea L. Verdc.)* genotypes under the multi-environmental trials (METs). *Sci. Rep*. 11. https://doi.org/10.1038/s41598-021-01411-2.
Konate L, Badu-Apraku B, Coulibaly M, Menkir A, Laouali MN, Meseka S, Mengesha W (2023). Agronomic performance and yield stability of extra-early maturing maize hybrids in multiple environments in the Sahel. *Heliyon* 9. https://doi.org/10.1016/j.heliyon.2023.e21659.
Kthiri Z, Hammami MDE, Jabeur MB, Marzougui O, Hamada W, Karmous C (2024). Drought tolerance assessment in maize hybrids: Morphophysiological and biochemical characterization. *SABRAO J. Breed. Genet.* 56(6): 2341-2350. http://doi.org/10.54910/sabrao2024.56.6.15.
Magar BT, Acharya S, Gyawali B. Timilsena K, Upadhayaya J, Shrestha J (2021). Genetic variability and trait associations in maize (*Zea mays* L.) varieties for growth and yield traits. *Heliyon* 7. https://doi.org/10.1016/j.heliyon.2021.e07939.
Matongera N, Ndhlela T, Biljon AV, Labuschagne M (2023). Genotype x environment interaction and yield stability of optimum and biofortified maize inbred lines in stress and non-stress environments. *Cogent Food Agric.* 9. https://doi.org/10.1080/23311932.2022.2163868.
Mousavi SMN, Bojtor C, Illés Á, Nagy J (2021). Genotype by trait interaction (GT) in maize hybrids on complete fertilizer. *Plants* 10. https://doi.org/10.3390/plants10112388.
Olivoto T, Lúcio AD (2020). Metan: An R package for multi-environment trial analysis. *Methods Ecol. Evol.* 11: 783–789. https://doi.org/10.1111/2041-210X.13384.
Rezende WS, Beyene Y, Mugo S, Ndou E, Gowda M, Sserumaga JP, Asea G, Ngolinda I, Jumbo M, Oikeh SO, Olsen M, Borem A, Cruz CD, Prasanna BM (2020). Performance and yield stability of maize hybrids in stress-prone environments in Eastern Africa. *Crop J.* 8: 107–118. https://doi.org/10.1016/j.cj.2019.08.001.
Shojaei SH, Mostafavi K, Bihamta MR, Omrani A, Mousavi SMN, Illes A, Bojtor C, Nagy J (2022). Stability on maize hybrids based on GGE biplot graphical technique. *Agronomy* 12:394–403. https://doi.org/10.3390/agronomy12020394.
Shojaei SH, Mostafavi K, Khosroshahli M, Khosroshahli M, Bihamta MR, Ramshini H (2020). Assessment of genotype-trait interaction in maize (*Zea mays* L.) hybrids using GGT biplot analysis. *Food Sci. Nutr.* 8: 5340–5351. https://doi.org/10.1002/fsn3.1826.
Shojaei SH, Mostafavi K, Omrani A, Omrani S, Mousavi SMN, Illes A, Bojtor C, Nagy J (2021). Yield stability analysis of maize (*Zea mays* L.) hybrids using parametric and AMMI methods. *Scientifica* https://doi.org/10.1155/2021/557669.
Singamsetti A, Shahi JP, Zaidi PH, Seetharam K, Vinayan MT, Kumar M, Singla S, Shikha K, Madankar K (2021). Genotype × environment interaction and selection of maize (*Zea mays* L.) hybrids across moisture regimes. *Field Crops Res.* 270. https://doi.org/10.1016/j.fcr.2021.108224.
Stansfield WD (1991). Theory and Problem of Genetics. Third Edition, McGraw-Hill Inc, New York.
Tandzi LN, Mutengwa CS, Ngonkeu ELM, Gracen V (2018). Breeding maize for tolerance to acidic soils: A review. *Agronomy 8*. https://doi.org/10.3390/agronomy8060084.
Yan W, Hunt LA, Sheng Q, Szlavnics Z (2000). Cultivar evaluation and mega-environment investigation based on GGE biplot. *Crop Sci.* 40: 597–605. https://doi.org/10.2135/cropsci2000.403597x.
Yan W, Rajcan I (2002). Biplot analysis of test sites and trait relations of soybean in Ontario. *Crop Sci.* 42: 11–20. https://doi.org/10.2135/cropsci2002.1100.
Zendrato YM, Suwarno WB, Marwiyah S (2024). Multi-trait selection of tropical maize genotypes under optimum and acidic soil conditions. *SABRAO J. Breed. Genet*. 56: 142–155. https://doi.org/10.54910/sabrao2024.56.1.13.