Yield performance and stability of maize hybrids of different maturity groups in multiple environments in Nigeria

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ABSTRACT

Background and Objective: Maize production in Nigeria faces challenges due to environmental stresses such as drought, heat, low soil fertility, pests, and diseases, compounded by regional variability. This study aimed to identify high-yielding early and extra-early maturing hybrids with stable performance for potential commercialization in Nigeria.

Methodology: 20 early and 19 extra-early maturing hybrids, along with two local checks, were evaluated across six locations over two years (2016 and 2017) in Nigeria using a randomized complete block design with three replications. Data were collected for grain yield, flowering traits, growth traits, and aspect ratings.

Main Results: Significant ($P < 0.01$ or $P < 0.05$) genotype, environment, and interaction effects were observed for grain yield in both maturity groups. Early maturing varieties had longer days to maturity, higher plant and ear heights, and greater grain yield than extra-early maturing varieties. Hybrids EYH-17 and EYH-21 had the highest yields (4,263 and 4,183 kg/ha) among early maturing hybrids, with yield advantages of 12.2% and 10.1% over the check. For extra-early maturing varieties, hybrids EEYH-54, EEYH-41, and EEYH-25 produced yields over 4,000 kg/ha, with yield advantages of 19.8% to 29.2% over the check. Lapai 2016 and Ilorin 2016 were the most discriminating and representative test environments for both maturity groups. GGE biplot analysis identified EYH-17 and EEYH-25 as the most stable hybrids with the highest mean grain yield. The principal component analysis highlighted flowering time, plant height, and ear height as primary contributors to variability in maize hybrids.

Conclusions: Hybrids EYH-17 and EEYH-25 are recommended for on-farm evaluation to confirm their yield potential and facilitate their commercialization in Nigeria. Lapai and Ilorin are ideal test environments for selecting superior hybrids with broad adaptation. Flowering time, plant height, and ear height should be prioritized in breeding programs to enhance maize breeding value.

Keywords: Biplot, early maturing, extra-early maturing, stability analysis, principal component analysis

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INTRODUCTION

Maize (*Zea mays* L.) is one of the most important cereal crops globally, serving as a staple food for millions of people and a vital raw material for various industries (Kamara *et al*., 2020; Bankole *et al*., 2023). It is widely cultivated in Nigeria as a significant food and cash crop, contributing to both food security and economic development. Hybrid maize, developed through controlled crosses of genetically distinct parental lines, remains the preferred choice among commercial farmers seeking to maximize productivity and profitability compared to traditional Open Pollinated Varieties (OPVs) due to its superior traits such as disease resistance, improved yield potential, and uniformity (Ndoli *et al*., 2019; Ifie *et al*., 2022).

Hybrids are categorized into distinct maturity groups based on their duration from planting to physiological maturity, namely early, intermediate, and late maturing varieties (Bankole *et al*., 2015; Oluwaranti *et al*., 2015). Early maturing varieties, including extra-early hybrids maturing within 80–85 days and early hybrids within 90–95 days, have gained prominence for their ability to contribute significantly to food security and farmer incomes, particularly in regions characterized by marginal rainfall patterns across West and Central Africa (Bankole *et al*., 2015; Oluwaranti *et al*., 2015). The flexibility in planting dates offered by these maize genotypes enables multiple plantings, thereby mitigating the risk of crop failure due to delayed onset of rainfall, mid-season, or terminal drought (Bankole *et al*., 2015).

The International Institute of Tropical Agriculture (IITA) and its partners have been at the forefront of developing multiple stress-tolerant maize hybrids, with a particular focus on extra-early and early maturing varieties tailored for regions like the Guinea Savannah Ecology, known for its terminal droughts and irregular rainfall patterns. However, before recommending improved maize varieties for production in target environments, a thorough evaluation in representative environments is essential to identify stable high-yielding varieties and ascertain their adaptation patterns (Badu-Apraku *et al*., 2011; Olaoye *et al*., 2017). This evaluation process is often complicated by genotype × environment interaction (GEI), which affects genotype performance rankings from one location to another, making it challenging to identify superior genotypes in multi-environment trials. As a result, different genotypes may need to be released for specific regions to enhance yield and reduce production costs (Badu-Apraku *et al*., 2011; Mafouasson *et al*., 2018).

Various statistical tools, including Shukla's stability variance, the additive main effects and multiplicative interaction (AMMI) model, the genotype plus genotype-by-environment interaction (GGE) biplot, Eberhart and Russell's regression model, and Francis and Kannenberg's coefficient of variation, have been utilized to reveal patterns of GEI in multilocation yield trials (Eberhart and Russell, 1966; Zobel *et al*., 1988; Mafouasson *et al*., 2018). While each of these tools has its merits, the GGE biplot is often preferred for several reasons. Shukla's stability variance, despite its usefulness in providing a clear measure of stability, does not capture GEI interactions as effectively as the GGE Biplot. The AMMI model, although effective in identifying GEI patterns, does not simultaneously consider genotype and environmental effects, limiting its comprehensive application. Eberhart and Russell's regression model, useful for understanding genotype responses to environmental changes, simplifies the complex nature of GEI to a single environmental index, potentially overlooking intricate interactions. Francis and Kannenberg's coefficient of variation uses the coefficient of variation (CV) to assess stability, with lower CV values indicating higher stability (Francis and Kannenberg, 1978). While straightforward, this method primarily focuses on variability and does not fully account for GEI effects.

On the other hand, the GGE biplot developed by Yan and Tinker (2006) allows for a more comprehensive analysis by integrating both genotype and environmental effects. Its visual representation facilitates the interpretation of complex data and the identification of stable and high-yielding genotypes across diverse environments, making it a versatile and powerful tool for stability analysis in plant breeding (Oliveira *et al*., 2017; Aboderin *et al*., 2023). Additionally, understanding the key traits contributing to variability in hybrid performance in multilocational trials is crucial for the effective selection and breeding of superior maize genotypes. One robust statistical method for identifying and analyzing these traits is Principal component analysis (PCA). PCA helps reduce the dimensionality of large datasets, highlights the most significant variables that account for variability, and simplifies complex relationships among traits (Ni *et al*., 2019). The objectives of this study were to identify high-yielding, stable hybrids suitable for commercialization in Nigeria, capable of withstanding diverse environmental stresses, compare the agronomic performance of extra-early and early maturing maize hybrids, and highlight key traits contributing to hybrid performance variability.

MATERIALS AND METHODS

Germplasm

The genetic materials used in this study consisted of nineteen (19) extra-early and twenty (20) early maturing multiple stress-tolerant maize hybrids sourced from the International Institute of Tropical Agriculture (IITA), Nigeria, as part of the materials included in the Stress Tolerant Maize for Africa (STMA) Project. Additionally, two local maize varieties were included as checks: one early maturing and the other extra-early maturing (Table 1).

Experimental Sites

Both sets of hybrids were evaluated at the Teaching and Research Farm of the University of Ilorin, Ibrahim Badamosi Babangida University in Lapai, and the College of Agriculture in Mokwa. Additionally, the extra-early maturing hybrids were evaluated at Kishi and Landmark University in Omu-Aran, while the early maturing hybrids were evaluated at the Research Farm in Ballah. The evaluation was carried out over two successive years (2016 and 2017), with the combination of years and locations considered as environments in the study. For the extra-early maturing hybrids, environments 1 to 6 corresponded to Kishi 2017, Omu-Aran 2017, Ilorin 2017, Ilorin 2016, Lapai 2016, and Mokwa 2016, respectively. For the early maturing hybrids, environments 1 to 6 represented Ilorin 2017, Lapai 2017, Mokwa 2017, Ballah 2016, Ilorin 2016, and Lapai 2016, respectively. Details about the testing sites are presented in Table 2.

Table 1 Details of the materials used for the study

Extra-early maturing			Early maturing		
Genotype	Grain color	Source	Genotype	Grain color	Source
EEYH-25	Yellow	IITA	EYH-16	Yellow	IITA
EEYH-30	Yellow	IITA	EYH-17	Yellow	IITA
EEYH-32	Yellow	IITA	EYH-19	Yellow	IITA
EEYH-36	Yellow	IITA	EYH-21	Yellow	IITA
EEYH-37	Yellow	IITA	EYH-23	Yellow	IITA
EEYH-40	Yellow	IITA	EYH-24	Yellow	IITA
EEYH-41	Yellow	IITA	EYH-36	Yellow	IITA
EEYH-42	Yellow	IITA	EYH-39	Yellow	IITA
EEYH-44	Yellow	IITA	EYH-46	Yellow	IITA
EEYH-45	Yellow	IITA	EYH-49	Yellow	IITA
EEYH-46	Yellow	IITA	EYH-51	Yellow	IITA
EEYH-47	Yellow	IITA	EYH-52	Yellow	IITA
EEYH-48	Yellow	IITA	EYH-53	Yellow	IITA
EEYH-49	Yellow	IITA	EYH-54	Yellow	IITA
EEYH-50	Yellow	IITA	EYH-55	Yellow	IITA
EEYH-51	Yellow	IITA	EYH-56	Yellow	IITA
EEYH-52	Yellow	IITA	EYH-57	Yellow	IITA
EEYH-53	Yellow	IITA	EYH-58	Yellow	IITA
EEYH-54	Yellow	IITA	EYH-59	Yellow	IITA
Local check		Ilorin	EYH-60	Yellow	IITA
			Local check		Ilorin

Table 2 Description of the experimental sites

Location	State	Latitude	Longitude	Altitude (m)	Mean annual rainfall (mm)	Temperature range (°C)
Ilorin	Kwara	8°30’N	4°32’60E	289	1,318	23–34
Eruwa	Oyo	7°32’0”N	3°25’0”E	370	1,367	21–32
Ballah	Kwara	13°22’0N	5°34’60E	249	1,150	21–37
Mokwa	Niger	9°16’60N	5°26’0E	87	1,250	17–37
Kishi	Oyo	9°46’0N	3°51’0E	372	2,000	20–38
Omu-Aran	Kwara	8°8’0”N	5°6’0”E	536	1,200	17–33
Lapai	Niger	9°3’0N	6°9’0E	117	1,300	16–34

Field Evaluation and Management

The trial was established at each location using a randomized complete block design with three replications. Evaluations were conducted during the rainy seasons of 2016 and 2017. Double rows, each measuring 5 m in length, were employed with inter and intra-row spacings set at 0.75 m and 0.4 m, respectively. Initially, three seeds were planted per hole and subsequently thinned to two plants per hill two weeks after planting (WAP) to achieve a population density of 66,666 plants/ha. Fertilizer application was carried out in split dosages, with a rate of 60 kg/ha N, 60 kg/ha P_2O_5, and 60 kg/ha K_2O using compound fertilizer (NPK 15:15:15) at 3WAP, followed by an additional top dressing of 60 kg/ha of urea at 5WAP. Weed control was implemented through chemical means utilizing extra force (Atrazine and Metolachlor) at a rate of 3 L/ha and Paraforce (paraquat) at 5 L/ha. Additionally, hand weeding was carried out to complement chemical weed control.

During the testing years 2016 and 2017, Nigeria experienced an invasion of the fall armyworm (*Spodoptera frugiperda*). At that time, little was known about effective management strategies for this pest. Various broad-spectrum pesticides, such as Chlorpyrifos, Lambda-cyhalothrin, and Cypermethrin, were used in different combinations as recommended by weed scientists. Regular monitoring of the fields for early detection of the pests and cultural practices, such as removing and destroying infested plants, were also implemented to reduce pest populations. Despite these efforts, some plants were lost while others managed to survive. Due to the three replications used in the study, significant efforts were made to obtain data from at least one replication, which was then used to estimate the yield and other agronomic traits of the hybrids. In locations where planting was done early due to the early onset of rainfall, the loss was minimal. In such locations, replanting of damaged plants was carried out to ensure sufficient data for evaluation.

Data Collection and Analyses

Phenotypic data were collected for each genotype on a whole plot basis, covering flowering traits (days to anthesis, days to silking, and anthesis-silking interval), growth traits (plant height and ear height), aspect ratings (plant and ear), and number of ears per plant. Days to anthesis (DP) represented the duration from planting to when 50% of the plant population in a plot had released their pollen, while days to silking (DS) denoted the duration from planting to when 50% of the plant population had emerged silks. The anthesis-silking interval (ASI) was calculated as the difference between days to anthesis and days to silking. Plant height (PHT) and ear height (EHT) were determined using a meter rule, measuring the mean height of ten randomly selected plants within each plot from the base of the plant to the beginning of the tassel branch (PHT) and from the base to the node bearing the uppermost ear (EHT). Aspect ratings for plant and ear characteristics were visually assessed using a phenotypic scale ranging from 1 to 5; where 1 denoted excellent phenotypic appeal, indicating uniform plant structure, healthy foliage, and well-formed ears, 2 indicated good phenotypic appeal with minor deviations, 3 represented average phenotypic appeal with acceptable trait variations, 4 signified below-average phenotypic appeal with significant deviations, and 5 indicated poor phenotypic appeal with major deficiencies. The number of ears per plant (EPP) was estimated as the ratio of the ears harvested per plot to the number of plants. Representative samples of ears harvested per plot were shelled to determine percentage moisture content. Grain yield (kg/ha) was computed from the field weight of the ears harvested per plot and moisture content with an assumed 80% shelling percentage adjusted to 15% moisture content.

The analysis of variance was conducted on the agronomic data collected using SAS software (SAS, 2008). Means of traits showing significant differences among the maize hybrids were separated using the least significant difference (Steel and Torrie, 1980). Additionally, the grain yield data was subjected to genotype main effect plus genotype-by-environment interaction (GGE) biplot analysis to decompose the genotype main effect and G × E interactions of each experiment using the GEA-R Window software (Pacheco *et al*., 2016). This analysis was done to identify hybrids in each maturity group with stable and superior yield performance within each location as well as across the test locations. GGE model equation:

$$Y_{ij} - Y_j = \lambda_1 \varepsilon_{i1} \eta_{j1} + \lambda_2 \varepsilon_{j2} \eta_{j2} + \sum_{ij}$$

where Y_{ij} = genotype i average yield in j environment, Y_j = the average yield of all genotypes in j environment; the singular values λ_1 and λ_2 represent the amount of variation explained by principal component (PC) 1 and PC2, respectively. The scores ε_{i1} and ε_{j2} represent the contribution of the genotype and environment to PC1 and PC2, respectively. The scores η_{j1} and η_{j2} represent the contribution of the environment to PC1 and PC2, respectively. The residual $\sum_{ij}$ represents the deviation of the observed yield from the expected yield based on the model (Yan and Tinker, 2006).

The PCA was conducted using SAS 9.2 statistical software to highlight key traits contributing to variability in the hybrid performance. Initially, all trait data were standardized to ensure equal contribution to the analysis, irrespective of their original scales.

RESULTS AND DISCUSSION

Hybrid Performance in Each Maturity Group

The combined analysis of variance for grain yield and other related traits in 20 early and 19 extra-early maturing maize hybrids evaluated in six different environments are presented in Tables 3–4. Environment mean squares were highly significant ($P < 0.01$) for grain yield (GY) and all measured traits in both maturity groups, indicating the strong influence of environmental factors on trait expression (Oyekunle *et al*., 2017; Bankole *et al*., 2023; Matongera *et al*., 2023). Significant genotype mean squares were observed for grain yield, days to silking, plant height, and anthesis silking interval in both maturity groups, along with days to anthesis in early maturing and ear height in extra-early maturing varieties. These results underscore the genetic diversity within the maize population, affirming the presence of sufficient variation among the tested hybrids for potential trait improvement (Aboderin *et al*., 2023).

Significant genotype by environment (G × E) interaction effects were observed for grain yield and days to silking in both maturity groups, as well as for ear height and plant height in early maturing hybrids. This indicates differential hybrid performance across test environments, with inconsistent rankings for grain yield in each environment (Aboderin *et al*., 2023). Consequently, selecting superior hybrids based on single-environment data is challenging, highlighting the necessity for multi-environment testing to identify superior hybrids with stable performance across diverse agroecologies before making genotype recommendations (Bankole *et al*., 2023; Konate *et al*., 2023).

Table 3 Mean squares from combined ANOVA for grain yield and other agronomic traits in 20 early maturing yellow maize hybrids and local check evaluated across 6 environments in the Southern Guinea Savannah of Nigeria

Source	df	Grain yield (kg/ha)	Days to anthesis (day)	Days to silking (day)	Anthesis silking interval (day)	Plant height (cm)	Ear height (cm)	Ear per plant (no)	Plant aspect (1–5)	Ear aspect (1–5)
Environment (E)	5	95612570**	356.72**	498.89**	372.21**	3813.61**	881.06**	0.03**	41.80**	49.91**
Rep/Environment	12	6474079	12.35	14.53	1.33	395.25	452.48	0.01	2.04	0.99*
Genotype (G)	20	1870532**	11.01**	12.60**	2.80*	378.16**	85.28	0.003	1.12	0.47
G × E	100	1186951*	6.28	8.13**	2.02	268.75**	103.89*	0.004	1.49	0.37
Pooled error	240	141161263	4.80	5.09	1.62	130.82	67.07	0.003	1.60	0.42
CV (%)		31.49	4.14	4.02	39.63	7.64	12.38	5.64	20.50	23.85

Note: *, ** Significant at 0.05 and 0.01 probability levels, respectively. For plant and ear aspect; 1 = excellent phenotypic appeal, 2 = good phenotypic appeal, 3 = average phenotypic appeal, 4 = below-average phenotypic appeal, 5 = poor phenotypic appeal.

Table 4 Mean squares from combined ANOVA for grain yield and other agronomic traits in 19 extra-early maturing yellow maize hybrids and local check evaluated across 6 environments in the Southern Guinea Savannah of Nigeria

Source	df	Grain yield (kg/ha)	Days to anthesis (day)	Days to silking (day)	Anthesis silking interval (day)	Plant height (cm)	Ear height (cm)	Earper plant (no)	Plant aspect (1–5)	Ear aspect (1–5)
Environment (E)	5	94465053.4**	337.82**	705.4**	1927.97**	44093.72**	9137.72**	0.30**	50.10**	51.24**
Rep/Environment	12	901760.6	4.66	0.62	3.14	163.69	197.61	0.21	0.43	0.24
Genotype (G)	19	1823284.3*	5.75	6.74**	8.14*	612.67**	191.52*	0.09	0.28	0.38
G × E	95	2254097.5**	4.25	3.83**	4.62	230.45	120.35	0.10	0.35	0.34
Pooled error	228	891902.3	3.80	1.93	3.99	157.82	98.28	0.10	0.30	0.28
CV (%)		43.01	51.71	2.72	3.65	8.97	16.73	33.84	26.21	22.93

Note: *, ** Significant at 0.05 and 0.01 probability levels, respectively. For plant and ear aspect; 1 = excellent phenotypic appeal, 2 = good phenotypic appeal, 3 = average phenotypic appeal, 4 = below-average phenotypic appeal, 5 = poor phenotypic appeal.

The hybrids of both maturity groups exhibited significant differences in yield performance across the test locations, with some hybrids outperforming others (Tables 5–6). Among the early maturing hybrids, the mean grain yield stood at 3,143 kg/ha, with hybrid EYH-17 recording the highest yield (4,263 kg/ha) and EYH-39 the lowest (2,209 kg/ha). The grain yield of the local check was 3,799 kg/ha, and only hybrids EYH-17 and EYH-21 surpassed the local check, with yield advantages of 12.2% and 10.1%, respectively. For the extra-early maturing varieties, grain yield ranged from 1,487 (EEYH-51) to 4,528 kg/ha (EEYH-54), with a mean of 3,063 kg/ha. The grain yield of the local check was 3,504 kg/ha, with only six hybrids (EEYH-53, EEYH-50, EEYH-42, EEYH-25, EEYH-41, and EEYH-54) outperforming the local check by 0.8% to 29.2%. The results indicate that early maturing hybrids, on average, exhibited higher grain yield compared to extra-early maturing varieties. Notably, early maturing hybrids EYH-17 and EYH-21, along with extra-early maturing hybrids EEYH-54, EEYH-41, and EEYH-25, demonstrated excellent yield performance across the test environments in the Southern Guinea savanna regional trials. Their superior *per se* performance and yield advantage over the check indicate their inherent genetic potential to thrive under various stress conditions, making them beneficial options for farmers in this region.

Table 5 Mean yield performance and other agronomic characters of 19 extra-early maturing yellow maize hybrids and local check evaluated across 6 environments in the Southern Guinea Savannah of Nigeria

Hybrids	GY (kg/ha)	DP (day)	DS (day)	ASI (day)	PHT (cm)	EHT (cm)	EPP (no)	PA (1–5)	EA (1–5)
EEYH-25	4,199	51.0	54.0	3.0	149.0	56.0	1.0	1.9	2.2
EEYH-30	2,754	51.0	55.0	4.0	145.0	55.0	1.0	2.3	2.2
EEYH-32	2,670	51.0	55.0	3.0	139.0	53.0	1.0	2.2	2.3
EEYH-36	2,758	52.0	54.0	2.0	134.2	50.0	1.0	2.3	2.5
EEYH-37	2,568	52.0	56.0	4.0	143.0	57.0	1.0	2.0	2.0
EEYH-40	2,610	52.0	56.0	4.0	156.0	62.0	1.0	2.0	2.3
EEYH-41	4,443	50.0	54.0	4.0	134.2	50.0	1.0	2.1	2.3
EEYH-42	3,562	51.0	55.0	4.0	139.0	51.0	1.0	2.0	2.3
EEYH-44	2,840	52.0	56.0	4.0	145.0	56.2	1.0	1.9	2.2
EEYH-45	3,107	52.0	56.0	4.0	137.4	52.0	1.0	2.3	2.5
EEYH-46	2,177	51.0	54.0	3.0	134.2	55.0	1.0	1.9	2.2
EEYH-47	3,498	51.0	55.0	4.0	140.0	55.3	1.0	2.1	2.4
EEYH-48	2,207	52.0	55.0	3.0	136.0	51.0	1.0	2.1	2.2
EEYH-49	2,230	51.0	54.0	4.0	135.0	50.0	1.0	2.2	2.5
EEYH-50	3,536	52.0	55.0	3.0	148.0	52.0	1.0	2.1	2.2
EEYH-51	1,487	51.0	55.0	3.0	148.0	55.0	1.0	2.0	2.5
EEYH-52	3,052	52.0	54.0	3.0	146.0	52.0	1.0	2.1	2.5
EEYH-53	3,531	52.0	54.0	3.0	149.0	54.2	1.0	2.1	2.4
EEYH-54	4,528	52.0	55.0	3.0	136.0	54.0	1.0	2.1	2.2
Local check	3,504	52.0	56.0	4.0	145.0	56.0	1.0	2.4	2.3
LSD	570	0.9	1.4	1.2	8.8	6.0	0.0	0.0	0.0
Mean	3,063	51.5	54.9	3.5	141.9	53.8	1.0	2.1	2.3

Note: GY = grain yield, DP = days to anthesis, DS = days to silking, ASI = anthesis silking interval, PHT = plant height, EHT = ear height, EPP = number of ears per plant, PA = plant aspect, EA = ear aspect For plant and ear aspect; 1 = excellent phenotypic appeal, 2 = good phenotypic appeal, 3 = average phenotypic appeal, 4 = below-average phenotypic appeal, 5 = poor phenotypic appeal.

Table 6 Mean yield performance and other agronomic characters of 20 early maturing yellow maize hybrids and local check evaluated across 6 environments in the Southern Guinea Savannah of Nigeria

Hybrids	GY (kg/ha)	DP (day)	DS (day)	ASI (day)	PHT (cm)	EHT (cm)	EPP (no)	PA (1–5)	EA (1–5)
EYH-16	3,176	53.0	56.0	3.0	152.0	64.2	1.0	1.2	2.2
EYH-17	4,263	53.0	56.0	3.0	141.0	61.0	1.0	1.3	1.8
EYH-19	3,715	51.0	56.0	4.0	149.0	66.0	1.0	1.2	2.4
EYH-21	4,183	53.0	56.0	3.0	150.0	67.0	1.0	1.2	1.7
EYH-23	2,637	55.0	58.0	3.0	144.2	66.1	1.0	1.1	3.2
EYH-24	2,687	53.0	56.0	3.0	157.2	68.0	1.0	1.2	2.8
EYH-36	3,157	54.0	58.0	3.0	148.3	66.0	1.0	4.3	2.9
EYH-39	2,209	52.0	55.0	3.0	143.2	63.0	1.0	1.2	2.7
EYH-46	2,987	53.0	56.0	4.0	145.0	64.2	1.0	1.0	2.7
EYH-49	2,807	53.0	56.0	3.0	152.0	64.0	1.0	1.2	2.8
EYH-51	2,974	53.0	56.0	3.0	157.0	63.0	1.0	1.7	2.3
EYH-52	2,917	53.0	56.0	4.0	151.0	67.0	1.0	1.0	2.8
EYH-53	2,882	54.0	57.0	3.0	150.0	65.0	1.0	1.2	2.5
EYH-54	2,667	52.0	54.0	2.0	144.2	63.0	1.0	1.2	2.8
EYH-55	3,341	52.0	56.0	4.0	155.0	70.0	1.0	1.1	2.7
EYH-56	2,278	53.0	56.0	3.0	146.0	65.0	1.0	1.2	2.8
EYH-57	3,049	54.0	57.0	4.0	152.0	69.0	1.0	1.2	3.0
EYH-58	3,087	53.0	57.0	3.0	149.0	67.0	1.0	1.4	3.2
EYH-59	3,678	53.0	56.0	2.0	155.0	70.0	1.0	1.3	3.1
EYH-60	3,510	52.0	55.0	3.0	156.0	68.0	1.0	1.7	2.9
Local check	3,799	53.0	56.0	3.0	154.2	65.0	1.0	1.2	3.0
LSD	638	1.6	1.6	0.9	8.2	5.9	0.0	0.1	0.1
Mean	3,143	53.0	56.1	3.1	150.0	65.8	1.0	1.4	2.7

Note: GY = grain yield, DP = days to anthesis, DS = days to silking, ASI = anthesis silking interval, PHT = plant height, EHT = ear height, EPP = number of ears per plant, PA = plant aspect, EA = ear aspect For plant and ear aspect; 1 = excellent phenotypic appeal, 2 = good phenotypic appeal, 3 = average phenotypic appeal, 4 = below-average phenotypic appeal, 5 = poor phenotypic appeal.

Regarding flowering traits, extra-early maturing varieties took fewer days to reach anthesis and silking with mean values of 51.5 days (DP) and 54.9 days (DS), compared to early maturing varieties, with mean values of 53.0 days for anthesis and 56.1 days for silking (Tables 5−6). In terms of plant morphology, early maturing hybrids exhibited taller plants and ears than extra-early maturing varieties, with better plant aspect ratings. Despite these differences, the number of ears per plant was similar for both maturity groups. This morphological and phenological differentiation between early and extra-early maturing varieties provides insights into their yield performance. Early maturing varieties, being later to maturity, had higher plant and ear heights, which likely contributed to their higher grain yields compared to extra-early maturing varieties. This trend can be attributed to the longer duration of growth for early maturing hybrids, allowing them to accumulate more biomass. The increased plant and ear height provides a structural advantage for enhanced grain production, as supported by previous studies that have shown a positive correlation between plant height and grain yield (Hussain *et al*., 2010; Bello *et al*., 2012; Pedersen *et al*., 2022). Longer duration hybrids, such as the early maturing varieties in this study, typically have more time to develop a larger plant structure, leading to better kernel filling and heavier grain weight. This is consistent with findings by Gambín *et al*. (2007), Hussain *et al*. (2011), and Bello *et al*. (2012), which demonstrated that hybrids with a longer growing period tend to accumulate more biomass, leading to improved yield outcomes. In contrast, extra-early maturing hybrids, while advantageous for regions requiring shorter crop cycles, reach maturity faster, limiting their time for biomass accumulation and grain development.

Principal Component Analysis

Table 7 presents the results of the PCA conducted on agronomic traits of maize hybrids evaluated across six environments in Nigeria. The traits were analyzed for two groups: extra-early maturing and early maturing hybrids. The eigenvalues for the early maturing group ranged from 0 to 2.24, with the proportion of variance ranging from 0.00% to 28.05%. For the extra-early maturing varieties, the eigenvalues ranged from 0.00 to 2.64, while the proportion of variance ranged from 0.00% to 32.99%. In both maturity groups, only the first four principal components were retained due to their eigenvalues being greater than 1 and their proportion of variance being around 9% or higher, which is typically considered significant (Jain and Patel, 2016; Olakojo *et al*., 2021). These first four components explained over 80% of the total variance, suggesting that they were sufficient to describe the majority of the variability in agronomic traits for both early and extra-early maturing hybrids. The loadings of individual variables in each principal component were calculated to understand their contribution to the PCs, with loadings greater than 0.3 or less than -0.3 considered meaningful (Jain and Patel, 2016).

For the extra-early maturing hybrids, the first principal component (PC1) explained 32.99% of the total variance and was positively correlated with traits such as days to silking, ear height, and plant height. The second principal component (PC2) accounted for 18.17% of the variance, showing a strong positive association with days to anthesis, plant aspect, and ear aspect. The third principal component (PC3) explained 16.50% of the variance and was notably associated with the anthesis silking interval and plant aspect, while PC4 contributed 12.70% of the variance, primarily associated with grain yield and days to anthesis. For the early maturing hybrids, PC1 explained 28.05% of the total variance, with strong positive loadings for days to silking and days to anthesis. The PC2 accounted for 21.77% of the variance and was positively associated with plant height and ear height. The PC3 explained 17.67% of the variance, with grain yield and ear aspect being significant contributors. The PC4 contributed 13.86% of the variance, with a strong negative association with the anthesis silking interval and a positive correlation with the plant aspect.

The above PCA results revealed key insights into the agronomic traits contributing to variability in maize hybrids across different maturity groups. For both hybrid groups, flowering time traits (days to silking and days to anthesis) were significant contributors to either PC1 or PC2, indicating their consistent influence across different maturity categories. Plant height and ear height were also major contributors to variability, underscoring their importance in maize hybrid performance. Additionally, the plant aspect was a major determinant of variability in extra-early maturing varieties, while the ear aspect was significant in early maturing groups. The identified traits should be prioritized in the maize improvement program.

Table 7 Eigen value, variance and eigenvectors for agronomic traits of maize hybrids evaluated across 6 environments in Nigeria

Character	Extra-early maturing				Early maturing			
	PC1	PC2	PC3	PC4	PC1	PC2	PC3	PC4
GY (kg/ha)	-0.06	-0.32	0.28	0.75	-0.16	0.25	0.67	0.21
DP (day)	0.24	0.55	-0.24	0.46	0.50	-0.32	0.12	-0.05
DS (day)	0.47	0.29	0.35	0.00	0.57	-0.15	0.33	-0.18
ASI (day)	0.28	-0.11	0.67	-0.30	0.07	0.23	0.21	-0.79
PHT (cm)	0.44	0.06	-0.31	-0.02	0.14	0.61	0.01	0.27
EHT (cm)	0.55	-0.06	-0.14	-0.11	0.33	0.59	-0.03	0.03
EPP (no)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PA (1–5)	-0.20	0.57	0.41	0.15	0.30	-0.20	0.28	0.47
EA (1–5)	-0.33	0.41	-0.07	-0.33	0.42	0.11	-0.55	0.06
Eigenvalue	2.64	1.45	1.32	1.02	2.24	1.74	1.41	1.11
Variance (%)	32.99	18.17	16.50	12.70	28.05	21.77	17.67	13.86
Cumulative variance (%)	32.99	51.16	67.67	80.36	28.05	49.82	67.49	81.36

Note: GY = grain yield, DP = days to anthesis, DS = days to silking, ASI = anthesis silking interval, PHT = plant height, EHT = ear height, EPP = number of ears per plant, PA = plant aspect, EA = ear aspect For plant and ear aspect; 1 = excellent phenotypic appeal, 2 = good phenotypic appeal, 3 = average phenotypic appeal, 4 = below-average phenotypic appeal, 5 = poor phenotypic appeal.

Hybrids Adaptation to Test Environments

The “Which-Won-Where” polygon view of the GGE biplot illustrates the grain yield performance of 19 extra-early maturing hybrids and 1 local check across 6 environments (Figure 1). Similarly, Figure 2 shows the biplot view for grain yield of 20 early maturing hybrids and 1 local check across 6 environments in the Southern Guinea Savannah of Nigeria. Together, the two principal components (PC1 and PC2) accounted for 85.83% and 81.02% of the total variation in grain yield for early and extra-early maturing varieties, respectively.

In the “Which-Won-Where” polygon view, the genotype positioned at the vertex (endpoint) of the polygon closest to the environment point, signifies the top-performing genotype in that specific environment (Yan and Tinker, 2006). Early maturing hybrid EHY-21 (G4) emerged as the highest yielding in environments E2 (Lapai 2017), E5 (Ilorin 2017), and E6 (Lapai 2016), while EYH-17 (G2) recorded the highest yield in environments E1 (Ilorin 2016), E3 (Mokwa 2017), and E4 (Ballah 2016) (Figure 1). Similarly, extra-early maturing hybrid EEYH-25 (G1) achieved the highest yield in environments E4 (Ilorin 2016), E5 (Lapai 2016), and E6 (Mokwa 2016), while EEYH-54 (G19) emerged as the top yielder in E1 (Kishi 2017), E2 (Omu-Aran 2017), and E3 (Ilorin 2017). Considering their consistent high-yield performance across multiple environments, early maturing hybrids EHY-21 and EHY-17, as well as extra-early maturing hybrids EEHY-25 and EEHY-54, demonstrated broad adaptation.

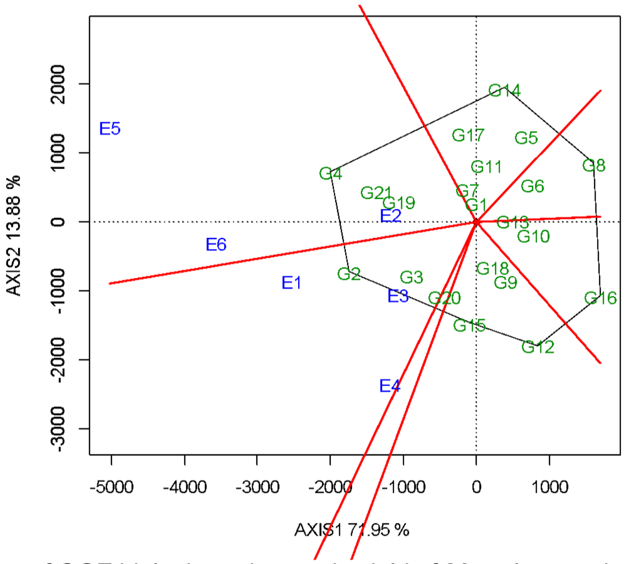

Figure 1 Polygon view of GGE biplot based on grain yield of 20 early maturing multiple stress tolerant maize hybrids and 1 local check evaluated across 6 environments in Nigeria. G1 = EYH-16, G2 = EYH-17, G3 = EYH-19, G4 = EYH-21, G5 = EYH-23, G6 = EYH-24, G7 = EYH-36, G8 = EYH-39, G9 = EYH-46, G10 = EYH-49, G11 = EYH-51, G12 = EYH-52, G13 = EYH-53, G14 = EYH-54, G15 = EYH-55, G16 = EYH-56, G17 = EYH-57, G18 = EYH-58, G19 = EYH-59, G20 = EYH-60, G21 = Check-1, E1 = Ilorin 2016, E2 = Lapai 2017, E3 = Mokwa 2017, E4 = Ballah 2016, E5 = Ilorin 2017, E6 = Lapai 2016.

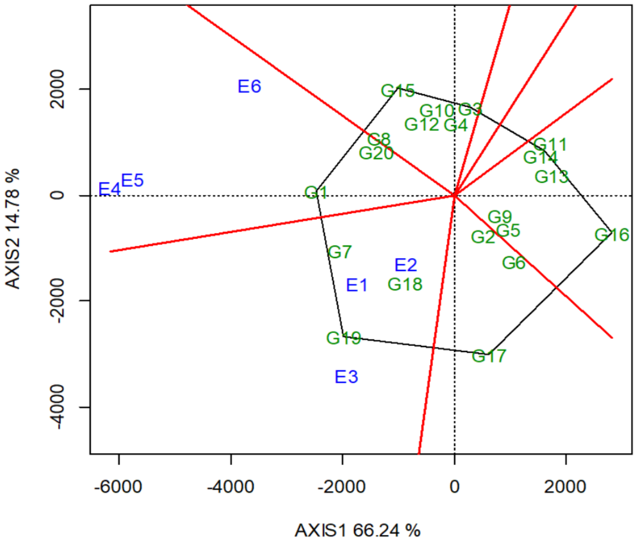

Figure 2 Polygon view of GGE biplot based on grain yield of 19 extra-early maturing multiple stress tolerant maize hybrids and 1 local check evaluated across 6 environments in Nigeria. G1 = EEYH-25, G2 = EEYH-30, G3 = EEYH-32, G4 = EEYH-36, G5 = EEYH-37, G6 = EEYH-40, G7 = EEYH-41, G8 = EEYH-42, G9 = EEYH-44, G10 = EEYH-45, G11 = EEYH-46, G12 = EEYH-47, G13 = EEYH-48, G14 = EEYH-49, G15 = EEYH-50, G16 = EEYH-51, G17 = EEYH-52, G18 = EEYH-53, G19 = EEYH-54, G20 = Check, E1 = Kishi 2017, E2 = Omu-Aran 2017, E3 = Ilorin 2017, E4 = Ilorin 2016, E5 = Lapai 2016, E6 = Mokwa 2016.

Mean Performance vs Stability of the Maize Hybrids Across the Test Environments

In the GGE biplot (Figures 3–4), the single-arrowed line represents the average environment coordinate (AEC) axis, indicating the direction of higher mean grain yield. Hybrids positioned further along this axis exhibited higher mean grain yield across the test environments. The line without an arrow separated hybrids with below-average mean grain yield from those with above-average mean grain yield. Hybrid stability was assessed by their projections onto the line representing the average-tester coordinate axis (single-row line), with shorter projections indicating greater stability (consistent performance) across environments (Yan and Tinker, 2006). Among the early maturing varieties, G2 (EYH-17) and G4 (EYH-21) demonstrated the highest mean grain yield, with EYH-17 being the most stable hybrid with the highest yield performance. For the extra-early maturing varieties, G19 (EEYH-54), G1 (EEYH-25), and G7 (EEYH-41) showcased the highest mean grain yield. However, while EEYH-54 had the highest mean grain yield, its performance was highly unstable across environments. Conversely, EEYH-25 emerged as the most stable hybrid with the highest mean grain yield.

The GGE biplot analysis highlighted EYH-17, an early maturing hybrid, and EEYH-25, an extra-early maturing hybrid, as the top performers in mean grain yield and stability. Both hybrids exhibited superior yields in three different environments, demonstrating broad adaptability. Their ability to perform well under multiple stresses, including drought, fluctuating soil fertility, and pests, positions them as reliable choices for local farmers seeking consistent high yields (Badu-Apraku *et al*., 2015; Konate *et al*., 2023). For seed companies, the commercial potential of these hybrids is enhanced by their demonstrated high yield and stability. Seed companies can market these hybrids as reliable products that meet the needs of both smallholder and large-scale farmers, thereby improving market penetration and profitability.

Discriminativeness vs. Representativeness of Test Environments

Discriminativeness refers to a test environment's ability to effectively differentiate between genotypes based on their performance, indicated by the vector length in the biplot. Longer vectors signify higher discriminating power (Yan *et al*., 2007). Conversely, representativeness gauges an environment's ability to represent the broader mega-environment, determined by the angle between the test environment and the AEC (Badu-Apraku *et al*., 2011). Smaller angles signify greater representativeness, while larger angles suggest less representativeness.

In the GGE biplot for early maturing varieties, the test environments were divided into two mega-environments (Figure 5). Environments E5 (Ilorin 2016), E6 (Lapai 2016), and E2 (Lapai 2017) formed the first mega-environment due to their strong correlation, indicated by small angles of <90° among them. Environments E1 (Ilorin 2016), E3 (Mokwa 2017), and E4 (Ballah 2016) constituted the second mega-environment. Analyzing vector length, environments E2 and E3 in mega-environments 1 and 2, respectively, had relatively short vectors, indicating lower discriminative power. Environments E6 and E1 were both discriminative and representative, while E4 and E5 were discriminative but non-representative.

Similarly, for the extra-early maturing varieties, the test environments were divided into two mega-environments (Figure 6). Environments E6 (Mokwa 2016), E5 (Lapai 2016), and E4 (Ilorin 2016) constituted the first mega-environment, while E1 (Kishi 2017), E2 (Omu-aran 2017), and E3 (Ilorin 2017) formed the second mega-environments. Environments E1 and E2 from the second mega-environment displayed relatively short vector lengths, indicating lower discriminatory power. Conversely, environments E4 and E5 from the first mega-environment were the most discriminating and representative, while E6 and E3 were discriminative but non-representative.

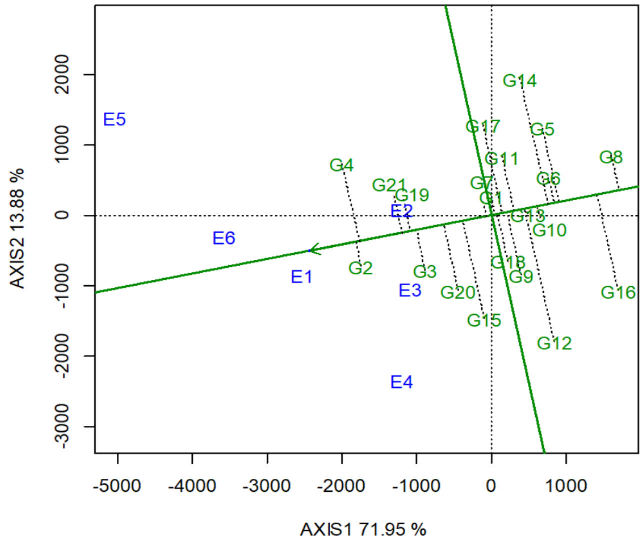

Figure 3 Mean versus stability view of GGE biplot showing the mean performance and stability of 20 early maturing multiple stress tolerant maize hybrids and 1 local check evaluated across 6 environments in Nigeria. G1 = EYH-16, G2 = EYH-17, G3 = EYH-19, G4 = EYH-21, G5 = EYH-23, G6 = EYH-24, G7 = EYH-36, G8 = EYH-39, G9 = EYH-46, G10 = EYH-49, G11 = EYH-51, G12 = EYH-52, G13 = EYH-53, G14 = EYH-54, G15 = EYH-55, G16 = EYH-56, G17 = EYH-57, G18 = EYH-58, G19 = EYH-59, G20 = EYH-60, G21 = Check-1, E1 = Ilorin 2016, E2 = Lapai 2017, E3 = Mokwa 2017, E4 = Ballah 2016, E5 = Ilorin 2017, E6 = Lapai 2016.

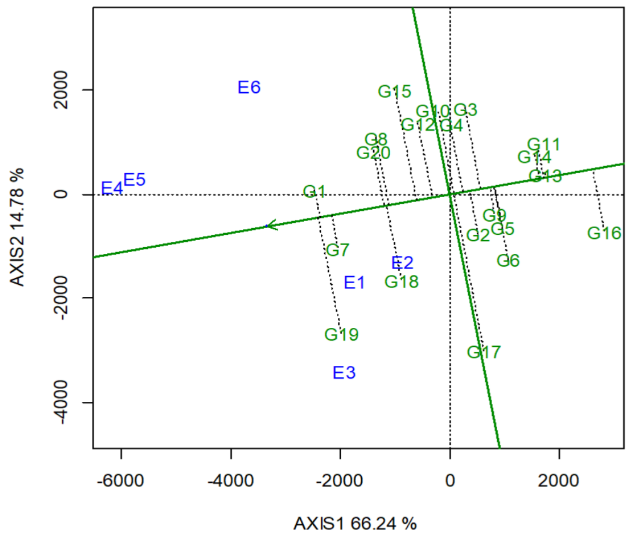

Figure 4 Mean versus stability view of GGE biplot showing the mean performance and stability of 19 extra-early maturing multiple stress tolerant maize hybrids and 1 local check evaluated across 6 environments in Nigeria. G1 = EEYH-25, G2 = EEYH-30, G3 = EEYH-32, G4 = EEYH-36, G5 = EEYH-37, G6 = EEYH-40, G7 = EEYH-41, G8 = EEYH-42, G9 = EEYH-44, G10 = EEYH-45, G11 = EEYH-46, G12 = EEYH-47, G13 = EEYH-48, G14 = EEYH-49, G15 = EEYH-50, G16 = EEYH-51, G17 = EEYH-52, G18 = EEYH-53, G19 = EEYH-54, G20 = Check, E1 = Kishi 2017, E2 = Omu-Aran 2017, E3 = Ilorin 2017, E4 = Ilorin 2016, E5 = Lapai 2016, E6 = Mokwa 2016.

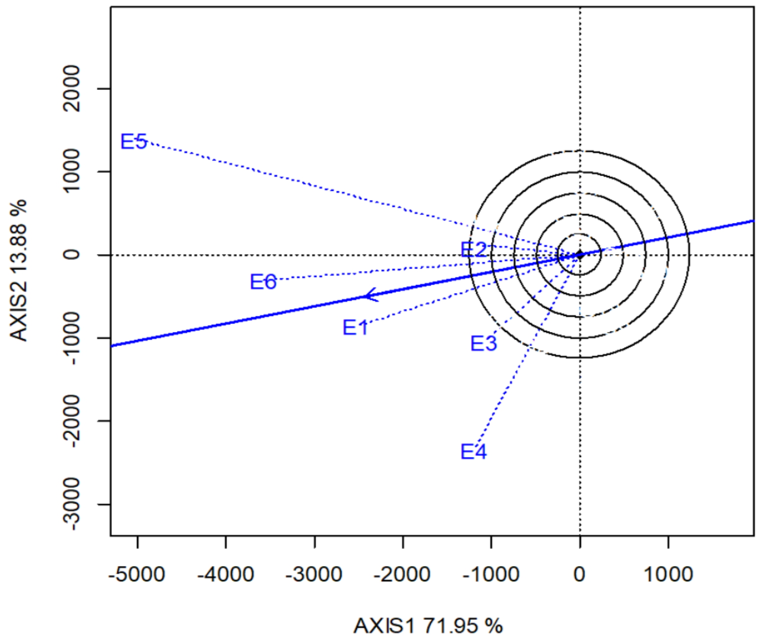

Figure 5 Vector view of GGE biplot showing ideal environments based on their discriminating power and representativeness. E1 = Ilorin 2016, E2 = Lapai 2017, E3 = Mokwa 2017, E4 = Ballah 2016, E5 = Ilorin 2017, E6 = Lapai 2016.

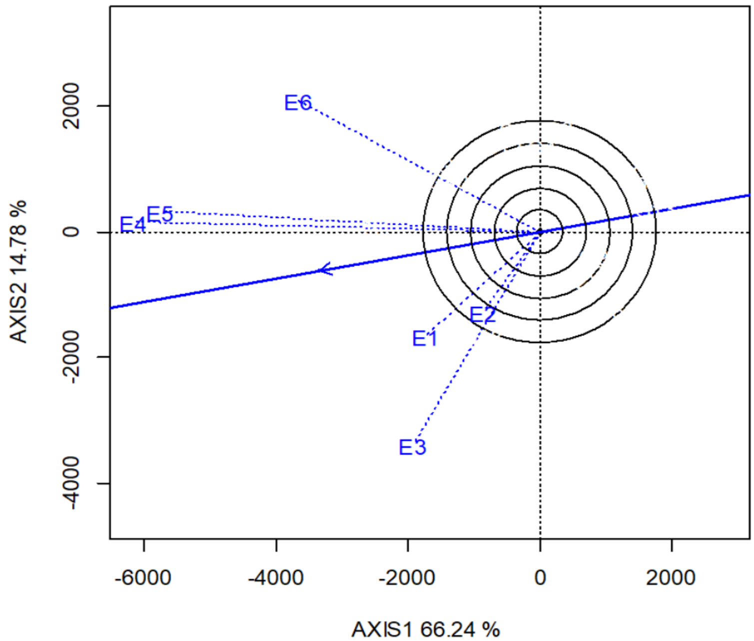

Figure 6 Vector view of GGE biplot showing ideal environments based on their discriminating power and representativeness. E1 = Kishi 2017, E2 = Omu-Aran 2017, E3 = Ilorin 2017, E4 = Ilorin 2016, E5 = Lapai 2016, E6 = Mokwa 2016.

The purpose of test environment evaluation is to determine the ideal environments for effectively identifying superior genotypes in a mega-environment (Yan and Tinker, 2006; Badu-Apraku *et al*., 2011). Discriminating but non-representative test environments are valuable for selecting specifically adapted genotypes when the test environments can be categorized into mega-environments. Test environments with short vectors (non-discriminating) are less useful as they offer limited discriminating information about genotypes (Yan *et al*., 2007). In this study, Lapai 2016 and Ilorin 2016 consistently emerged as the most discriminating and representative environments in GGE biplot analysis for both early and extra-early maturing varieties. Hence, they are considered the ideal environments for evaluating either early or extra-early maturing varieties and selecting superior hybrids with broad adaptation.

CONCLUSIONS

This study identified Lapai 2016 and Ilorin 2016 as the ideal test environments for selecting superior early and extra-early maturing maize hybrids due to their representative and discriminating nature. Through GGE biplot analysis, early maturing hybrid EYH-17 and extra-early maturing hybrid EEYH-25 emerged as the most stable hybrids with the highest yield performance across all test environments. These hybrids present significant benefits to both local farmers and seed companies in the region. For farmers, they offer reliable, high-yielding options that are resilient to multiple stresses, thereby improving food security and economic stability. For seed companies, these hybrids represent commercially viable products that can meet the diverse needs of both smallholder and large-scale farmers. Further evaluations across multiple seasons and a broader range of environmental conditions, including on-farm assessments, are recommended to affirm their yield potential and suitability for commercialization in Nigeria. Additionally, flowering time, plant height, and ear height should be prioritized in breeding programs to enhance the breeding value of maize.

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