Selcuk Journal of Agriculture and Food Sciences
https://dergipark.org.tr/tr/pub/selcukjafsci
Research Article

(2025) 39(1), 208-228 DOI:10.15316/SJAFS.2025.018 e-ISSN: 2458-8377 Selcuk J Agr Food Sci

Yield Stability and Agronomic Performance of Late-Maturing Pro-Vitamin A Maize in Southwest Nigeria Using GGE Biplot Analysis

Adewole Taiwo Akintunde[1,*], **Oloruntoba Olatayo Olakojo**[2], **Kolawole Gbemavo Godonu**[3]
Samuel A. Olakojo[1], **Omolayo Johnson Ariyo**[4]

[1]Institute of Agricultural Research and Training, Maize Improvement Programme, Moor Plantation, Ibadan, Oyo State, Nigeria

[2]University of Ilorin, Faculty of Agriculture, Department of Agronomy, Ilorin, Kwara State, Nigeria

[3]Lagos State University of Science and Technology, Ikorodu, Lagos State, Nigeria

[4]Federal University of Agriculture, Abeokuta, Ogun State, Nigeria

HIGHLIGHTS

- Variations in environmental conditions lead to significant annual fluctuations in maize yield performance.
- GGE biplot analysis was effectively used to assess genotype stability and performance.

Abstract

Maize is one of the most essential cereal crops grown across the major agroecological zones of Nigeria, both in terms of production and consumption. However, significant differences in soil properties and climatic conditions have led to wide fluctuations in the yield performance of maize genotypes annually, making the study of genotype by environment interactions crucial for plant breeders. Given the crop's importance as a staple food in Sub-Saharan Africa, this study evaluated the yield performance and stability of open-pollinated maize genotypes (OPVs) across diverse agroecological environments in Nigeria over two cropping seasons (2019 and 2020). In 2019 and 2020, fourteen open-pollinated cultivars were examined in three sites utilizing a Randomized Complete Block Design (RCBD) with three replications. The commercial check entry (3.73 t ha^{-1}) and the local check variety (3.68 t ha^{-1}) yielded far less than the genotype with the maximum grain yield, which produced 4.24 t ha^{-1}. The tested genotypes and the commercial check exhibited greater stability than the local check. Results indicated that the genotypes AFLATOXIN SYN-YF2 and PVA SYN 13 demonstrated both high yield and stability, making them valuable resources for breeding programs focused on developing improved maize varieties for small-scale farmers in Nigeria, many of whom have limited access to commercial maize hybrids. Additionally, locations - Ibadan'19 and Orin-Ekiti'20 emerged as the most discriminating and representative test environments for maize selection. The study underscores the need for breeding programs to prioritize genotypes with short anthesis-silking intervals (ASI), moderate plant and ear heights, and strong disease resistance for enhanced yield stability. These findings provide critical insights for maize breeders and small-scale farmers, promoting sustainable maize production in Nigeria amid changing climatic conditions.

Keywords: Genotype by environment (G x E); environments; open pollinated variety (OPV); stability; *Zea mays* L.

Citation: Akintunde AT, Olakojo OO, Godonu KG, Olakojo SA, Ariyo OJ (2025). Yield stability and agronomic performance of late-maturing pro-vitamin a maize in Southwest Nigeria using GGE biplot analysis. *Selcuk Journal of Agriculture and Food Sciences*, 39(1), 208-228. https://doi.org/10.15316/SJAFS.2025.018

***Correspondence:** akintundeadewole@gmail.com

Received date: 23/11/2024
Accepted date: 19/03/2025

1. Introduction

Maize is a major food security crop in Sub-Saharan Africa (SSA) and other developing world regions, providing sustenance for millions of people (FAOSTAT 2021). The significance of maize in the diet of Nigerians has compelled researchers to focus more on enhancing the productivity of new maize varieties through breeding and agronomic evaluation under a wide range of climatic variables, including moisture stress. This effort is to generate high-yielding, stable varieties, and nutritionally acceptable maize genotypes for farmers with limited resources to adopt, for enhanced yield and improved standard of living.

Maize (*Zea mays* L.) is a critical component of Nigeria's food security and economy, with production reaching 12.75 million metric tons in 2021 (Statista 2023). Although maize production grew at an annual rate of 4.2% between 2010 and 2020, yields have remained stagnant at 1.7 t/ha since 2017, significantly lower than those of South Africa (4.9 t/ha) and Ethiopia (4.2 t/ha) (Wossen et al. 2023). This yield gap underscores the need for improved agricultural practices and innovations to enhance productivity. Furthermore, conventional maize varieties often lack sufficient micronutrient content, which is critical for human health, especially in rural regions where food supplements are scarce. By raising the amounts of vital vitamins and minerals in staple crops, biofortification can assist in solving this issue in a more sustainable and cost-effective manner(Avnee et al. 2023). Notably, provitamin A maize can provide more than 50% of the recommended dietary vitamin A intake (Goredema-Matongera et al. 2021). Furthermore, studies indicate that its consumption effectively improves body vitamin A stores, similar to supplementation (Gannon et al. 2014). However, the adoption of biofortified crops depends on several factors, including government policies and resource availability (Onyeneke et al. 2019).

Vitamin A is essential for vision, immune function, and growth (Huang et al. 2018). Its deficiency leads to severe health consequences, such as night blindness, increased susceptibility to infections, and stunted growth (Song et al. 2023; Villamor et al. 2000). Additionally, a study in Uganda found a significant correlation between VAD and growth failure in preschool children (Ssentongo et al. 2020), reinforcing the importance of adequate vitamin A intake in early childhood development. In many resource-poor regions, micronutrient deficiencies are exacerbated by chronic gastrointestinal infections, which impair vitamin A absorption. This issue is further compounded by zinc deficiency, as zinc plays a crucial role in vitamin A absorption and transport (Hotz et al. 2012; Rahman et al. 2002). About 30% of children under five suffer from VAD, which is still a serious public health problem worldwide and accounts for 2% of these children's fatalities (Hodge and Taylor 2023; Wirth et al. 2017). Therefore, vitamin A-biofortified maize in Nigeria has the potential to significantly decrease vitamin A deficiency, improving overall health and nutrition for communities vulnerable to micronutrient deficiencies.

Despite the success of maize hybrids in Nigeria, their adoption by smallholder farmers remains limited due to high production costs, technical complexity, and the need for substantial inputs, which contrast with the affordability and ease of managing open-pollinated varieties (Eze et al. 2020). However, enhanced maize populations and the hybrids derived from them offer valuable alternatives to traditional single-cross hybrids and serve as crucial resources for developing new inbred lines (Kutka 2011). These improved populations provide a broad genetic base that can be harnessed to create inbred lines with desirable traits, contributing to sustained genetic gains in maize breeding (Yong et al. 2019). This genetic diversity is essential for addressing environmental stresses and evolving pest and disease pressures. Additionally, population-derived hybrids demonstrate better adaptation to specific agroecological conditions, with some outperforming commercial hybrids in challenging environments, presenting viable alternatives for improving productivity and resilience (Eze et al. 2020).

Finding stable, high-yielding maize hybrids is challenging due to the significant influence of genotype-environment interaction (GEI), which is magnified by environmental changes (Akcura et al. 2011). Grain yield, a crucial agronomic and economic trait, typically shows GEI, complicating efforts to achieve yield stability (Fan et al. 2007; Bocianowski et al. 2024). GEI plays a significant role in genotype performance, particularly in environments with variable climatic conditions (Sibiya et al. 2012). Shrestha (2013) examined the stability of six high-quality protein maize (QPM) varieties over two years at eleven sites. The results showed that environmental factors had a highly significant impact, while GEI was not significant in the Combined

ANOVA. Similarly, Abakemal et al. (2016) evaluated the yield stability of QPM single-cross hybrids in tropical highlands, finding significant differences among hybrids and environments, with some hybrids showing stable performance across diverse conditions. Dosho et al. (2022) assessed QPM hybrids under varying soil nitrogen conditions, revealing significant GEI effects, which helped identify stable genotypes. Bankole et al. (2023) found that environmental factors strongly influenced grain yield, with certain QPM hybrids demonstrating superior stability and adaptability under rainfed conditions.

It's vital to introduce, assess, and modify potential germplasm or hybrids to satisfy the expanding need for maize to meet its growing demand. The GGE biplot is a valuable tool for predicting increased performance and grain yield stability across new situations in this respect (Daemo and Ashango 2024). The GGE biplot analysis is beneficial as it enables the prediction of average genotype yield in a specific environment and helps identify the most stable genotype for a given location (Yan 2014). G x E studies can maximize grain yield potential while lowering production costs by identifying the optimal site for each genotype (Oyekunle et al. 2017). Research by Kumar et al. (2024) showed that GGE biplot analysis effectively evaluates yield stability and adaptability of various maize hybrids, allowing for better prediction of their performance across different environmental conditions. This is because maize cultivars vary greatly in yield depending on the cultivation area (Olakojo and Iken 2001; Guo et al. 2022). As a result, maize varieties must be assessed for their ability to adapt to different agroecological zones and production potential (Olaoye 2009). To better adapt germplasm to varied production environments, it's crucial to understand the link between yield testing locations (Trethowan et al. 2001; Bassa and Goa 2016). This study looked at the yield performance and stability of 14 open-pollinated varieties in South-west Nigeria, and the connections between test environments in various agro-ecologies. Late-maturing maize genotypes were favored for this research for their higher yield potential. Their extended growth phases enhance biomass accumulation and optimize resource use, leading to greater grain yield.

2. Materials and Methods

Field trials were conducted in 2019 and 2020 at the Teaching and Research Farms of the Institute of Agricultural Research and Training (IAR&T), Ibadan (7°23'10''N, 3°50'21''E; and 1250 – 1500 mm annual rainfall), Eruwa (7°53'04''N, 3°41'70''E; and 1200 – 1300 mm annual rainfall), and Orin-Ekiti (7°49'48''N, 5°14'24''E; and 1333.2 - 1400 mm annual rainfall) in Nigeria. Thirteen elite open-pollinated maize varieties derived from late-maturing pro-vitamin A breeding populations of IITA were evaluated. A total of fifteen entries, comprising thirteen OPV maize genotypes, one commercial check, and one farmer's check, were assessed for grain yield performance across six different environments under optimal growing conditions in 2019 and 2020.

The six environments were characterized by variations in total rainfall and planting periods (Appendix 1). Trials conducted under optimal conditions were established during the main maize planting season, coinciding with adequate rainfall. The environmental conditions varied significantly concerning water availability, while differences in seasonal rainfall distribution contributed to location-specific variations. The general strategy of the conducted trial series was to assess genotype performance across multiple environments within a short period, thereby capturing agroecological variability that would typically require multi-year testing.

The experiment was laid out in a Randomized Complete Block Design (RCBD) with three replications per location. Each experimental unit consisted of two-row plots, each measuring 5 meters in length with a row spacing of 0.75 m and an intra-row spacing of 0.50 m. Three seeds were initially sown per hill, and approximately two weeks after emergence, the seedlings were thinned to two per hill to achieve a final plant population density of about 53,333 plants ha^{-1}. Weed control was achieved through the application of pre-and post-emergence herbicides. Paraquat (0.75 kg a.i. ha^{-1}) and Atrazine (2.5 kg a.i. ha^{-1}) were applied immediately after planting. Additional hand weeding was carried out as necessary to ensure effective weed management throughout the growing season. The fertilizer application followed a two-step process. A basal application of NPK 20-10-10 was carried out at a rate of 80 kg N ha^{-1}, 40 kg P_2O_5 ha^{-1}, and 40 kg K_2O ha^{-1} three weeks after planting. This was followed by a top-dressing of Urea (46-0-0) six weeks after planting to ensure adequate nitrogen availability for optimal crop growth and grain development.

2.1. Collection of Agronomic and Yield Data

A scale of 1 to 5 is used to rate diseases, and the data collected includes days to 50 % anthesis, days to 50 % silking, plant and ear heights (cm), root lodging (number of plants leaning more than 30^o from vertical), stalk lodging (stalks broken at or below highest ear node), ear aspect, and number of plants harvested. All the data and scoring in this study were according to Badu-Apraku et al. 2012.

Table 1. Description of Open-pollinated genotypes tested across three locations in 2019 and 2020.

Code	Entry Name	Source
1	ACR.91 SUWAN 1-SR C1	IITA
2	AFLATOXIN SYN-YF2	IITA
3	F2SCA1413-12	IITA
4	F2SCA1413-36	IITA
5	F2TWLY100121	IITA
6	F2TWLY100123	IITA
7	F2TWLY131211	IITA
8	F2TWLY131228	IITA
9	F2TWLY13124	IITA
10	Local Check	Farmer’s Variety
11	PVA SYN HGA C2	IITA
12	PVA SYN HGB C0	IITA
13	PVA SYN HGB C2	IITA
14	Sammaz 52(PVA SYN 13)	IITA
15	PVA SYN-6	IITA

2.2. Statistical Analysis

To ascertain if the G x E interaction effects were significant, the data were first examined independently for each site before being merged and examined for grain yield across locations using PROC GLM in SAS (SAS version 9.2). The standard error of the mean (S.E.) at P <0.05 and the New Duncan Multiple Range Test at P <0.05 were used to differentiate the means. The grain yield data were then subjected to GGE biplot analysis to ascertain the stability of grain yield as well as the genotype response pattern assessed in each of these environments.

2. Results

3.1. Analysis of Variance

The combined ANOVA showed that genotypes performed differently (P <0.05) from one environment to another, showing the diversity of the test environments (E). For grain yield, however, the associations of genotype x location x year were not significant. Except for root lodging, all fifteen of the maize genotypes showed highly significant (P <0.01) location impacts on grain yield and agronomic traits (Table 2). Genotypes also varied significantly (P <0.01) for grain yield, husk cover, anthesis-silking interval, and stalk lodging. Similarly, days to silking, plant height, and stalk lodging were significant at P <0.05. On the contrary, there were no significant differences among the genotypes for days to pollen shed, plant height, ear height, plant and ear aspect, ear per plant, root lodging, ear rot, blight syndrome rating, and *Curvularialunata* disease syndrome rating. Genotype x location effects were not significantly different except for husk cover, rust, and curvularia in this study (Tables 2 and 3). Furthermore, genotype x year interaction was not significant for all measured traits except for plant height and curvularia leaf spot ratings which differed significantly at P <0.01. On the other hand, location x year interaction was significant for all measured traits (P <0.01) except for ear aspect and ear rot. Genotype x location x year interactions were however observed to be highly significant for plant height and curvularia. This suggests that climatic variables of the test environment in the two years had a pronounced effect only on the expression of most of the traits studied (Tables 2 and 3), while the interactive effects of G x Y were significant for plant height and curvularia leaf spot.

3.2. Performance of the Maize Genotypes for Grain Yield and Agronomic Traits in 2019 and 2020

The grain yield of open-pollinated maize genotypes (OPVs) varied significantly across Eruwa, Ibadan, and Orin-Ekiti during the 2019 and 2020 cropping seasons, largely influenced by prevailing weather conditions (Appendix I). Mean grain yield was higher in 2019, with Ibadan recording the highest yield (4.14 t ha^{-1}), followed by Eruwa (3.77 t ha^{-1}) and Orin-Ekiti (3.27 t ha^{-1}) (Table 4). However, yields declined in 2020, with the sharpest reduction in Eruwa (2.80 t ha^{-1}), followed by Ibadan (3.78 t ha^{-1}) and Orin-Ekiti (3.69 t ha^{-1}). These decreases corresponded with reduced annual rainfall across all locations. The highest yielding genotypes recorded 4.24 and 4.23 t ha^{-1} for F2TWLY100123 and ACR.91 Suwan 1-SR C1 respectively. The two highest-ranking genotypes were statistically different from the checks (Commercial and local check). The highest-yielding check was the commercial check PVA SYN-13 (Sammaz 52) with a mean grain yield of 3.73 t ha^{-1} while the local check had a mean grain yield of 3.68 t ha^{-1}. The highest mean yields across the three locations were from F2TWLY100123 and ACR.91 Suwan 1-SR C1 with 4.24 and 4.23 t ha^{-1} respectively while the lowest yielding genotype was PVA SYN HGB C0 with 2.89 t ha^{-1}.

The intricate interplay between genotype and environment on the grain yield of the examined maize varieties, as illustrated in Table 4, reveals a striking truth: all genotypes exhibited superior yields in the year 2019 when juxtaposed with their performance in 2020. This divergence can likely be attributed to the protracted moisture stress and the erratic distribution of rainfall that marred the agricultural landscape of 2020 across various locations. In Eruwa, rainfall dropped from 1,777.39 mm in 2019 to 1,013.50 mm in 2020, while Ibadan experienced a decline from 1,774.61 mm to 1,104.50 mm, and Orin-Ekiti from 2,099.94 mm to 1,497.97 mm. The most pronounced reduction in Eruwa aligned with its largest yield drop, indicating that moisture stress played a critical role in limiting productivity. The temperature remained relatively stable, with minor fluctuations. In Eruwa, the mean temperature was 27.92°C in 2019 and 27.42°C in 2020, while Ibadan recorded 27.17°C in 2019 and 27.08°C in 2020. Orin-Ekiti had the lowest temperatures, at 25.67°C in 2019 and 25.42°C in 2020. However, relative humidity (RH) increased in 2020 despite lower rainfall, rising from 71.17% to 76.25% in Eruwa and from 73.08% to 77.17% in Ibadan. This higher RH may have elevated disease pressure, particularly fungal infections like maize rust and gray leaf spot, contributing to further yield reductions. Wind speed also increased slightly in 2020. In Orin-Ekiti, it rose from 7.46 kmph in 2019 to 7.60 kmph in 2020, while in Eruwa, it changed from 7.42 kmph to 7.27 kmph. Stronger winds during the flowering and grain-filling stages may have led to lodging and reduced pollination efficiency, further impacting yields.

Varietal performance varied across locations. ACR.91 SUWAN 1-SR C1 recorded the highest mean yield (4.23 t ha^{-1}), performing exceptionally well in Eruwa (6.04 t ha^{-1} in 2019). However, its yield declined significantly in 2020, particularly in Eruwa (3.78 t ha^{-1}) and Orin-Ekiti (2.99 t ha^{-1}). F2TWLY100123 also performed well, averaging 4.24 t ha^{-1} across locations. In contrast, PVA SYN HGB C0 had the lowest mean yield (2.89 t ha^{-1}), suggesting lower adaptability to environmental fluctuations, particularly under drier conditions. The local check variety exhibited moderate performance (3.68 t ha^{-1}), indicating adaptation to local conditions but without significant yield advantages over improved OPVs.

Table 5 presents the mean performance of the maize genotypes across locations for the measured traits. Days to Anthesis ranged from 56.22 to 58.28 days, while days to silking ranged between 59.06 and 61.17 days, resulting in an anthesis-silking interval (ASI) of 1.78 to 3.89 days. The shortest ASI of 1.78 days was observed in PVA SYN HGB C2. Conversely, F2TWLY100123 exhibited the longest ASI of 3.89 days. Significant variation in plant and ear height was observed among genotypes. ACR.91 SUWAN 1-SR C1 attained the tallest stature at 155.89 cm, with the highest ear placement of 69.78 cm. In contrast, PVA SYN HGB C2 recorded the shortest plants at 140.28 cm. The lowest ear height was noted in PVA SYN-6 at 58.06 cm, which may confer better lodging resistance. Plant aspect (PA) and ear aspect (EA) scores varied across genotypes, with lower values indicating more desirable traits. PA scores ranged from 1.94 to 2.56, while EA scores ranged from 1.89 to 2.44.

Table 2. Mean Square values from the combined analysis of Variance (ANOVA) of grain yield and yield-related traits of fifteen OPVs evaluated across three locations in 2019 and 2020

Source of Var.	Df	Days to pollen	Days to Silking	ASI	Plant Height	Ear Height	Husk Cover	Plant Aspect	Ear Aspect	EPP	Grain Yield
Rep	2	4.25	1.05	5.61	2964.28	338.54	0.09	1.30	0.68	0.001	1.82
Year	1	2632.03**	2011.74**	41.61**	87480.00**	39240.83**	22.53**	4.80**	0.004	0.023**	6.23**
Genotype	14	5.53	7.31*	6.33**	512.89	147.80	0.22**	0.47	0.45	0.001	2.50**
Location	2	817.60**	341.14**	102.78**	6920.78**	1231.30**	27.91**	7.78**	21.54**	0.064**	11.00**
Gen. x Loc.	28	3.64	3.56	3.49	336.55	179.99	0.17*	0.51	0.52	0.002	1.13
Gen. x Year	14	4.81	4.01	3.83	701.02**	199.17	0.15	0.26	0.22	0.002	1.07
Loc. x Year	2	489.43**	201.16**	69.00**	5503.01**	404.68*	17.63**	2.80**	0.18	0.066**	11.04**
G x L x Y	28	2.93	6.73*	4.13	464.55*	181.88	0.13	0.53	0.36	0.002	0.95
Error	178	3.23	4.12	2.93	300.92	132.27	0.10	0.45	0.44	0.01	0.91
Means		57.40	60.36	2.96	141.54	62.10	1.68	2.27	2.14	0.99	3.58
CV (%)		3.13	3.36	57.76	12.26	18.52	18.46	29.71	31.00	4.57	26.66

* = P*<0.05, *** = P*<0.01, ASI = Anthesis-Silking-Interval, EPP = Number of ears per plant respectively*

Table 3. Mean Square values from the combined analysis of variance of lodging and disease reaction of fifteen OPVs evaluated across three locations in 2019 and 2020

Source of Variation	df	Root Lodging	Stalk Lodging	Ear Rot	Streak	Rust	Blight	Curvularia
Rep	2	0.03	0.07	0.41	0.05	0.01	0.29	0.01
Year	1	0.37	0.37	0.30	0.37	0.45**	1.07**	9.26**
Genotype	14	0.09	0.31**	0.58	0.26**	0.13**	0.20	0.09
Location	2	0.08	3.13**	9.14**	1.66**	1.08**	3.21**	16.48**
Gen. x Loc.	28	0.18	0.15	0.48	0.14	0.09*	0.25	0.08*
Gen. X Year	14	0.27	0.08	0.48	0.16	0.07	0.21	0.12**
Loc. x Year	2	3.51**	1.08**	1.03	2.50**	1.78**	3.61**	6.71**
G x L x Y	28	0.15	0.19*	0.62	0.15	0.10**	0.13	0.11**
Error	178	0.22	0.13	0.56	0.11	0.06	0.17	0.05
Means		1.20	1.21	1.46	1.19	1.10	1.31	1.53
CV (%)		39.14	29.46	51.45	28.21	21.52	31.61	14.92

* = P <0.05, ** = P <0.01 *respectively*

Table 4. Mean grain yield (t ha^{-1}) of the OPVs maize in 2019 and 2020 cropping season

	Eruwa		**Ibadan**		**Orin-Ekiti**		
Varieties	**2019**	**2020**	**2019**	**2020**	**2019**	**2020**	**Mean**
ACR.91 SUWAN 1-SR C1	6.04	3.78	4.27	4.33	3.98	2.99	4.23
AFLATOXIN SYN-YF2	3.62	3.34	4.00	3.35	3.61	4.05	3.66
F2SCA1413-12	3.55	2.29	3.60	4.55	2.67	3.26	3.32
F2SCA1413-36	3.17	2.36	3.79	3.74	3.48	4.55	3.52
F2TWLY100121	3.79	2.42	5.38	4.03	3.29	4.21	3.85
F2TWLY100123	3.67	3.78	5.97	3.98	3.34	4.68	4.24
F2TWLY131211	3.60	3.05	4.48	3.53	3.98	2.80	3.57
F2TWLY131228	3.50	2.68	4.53	3.51	3.03	4.66	3.65
F2TWLY13124	3.74	2.83	3.67	3.28	3.42	4.98	3.65
Local Check	4.31	3.12	4.45	3.61	3.44	3.13	3.68
PVA SYN HGA C2	3.54	2.64	3.02	4.42	2.68	3.30	3.27
PVA SYN HGB C0	3.17	2.25	3.25	3.32	2.27	3.04	2.89
PVA SYN HGB C2	3.03	2.17	2.99	3.61	3.31	3.59	3.12
Sammaz 52	4.07	2.52	5.50	3.94	3.49	2.86	3.73
PVA SYN-6	3.75	2.72	3.24	3.55	3.06	3.32	3.27
Mean	3.77	2.80	4.14	3.78	3.27	3.69	3.58
CV (%)	30.68		28.38		30.29		30.68
S.E (0.05)	0.11		0.12		0.11		0.07

Table 5. Mean performance of fifteen (15) genotypes for grain yield and agronomic traits across three locations over two (2) years.

Entry Name	**Grain Yield ($t\ ha^{-1}$)**	**Days to Anthesis (days)**	**Days to Silking (days)**	**ASI (days)**	**Plant height (cm)**	**Ear Height (cm)**	**Plant Aspect (1-5)**	**Ear Aspect (1-5)**	**Husk cover (1-5)**	**Streak (1-5)**	**Blight (1-5)**	**Curv. (1-5)**	**Rust (1-5)**
ACR.91 SUWAN 1-SR C1	4.23a	56.22d	59.06d	2.83abcde	155.89a	69.78a	1.94c	1.89b	1.56cd	1.11cde	1.33abcd	1.50bc	1.22a
AFLATOXIN SYN-YF2	3.66abc	56.83cd	59.67bcd	2.83abcde	144.56ab	61.89b	2.22abc	2.06ab	1.78ab	1.00e	1.28abcd	1.50bc	1.00b
F2SCA1413-12	3.32bcd	57.72abc	61.06a	3.33abc	138.28bc	61.89b	2.28abc	2.06ab	1.72bc	1.22bcd	1.33abcd	1.61ab	1.06b
F2SCA1413-36	3.52bc	57.78abc	60.83ab	3.06abcd	142.44bc	59.06b	2.33abc	1.89b	1.72bc	1.06de	1.50a	1.56bc	1.06b
F2TWLY100121	3.85ab	57.56abc	61.00ab	3.44ab	142.44bc	64.00ab	2.22abc	2.11ab	1.61bcd	1.28abc	1.44ab	1.50bc	1.11ab
F2TWLY100123	4.24a	57.00bcd	60.89ab	3.89a	141.56bc	62.83ab	2.11bc	1.89b	1.67bcd	1.11cde	1.39abc	1.44c	1.06b
F2TWLY131211	3.57bc	57.28abcd	60.61abc	3.33abc	131.67c	58.22b	2.44ab	2.22ab	1.72bc	1.11cde	1.11d	1.56bc	1.06b
F2TWLY131228	3.65abc	57.83abc	61.17a	3.33abc	143.61b	64.22ab	2.39ab	2.28ab	1.72bc	1.33ab	1.39abc	1.50bc	1.00b
F2TWLY13124	3.65abc	57.33abcd	60.61abc	3.28abc	141.94bc	62.89ab	2.06bc	2.06ab	1.67bcd	1.17bcde	1.22bcd	1.44c	1.06b
Local Check	3.68abc	58.06ab	60.33abcd	2.28cde	145.94ab	61.50b	2.39ab	2.22ab	1.94a	1.44a	1.28abcd	1.72a	1.22a
PVA SYN HGA C2	3.27bcd	57.83abc	60.44abc	2.61bcde	141.22bc	60.72b	2.11bc	2.06ab	1.67bcd	1.11cde	1.17cd	1.50bc	1.11ab
PVA SYN HGB C0	2.89d	57.28abcd	59.28cd	2.00de	142.28bc	60.83b	2.56a	2.44a	1.61bcd	1.22bcd	1.33abcd	1.56bc	1.11ab
PVA SYN HGB C2	3.12cd	58.28a	60.06abcd	1.78e	140.28bc	63.56ab	2.39ab	2.28ab	1.56cd	1.17bcde	1.22bcd	1.50bc	1.22a
Sammaz 52	3.73abc	57.28abcd	60.17abcd	2.89abcde	138.11bc	62.06b	2.28abc	2.06ab	1.78ab	1.33ab	1.33abcd	1.56bc	1.00b
PVA SYN-6	3.27bcd	56.67cd	60.22abcd	3.56ab	135.78bc	58.06b	2.28abc	2.22ab	1.500d	1.11cde	1.39abc	1.56bc	1.22a
Mean	3.58	57.40	60.36	2.96	141.54	62.10	2.27	2.14	1.68	1.19	1.31	1.53	1.10
S.E. (0.05)	0.07	0.29	0.24	0.13	1.71	1.06	0.05	0.05	0.04	0.02	0.03	0.03	0.02
CV (%)	30.68	8.34	6.61	73.44	19.80	28.07	32.81	35.67	35.67	33.63	36.58	34.02	27.32

ACR.91 SUWAN 1-SR C1 recorded the lowest EA score of 1.89, suggesting superior ear quality. Husk cover scores varied between 1.50 and 1.94, with PVA SYN-6 exhibiting the lowest score of 1.50, indicative of better husk protection against pest damage and grain deterioration.

Genotypic differences in disease resistance were also observed. Rust, blight, and streak scores ranged from 1.00 to 1.50, with most genotypes exhibiting moderate resistance. Notably, the local check variety had higher blight and streak scores, indicating greater susceptibility compared to improved open-pollinated varieties (OPVs). AFLATOXIN SYN-YF2 displayed the best resistance to maize streak virus, with a streak score of 1.00. Blight scores ranged from 1.11 to 1.50, with the lowest susceptibility recorded in F2TWLY131211. Rust resistance scores varied between 1.00 and 1.22, while curvularia leaf spot scores ranged from 1.44 to 1.72, indicating varying levels of tolerance among the genotypes. Grain yield performance varied significantly among genotypes across three locations over two years. The mean grain yield ranged from 2.89 t ha^{-1} (PVA SYN HGB C0) to 4.24 t ha^{-1} (F2TWLY100123), with an overall mean of 3.58 t ha^{-1}. The highest-yielding genotypes were F2TWLY100123 (4.24 t ha^{-1}) and ACR.91 SUWAN 1-SR C1 (4.23 t ha^{-1}). Conversely, PVA SYN HGB C0 exhibited the lowest yield at 2.89 t ha^{-1}. The coefficient of variation (CV) for grain yield was 30.68%, indicating moderate variability among genotypes.

3.3. GGE Biplot Analysis

The environment-vector view of the GGE biplot showing similarities among test environments is presented in Figure 1. The environment vectors and the cosine of the angle between the vectors show a strong crossover GE and explain a very large GE considering the wide degree existing between Environment E and F. Dissimilarity in discriminating the genotypes is measured by the distance between two environments and this has successfully regrouped 6 test environments into 3. Environment A, C, D, and E formed a group, while Environment B and F are separately each in a class of its own.

Figure 2 shows the biplot of grain yield performance of 15 OPV maize tested in six environments. Varieties, ACR.91 SUWAN 1-SR C1, F2SCA1413-36, F2TWLY100123, F2TWLY131228, PVA SYN HGA C2, PVA SYN HGB C0, and PVA SYN HGB C2 were located at the vertex cultivar and represent the best-performing genotypes in terms of grain yield at the environments that fall within their sectors (Yan et al.2005). They are equally considered to be highly responsive having the farthest distance from the biplot origin. However, genotypes positioned within the polygon are therefore considered less responsive (Yan and Rajcan, 2002).

Figure 3 shows the discrimination and representativeness view of the GGE biplot showing discriminating ability and representativeness of test environments. It was observed that Orin-Ekiti'20 and Ibadan'19 both had a long vector length followed by Eruwa'19, while Orin-Ekiti'19, Eruwa'20, and Ibadan'20 had a short vector length. Moreover, Ibadan'19 has the smallest angle with the Average Environment Axis (AEA), followed by Orin-Ekiti'19 and Eruwa'20. (In Figure 3, It should be explained what the long or short vectors and the wide or narrow angles mean). The biplot's computational framework facilitated the visualization of environment vector lengths, which are directly proportional to the standard deviation within each environment and reflect the environment's ability to distinguish genotypes. As a result, test environments with longer vectors demonstrated a stronger capacity for genotype differentiation, whereas shorter vectors provided minimal or no useful information regarding genotype variations (Yan et al. 2007). The mean coordinates of all test environments were represented within the mean environment, depicted as a small circle at the tip of the arrow along the line (Fig. 4). The axis extending from the biplot's origin to the mean environment is referred to as the axis of the mean environment (AME). Test environments with shorter angles relative to the AME were considered the most representative (Yan and Tinker, 2006).

The average-environment coordination (AEC) view showing the mean performance and stability of 15 PVA maize is presented in Figure 4. The circle surrounding the image represented genotype yield and stability, assessed using the mean environment coordination (MEC) approach. The axis of the ideal environment was defined by a line passing through both the ideal environment and the biplot's origin. The optimal environment was identified by analyzing the principal component scores of each habitat, with the arrow pointing toward the highest genotypic value. The coordinate axis, perpendicular to the abscissa, indicated genotypes with lower stability, primarily influenced by genotype-environment interactions. Additionally, this axis differentiated genotypes with performance records above and below the average (Yan and Tinker, 2006). Results show that F2TWLY100123 followed by ACR.91 SUWAN 1-SR C1, PVA SYN-13, and F2TWLY100121 were the highest-yielding varieties. However, genotypes PVA SYN HGB C0, PVA SYN HGB C2, and PVA SYN HGA C2 performed below average with PVA SYN HGB C0 being the least yielding variety. In addition, lines PVA SYN HGB C2, PVA SYN HGB C0, AFLATOXIN SYN-YF2, and PVA SYN-13? had a short length of projection while ACR.91 SUWAN 1-SR C1, F2SCA1413-36, F2TWLY100123, F2TWLY131228 and F2TWLY13124 had a long length.

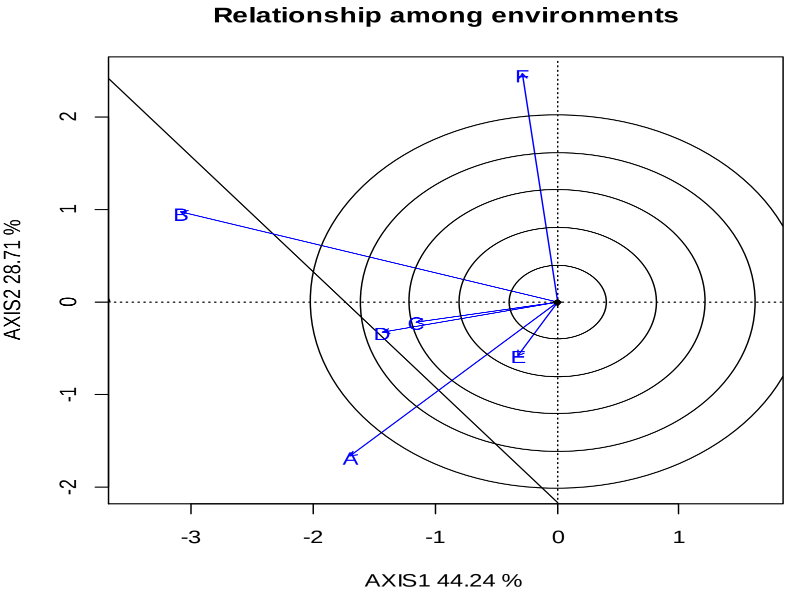

Figure 1. The environment-vector view of the GGE biplot showing similarities among test environments in discriminating PVA maize. Where A – Eruwa 2019; B – Ibadan 2019; C – Orin Ekiti 2019; D – Eruwa2020; E – Ibadan 2020; F - Orin Ekiti 2020

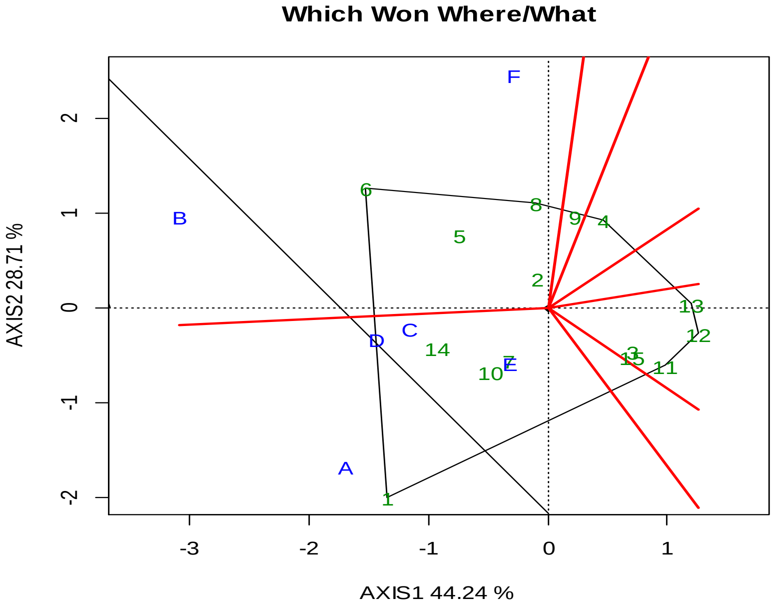

Figure 2. GGE biplot representing the which-won-where graph indicating the yield rankings of 15 OPVs. Where A – Eruwa 2019; B – Ibadan 2019; C – Orin Ekiti 2019; D – Eruwa2020; E – Ibadan 2020; F - Orin Ekiti 2020

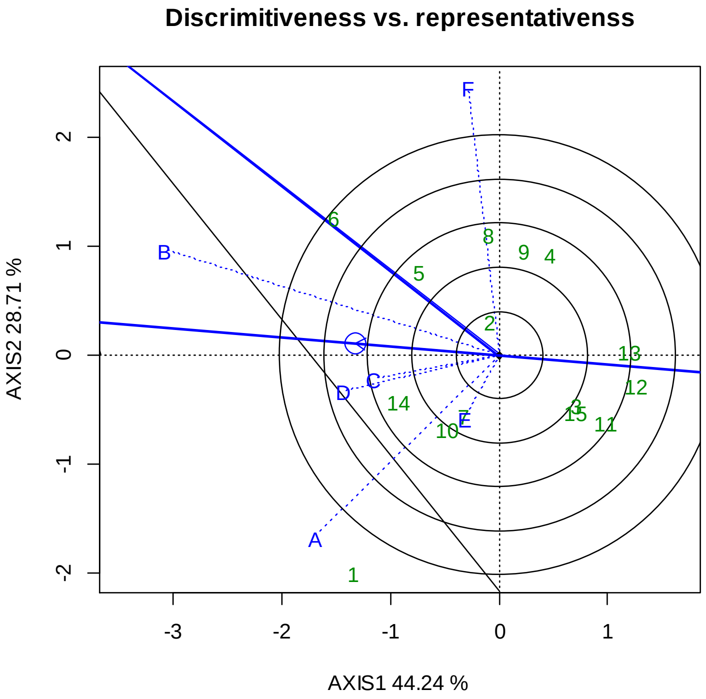

Figure 3. GGE biplot comparing 15 PVA OPVs evaluated according to the discriminating and representativeness of environments for grain yield (t ha -1). Where A – Eruwa 2019; B – Ibadan 2019; C – Orin Ekiti 2019; D – Eruwa 2020; E – Ibadan 2020; F - Orin Ekiti 2020

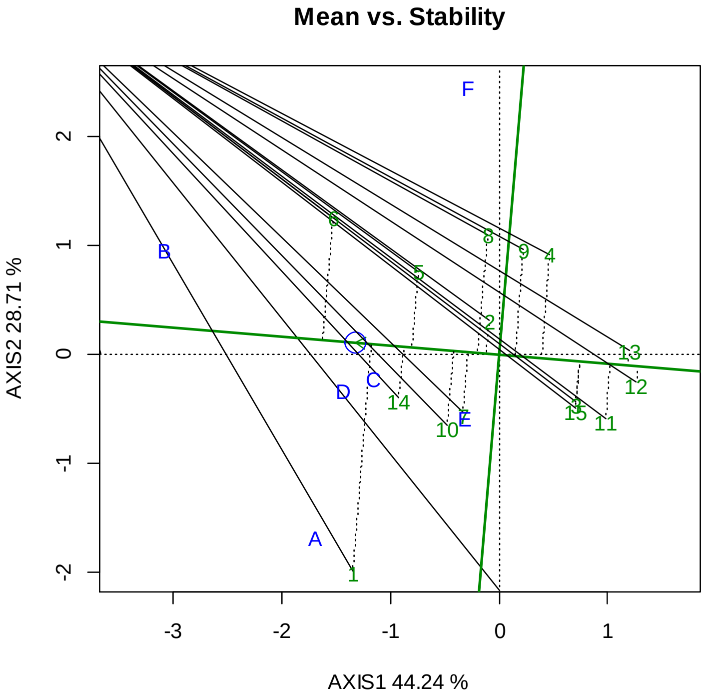

Figure 4. GGE biplot representing the 'mean vs. stability' indicating the yield rankings of 15 PVA OPVs and their respective production stabilities. Where A – Eruwa 2019; B – Ibadan 2019; C – Orin Ekiti 2019; D – Eruwa2020; E – Ibadan 2020; F - Orin Ekiti 2020;

3. Discussion

Comparing Nigeria's average maize production (1.7 t ha $^{-1}$) for the same period of years (1986–2011) with that of the United States (9.3 t ha^{-1}), it is relatively low (Olaniyan 2015; IITA 2020; Mani et al.2022). Since maize is an important staple food crop for the people of Sub-Saharan Africa, this has inspired breeding for high-yielding varieties of the crop (IITA 2009). Additionally, it is a widely distributed crop that is farmed by small-scale rural farmers. The goal of the current study was to assess maize varieties which are promising alternatives that were high-yielding, easily accessible, and affordable for use by small-scale farmers compared to expensive hybrid seeds.

The ongoing effects of climate change in the areas where subsistence farmers in Nigeria grow their crops have raised significant concerns, as the ideal conditions for production may increasingly be disrupted by erratic climate variations (Gaudin et al. 2015). The study was conducted in a range of environments that differed in terms of growing conditions, rainfall patterns, and various geographical and climatic factors. Assessing the yield stability of crops in diverse agroecosystems with high accuracy was highly emphasized by Mühleisen et al. (2014) and, therefore became imperative for optimum yield.

Different varieties of maize respond variably to environmental conditions, making it essential to improve stability in maize performance and select optimal genotypes for adaptation (Campos et al. 2006). Identifying ideal testing sites for superior and stable genotypes has become a key priority for maize breeders (Badu-Apraku et al. 2015a). The non-significant mean squares for grain yield in this study indicate remarkable stability in this trait across diverse testing environments. This stability suggests that a genotype showing promise in one locale is likely to perform well in other areas with similar agroecological characteristics. These findings align with Adu et al. (2013), who observed minimal genotype-by-environment (G × E) interactions among 54 maize genotypes across three sites in Ghana. Similarly, Ma et al. (2024) noted that while environmental factors significantly impacted yields, G × E interactions were not the dominant factor, emphasizing the need to select stable hybrids. Alam et al. (2022) echoed these conclusions, finding that environmental effects were notable, but G × E interactions were insignificant, indicating that certain hybrids perform consistently across various conditions.

The location's substantial mean square indicated that environmental factors significantly influenced the genetic potential of the genotypes. Koroma et al. (2017) similarly found that yield-limiting factors like minimum temperature, relative humidity, moisture stress, pests, and diseases largely impacted the genotype × environment interaction on maize yield. Do Couto et al. (2023) also observe that environmental variables accounted for a large portion of yield variation, emphasizing their influence on the genotypes' performance. Likewise, Ljubičić et al. (2023) reported that environmental factors predominantly determined yield variation, showing that maize genotype performance is highly dependent on the environmental context. These studies collectively highlight the substantial effect of environmental conditions on maize yield.

The anthesis-silking interval (ASI) is a critical trait in maize, as a prolonged ASI often leads to poor pollination and reduced kernel set, ultimately affecting grain yield (Bolaños and Edmeades 1996). The study revealed variations in ASI among genotypes indicating efficient pollination and a reduced risk of yield loss under stress conditions. On the other hand, long ASI could negatively impact grain filling. Similar findings by Araus et al. (2012) suggest that selecting genotypes with a short ASI enhances reproductive efficiency, particularly in drought-prone regions. Additionally, Tao et al. (2023) study demonstrated that overexpressing the ZmEXPA5 gene in maize reduced the ASI and improved grain yield under both drought and well-watered conditions.

Plant and ear heights influence lodging resistance and ease of mechanical harvesting (Xue et al. 2020). The observed differences in plant height among genotypes suggest varying genetic potentials for vegetative growth. The moderate ear heights observed in other genotypes suggest a balance between grain-filling potential and lodging resistance (Zhang et al. 2023). Taller plants have an advantage in capturing sunlight due to their elevated canopy, which can lead to increased photosynthesis and potentially higher yields. However, this increased height can make them more susceptible to lodging which is particularly problematic in high-wind environments (Stubbs et al. 2023). Conversely, shorter plants generally exhibit greater lodging resistance due to their reduced leverage and sturdier stature (Xue et al. 2020). This characteristic makes them more suitable for high-density planting systems, as they can maintain structural integrity even when planted closely together

Plant aspect, ear aspect, and husk cover are critical traits influencing maize grain quality and storability. Husk integrity is particularly vital in protecting ears from environmental stresses and biological threats. Drought and high temperatures before tasseling can cause ear extension beyond the husk, increasing susceptibility to mold, insect damage, and bird predation, which degrade grain quality. Thus, selecting maize varieties with well-filled ears and tight husk cover is essential for maintaining grain integrity (Jiang et al. 2020). Disease resistance is a key factor in maize production, especially in regions prone to fungal and bacterial infections. The local check variety exhibited higher disease scores, indicating greater susceptibility than improved OPVs. Breeding for disease resistance enhances yield stability and reduces reliance on chemical control measures (Badu-Apraku and Akinwale 2011). Abera et al. (2021) demonstrated that certain OPVs exhibit superior grain yield and resistance to Turcicum leaf blight, highlighting the potential of breeding programs in developing resilient varieties. Berger et al. (2020) reported yield losses of 36% to 72% in susceptible hybrids due to Northern Leaf Blight (NLB), whereas resistant hybrids showed no significant reductions, underscoring the success of local breeding efforts. Moreover, utilizing diverse germplasm and advanced breeding technologies can mitigate yield losses and reduce dependency on chemical controls (Garoma et al. 2024). This study reinforces the importance of breeding for disease resistance to ensure yield stability and promote sustainable agricultural practices.

The significant variation in grain yield among the open-pollinated maize genotypes (OPVs) across the three locations (Eruwa, Ibadan, and Orin-Ekiti) and the two cropping seasons (2019 and 2020) underscores the crucial influence of environmental factors, particularly rainfall distribution. The higher mean grain yield recorded in 2019 compared to 2020 suggests that adequate and well-distributed rainfall played a pivotal role in supporting maize productivity (Lobell et al. 2011; Obour et al. 2022). Liu et al. (2021) study emphasized that both the amount and distribution of rainfall are crucial for optimizing grain yield and water use efficiency in maize cultivation. Furthermore, Mekonnen et al. (2023) study investigating the effects of planting dates and environmental factors on maize grain yield reported that erratic and inconsistent rainfall distribution poses a significant threat to maize production. Ibadan consistently recorded the highest yields across both years, possibly due to relatively favorable climatic conditions, including adequate soil moisture retention and stable temperatures (Kamara et al. 2020).

The sharp reduction in grain yield in 2020, particularly in Eruwa, aligns with the pronounced decline in rainfall, emphasizing moisture stress as a key limiting factor in maize productivity. The relationship between rainfall and yield decline corroborates findings from previous studies, which established that prolonged moisture stress at critical growth stages, such as flowering and grain filling, significantly reduces maize yield potential (Bänziger et al. 2000). The drastic decline in Eruwa’s annual rainfall corresponds with its substantial yield reduction, further validating the assertion that water availability is a fundamental determinant of maize performance (Campos et al. 2004; Bagula et al. 2022; Șimon et al. 2023).

Genotypic performance varied significantly across environments indicating that these genotypes possess favorable traits that enhance yield resilience under fluctuating climatic conditions (Badu-Apraku et al., 2015). Conversely, the lowest-yielding genotype exhibited lower adaptability, particularly under moisture-stressed conditions, suggesting that its genetic makeup may not confer sufficient drought tolerance (Edmeades et al., 1999). The commercial check (PVA SYN-13) and local check mean grain yield across the years indicate that while improved varieties offer superior yield advantages, locally adapted genotypes may still perform moderately under prevailing conditions. This agrees with Ficiciyan et al. (2018) research which found that while modern varieties typically yield more, their performance declines under harsh conditions. In contrast, traditional landraces remain resilient and widely cultivated by small-scale farmers, especially in nutrient-poor soils.

Moreover, besides rainfall, relative humidity (RH) and wind speed also influenced yield performance. The unexpected rise in RH in 2020, despite lower rainfall, may have increased disease pressure, particularly fungal infections like maize rust and gray leaf spot, which thrive in high humidity potentially reducing maize yields. Likewise, stronger winds, especially in Orin-Ekiti, may have caused lodging and reduced pollination efficiency, negatively impacting grain development (Tollenaar and Wu 1999; Akintibu et al. 2023). Although temperature fluctuations were minor, their interaction with other climatic factors likely influenced yield outcomes, highlighting the complexity of genotype-environment interactions (Chapman and Edmeades 1999; Hudson et al. 2022).

Close association existing among environments within the same group implies that similar results could be obtained from other environments within the group as regards the genotypes. In other words, since test environments A, C, D, and E are considered to be correlated, therefore one of these environments can ably represent the others without losing much information which could result in a possible reduction in the cost of testing material across environments. The long vector length observed for Orin-Ekiti'20 and Ibadan'19 positions these two environments as the most discriminating while Orin-Ekiti'19, Eruwa'20, and Ibadan'20 were the least discriminating as a result of short distances to the biplot origin. This suggests that less discriminating environments (Orin-Ekiti'19, Eruwa'20, and Ibadan'20) are not strongly associated with those with long vector test environments (Orin-Ekiti'20 and Ibadan'19) and should be treated as independent test environments (Badu-Apraku et al. 2011). Similarly, Yan and Tinker (2006) discussed the utility of GGE biplot analysis in evaluating test environments and genotypes. They noted that environments with longer vector lengths in the biplot are more discriminating, whereas those with shorter vectors are less discriminating and may not effectively distinguish between genotypes. Including such environments in multi-environment trials might not contribute valuable insights into genotype performance. Orin-Ekiti'20 and Ibadan'19 being the most discriminating environments are also said to be most informative among other environments. The small angle observed between environments (Ibadan'19, Orin-Ekiti'19, and Eruwa'20) and AEA shows that they can be regarded as the most representative of the six tested environments (Yan et al. 2007). This implies that any of these three test environments can represent the other.

Yan and Tinker (2006) suggest that test environments that are both discriminating and representative are effective for selecting genotypes that are generally well-adapted. By focusing on such environments, breeders can identify genotypes that not only perform well in specific conditions but also exhibit stable performance across diverse environments. Similarly, Yan et al. (2007) emphasize the importance of selecting test environments that combine high discriminating power with representativeness. They argue that this approach enhances the efficiency of breeding programs by ensuring that selected genotypes are likely to perform consistently across various target environments.

The selection of genotypes that are precisely suited, on the other hand, may benefit from environments that are discriminating but not representative, especially if the target environments can be divided into discrete mega-environments (Yan and Tinker 2006). Nonetheless, it can also help remove unstable genotypes in a single environment; it should not be utilized for selection. Consequently, PVA maize cultivars that are especially suited to this climate may be chosen using Orin-Ekiti'20, which is discriminating but non-representative. Moreover, Ibadan'19 which appears to be both discriminating and representative, is indicative of its effectiveness as a test environment for selecting varieties that are generally adaptable.

Genotypes PVA SYN HGB C2, PVA SYN HGB C0, AFLATOXIN SYN-YF2, and PVA SYN-13 were the most stable as a result of the short length of their projection (Yan et al. 2005). While ACR.91 SUWAN 1-SR C1 and F2TWLY100123 were high-yielding but appeared less stable. In this study, PVA SYN-13 and AFLATOXIN SYN-YF2 are regarded as stable and high-yielding PVA maize varieties due to their short projection distance and above-average mean performance.

4. Conclusions

The findings of this study emphasize the importance of developing and promoting maize genotypes with enhanced drought tolerance and disease resistance to mitigate yield losses caused by erratic weather patterns.

The absence of significant genotype-by-environment (G × E) interactions for grain yield suggests that well-performing genotypes at one site are likely to be suitable for cultivation in other locations within the same agroecological zone. However, environmental factors still played a crucial role in genotype performance, underscoring the need for adaptive breeding strategies. Among the evaluated genotypes, AFLATOXIN SYN-YF2 and PVA SYN 13 demonstrated both high yield potential and stability, making them ideal for cultivation across multiple locations, including Eruwa, Ibadan, and Orin-Ekiti. Additionally, F2TWLY100123 and ACR.91 SUWAN 1-SR C1 exhibited strong adaptability and superior grain yield, particularly in moisture-limited environments, highlighting their potential for further breeding and large-scale adoption. Genotypes such as PVA SYN HGB C2 and F2TWLY131211, characterized by short anthesis-silking intervals (ASI) and moderate plant height, offer valuable traits for breeding drought-resilient maize varieties. To enhance maize productivity under changing climatic conditions, agronomic interventions such as moisture conservation practices, timely planting, and integrated disease management strategies should be prioritized. Future research should focus on the long-term impact of climatic variables on maize performance and explore breeding strategies that incorporate drought and disease resistance traits for sustainable production.

Furthermore, the observed variation in grain yield and agronomic traits provides valuable insights for breeding programs targeting high-yielding and stress-tolerant maize varieties. Given their promising performance, the evaluated genotypes warrant further testing for potential release to resource-limited farmers in southwestern Nigeria, contributing to improved food security and agricultural resilience in the region.

Author Contributions: Conceptualization, Akintunde Adewole, and Prof. Ariyo Omolayo; methodology – Prof. Olakojo Samuel; software, Olakojo Oloruntoba; validation, Akintunde Adewole, Olakojo Oloruntoba, and Prof. Olakojo Samuel; formal analysis, Olakojo Oloruntoba; investigation, Akintunde Adewole, and Godonu Kolawole; data curation, Akintunde Adewole, and Olakojo Oloruntoba; writing—original draft preparation, Akintunde Adewole; writing—review and editing, Akintunde Adewole, and Prof. Olakojo, Samuel.; supervision, Prof. Ariyo Omolayo and Prof. Olakojo Samuel. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: The authors appreciate the Maize Improvement Programme (MIP) of the International Institute of Tropical Agriculture (IITA), Ibadan, Oyo State, Nigeria for supporting this research through the provision of genetic materials.

Conflicts of Interest: The authors declare no conflict of interest.

References

Abakemal D, Shimelis H, Derera J (2016). Genotype-by-environment interaction and yield stability of quality protein maize hybrids developed from tropical-highland adapted inbred lines. *Euphytica,* 209: 757–769. https://doi.org/10.1007/s10681-016-1673-7

Abera N, Odong T, Kasozi, LC (2021). Phenotypic diversity and correlation coefficient analysis of open-pollinated maize varieties in Uganda. *Global Journal of Agricultural Research, 9*(1): 36–47. https://doi.org/10.37745/gjar.2013

Adu GB, Akromah R, Abdulai MS, Obeng-Antwi K, Kena AW, Tengan KML, Alidu H (2013). Assessment of genotype by environment interactions and grain yield performance of extra-early maize (*Zea mays* L.) hybrids. *Journal of Biology, Agriculture and Healthcare,* 3(12): 7-15.

Akcura M, Taner S, Kaya Y (2011). Evaluation of bread wheat genotypes under irrigated multi-environment conditions using GGE biplot analyses. *Agriculture,* 98: 35–40.

Akintibu TS, Oluwaranti A, Fakorede MAB (2023). The impacts of climatic variability on the grain yield performance of open-pollinated varieties (OPV) of maize in a rainforest location of Nigeria. *Journal of Agriculture and Ecology Research International, 24*(5): 28–36. https://doi.org/10.9734/JAERI/2023/v24i5539

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

Araus JL, Serret MD, Edmeades GO (2012). Phenotyping maize for adaptation to drought. *Frontiers in Physiology, 3*: 305. https://doi.org/10.3389/fphys.2012.00305

Avnee S, Sood S, Chaudhary DR, Jhorar P, Rana RS (2023). Biofortification: An approach to eradicate micronutrient deficiency. *Frontiers in Nutrition,* 10: 1233070. https://doi.org/10.3389/fnut.2023.1233070

Badu-Apraku B, Fakorede M, Oyekunle M, Akinwale R (2015). Genetic gains in grain yield under nitrogen stress following three decades of breeding for drought tolerance and *Striga* resistance in early maturing maize. *The Journal of Agricultural Science, 1*(4): 1–15. https://doi.org/10.1017/S0021859615000593

Bankole FA, Olajide OO, Olaoye G (2023). Performance and yield stability of quality protein maize (*Zea mays* L.) hybrids under rainfed condition. *Agriculture* (Poľnohospodárstvo), 69(2): 66–76. https://doi.org/10.2478/agri-2023-0006

Bassa D, Goa Y (2016). Performance evaluation and adaptation of improved maize (*Zea Mays* L) varieties for Highland of Alicho, Silti and Analemo Districts of Southern Ethiopia. *Journal of Natural Sciences Research,* 6(15): 28–32.

Badu-Apraku B, Akinwale R (2011). Identification of early-maturing maize inbred lines based on multiple traits under drought and low N environments for hybrid development and population improvement. *Canadian Journal of Plant Science, 91*(5), 931–942. https://doi.org/10.4141/cjps2011-024

Badu-Apraku B, Lum AF, Akinwale RO, Oyekunle M (2011a). Biplot analysis of diallel crosses of early maturing tropical yellow maize inbreds in stress and non-stress environments. *Crop Science,* 51: 173-188.

Badu-Apraku B, Fakorede MAB, Menkir A, Sanogo D (2012). Conduct and management of maize field trials. IITA, Ibadan, Nigeria. pp. 1-59.

Badu-Apraku B, Annor B, Oyekunle M, Akinwale RO, Fakorede MAB, Talabi AO, Akaogu IC, Melaku G, Fasanmade Y (2015a). Grouping of early maturing quality protein maize inbreds based on SNP markers and combining ability under multiple environments. *Field Crops Research,* 183: 169–183.

Bagula EM, Majaliwa JGM, Basamba TA, Mondo JGM, Vanlauwe B, Gabiri G, Tumuhairwe B, Mushagalusa GN, Musinguzi P, Akelo S (2022). Water use efficiency of maize (*Zea mays* L.) crop under selected soil and water conservation practices along the slope gradient in Ruzizi Watershed, Eastern D.R. Congo. *Land, 11*(10): 1833. https://doi.org/10.3390/land11101833

Bänziger M, Edmeades GO, Beck D, Bellon M (2000). Breeding for drought and nitrogen stress tolerance in maize: From theory to practice. *CIMMYT.*

Berger DK, Mokgobu T, de Ridder K, Christie N, Aveling TA (2020). Benefits of maize resistance breeding and chemical control against northern leaf blight in smallholder farms in South Africa. *South African Journal of Science, 116*(11–12), 1–7. https://doi.org/10.17159/sajs.2020/8286

Bocianowski J, Nowosad K, Rejek D (2024). Genotype-environment interaction for grain yield in maize (*Zea mays* L.) using the additive main effects and multiplicative interaction (AMMI) model. *Journal of Applied Genetics,*65: 653-664. https://doi.org/10.1007/s13353-024-00899-4

Bolaños J, Edmeades GO (1996). The importance of the anthesis-silking interval in breeding for drought tolerance in tropical maize. *Field Crops Research, 48*(1): 65–80. https://doi.org/10.1016/0378-4290(96)00036-6

Bouis HE, Saltzman A (2017). Improving nutrition through biofortification: a review of evidence from HarvestPlus, 2003 through 2016. *Global Food Security,* 12: 49–58. https://doi.org/10.1016/j.gfs.2017.01.009

Campos H, Cooper M, Habben JE, Edmeades GO, Schussler JR (2004). Improving drought tolerance in maize: A view from industry. *Field Crops Research, 90*(1): 19-34.

Campos H, Cooper M, Edmeades GO, Löffler C, Schussler JR, Ibañez M (2006). Changes in drought tolerance in maize associated with fifty years of breeding for yield in the U.S. Corn Belt. *Maydica,* 51: 369-381.

Chapman SC, Edmeades GO (1999). Selection improves drought tolerance in tropical maize populations: II. Direct and correlated responses among secondary traits. *Crop Science, 39*(5): 1315-1324.

Daemo BB, Ashango Z (2024). Application of AMMI and GGE biplot for genotype by environment interaction and yield stability analysis in potato genotypes grown in Dawuro Zone, Ethiopia. *Journal of Agriculture and Food Research,* 18(2): 1-9. https://doi.org/10.1016/j.jafr.2024.101287

Do Couto DP, Oliveira WB, de Oliveira JS, Guilhen JH, Bernardes CD, Posse SC, Ferreira MF, Ferreira A (2023). Analysis of the effect of the interaction of genotype and environment on the yield stability of maize varieties. genetic resources for breeding. *Agronomy,* 13(8): 1-15. https://doi.org/10.3390/agronomy13081970

Dosho BM, Ifie BE, Asante IK, Danquah EY, Zeleke H (2022). Genotype-by-environment interaction and yield stability for grain yield of quality protein maize hybrids under low and optimum soil nitrogen environments. *Journal of Crop Science and Biotechnology,* 25: 437–450. https://doi.org/10.1007/s12892-022-00143-7

Ebbisa A (2022). Mechanisms underlying cereal/legume intercropping as nature-based biofortification: A review. *Food Production, Processing and Nutrition,* 4(19): 1-17. https://doi.org/10.1186/s43014-022-00096-y

Edmeades GO, Bolaños J, Chapman SC, Lafitte HR, Bänziger M (1999). Selection improves drought tolerance in tropical maize populations: Gains in biomass, grain yield, and harvest index. *Crop Science, 39*(5): 1306-1315.

Eze CE, Akinwale RO, Michel S, Burstmayr H (2020). Grain yield and stability of tropical maize hybrids developed from elite cultivars in contrasting environments under a rainforest agro-ecology. *Euphytica,* 216: 1-13. https://doi.org/10.1007/s10681-020-02620-y

FAOSTAT (2021). FAO Stat. FAO, Rome. http://www.fao.org/faostat (access date: 12.04.2022)

Fan XM, Kang MS, Chen H, Zhang Y, Tan J, Xu C (2007). Yield stability of maize hybrids evaluated in multi-environment trials in Yunnan, China. *Agronomy Journal,* 99: 220-228.

Ficiciyan A, Loos J, Sievers-Glotzbach S, Tscharntke T (2018). More than yield: Ecosystem services of traditional versus modern crop varieties revisited. *Sustainability, 10*(8), 2834. https://doi.org/10.3390/su10082834

Gannon B, Kaliwile C, Arscott SA, Schmaelzle S, Chileshe J, Kalungwana N, Mosonda M, Pixley K, Masi C, Tanumihardjo SA (2014). Biofortified orange maize is as efficacious as a vitamin A supplement in Zambian children even in the presence of high liver reserves of vitamin A: A community-based, randomized placebo-controlled trial. *The American Journal of Clinical Nutrition, 100*(6): 1541–1550. https://doi.org/10.3945/ajcn.114.087379

Garoma B, Yadessa L, Tilahun B, Asefa G (2024). Comprehensive breeding approach for resistance to disease in crops: Research review. *Journal of Soil Science and Plant Physiology, 6*(3): 1-8. https://doi.org/10.36266/JSSPP/181

Gaudin ACM, Tolhurst TN, Ker AP, Janovicek K, Tortora C, Martin RC, Deen W (2015). Increasing crop diversity mitigates weather variations and improves yield stability. *PLoS ONE* 10(2): 1-20. https://doi.org/10.1371/journal.pone.0113261

Goredema-Matongera N, Ndhlela T, Magorokosho C, Kamutando CN, van Biljon A, Labuschagne M (2021). Multinutrient biofortification of maize (*Zea mays* L.) in Africa: Current status, opportunities, and limitations. *Nutrients, 13*(3): 1039. https://doi.org/10.3390/nu13031039

Guo S, Liu Z, Zhou Z, Lu T, Chen S, He M, Zeng X, Chen K, Yu H, Shangguan Y, Dong Y, Chen F, Liu Y, Qin Y (2022). Root System architecture differences of maize cultivars affect yield and nitrogen accumulation in Southwest China. *Agriculture,* 12: 1-14. https://doi.org/10.3390/agriculture12020209.

Hotz C, Chileshe J, Siamusantu W, Palaniappan U, Kafwembe E (2012). Vitamin A intake and infection are associated with plasma retinol among pre-school children in rural Zambia. *Public Health Nutrition, 15*(9): 1688–1696. https://doi.org/10.1017/S1368980012002731

Hodge C, Taylor C (2023). Vitamin A deficiency. In *StatPearls* [Internet]. StatPearls Publishing. Retrieved from https://www.ncbi.nlm.nih.gov/books/NBK567789/

Huang Z, Liu Y, Qi, G, Brand D, Zheng SG (2018). Role of vitamin A in the immune system. *Journal of Clinical Medicine, 7*(9): 258. https://doi.org/10.3390/jcm7090258

Hudson AI, Odell SG, Dubreuil P, Tixier MH, Praud S, Runcie DE, Ross-Ibarra J (2022). Analysis of genotype-by-environment interactions in a maize mapping population. *G3: Genes, Genomes, Genetics, 12*(3): jkac013. https://doi.org/10.1093/g3journal/jkac013

IITA (2009). Crops. http://www.iita.org (Access date: 01.05.2014).

IITA (2020). IITA-BIP sets record for maize production per hectare in Nigeria. https://www.iita.org/news-item/iita-bip-sets-record-for-maize-production-per-hectare-in-nigeria/ (access date:02.12.2021)

Koroma MS, Swaray M, Akromah R, Obeng-Antwi K (2017). Genotype by environment interaction and stability of extra-early maize hybrids (*Zea mays* L.) for yield evaluated under irrigation. *International Journal of Environment, Agriculture and Biotechnology,* 2: 2573-2580. https://doi.org/10.22161/ijeab/2.5.39.

Kutka F (2011). Open-Pollinated vs. hybrid maize cultivars. *Sustainability* 3: 1531–1554. https://doi.org/10.3390/su3091531

Kumar B, Choudhary M, Kumar P, Kumar S, Sravani D, Vinodhana NK, Kumar GS, Gami R, Vyas M, Jat BS, Dagla MC, Rakshit S (2024). GGE biplot analysis and selection indices for yield and stability assessment of maize (*Zea mays* L.) genotypes under drought and irrigated conditions. *Indian Journal of Genetics and Plant Breeding,* 84(02): 209–215. https://doi.org/10.31742/ISGPB.84.2.8

Jiang S, Zhang H, Ni P, Yu S, Dong H, Zhang A, Cao H, Zhang L, Ruan Y, Cui Z (2020). Genome-wide association study dissects the genetic architecture of maize husk tightness. *Frontiers in Plant Science,* 11:861. https://doi.org/10.3389/fpls.2020.00861

Kamara AY, Kamai N, Omoigui LO, Togola A, Onyibe JE (2020). *Guide to maize production in northern Nigeria*. International Institute of Tropical Agriculture (IITA).

Liu Y, Hou P, Huang G, Zhong X., Li, H, Zhao J, Li S, Mei X (2021). Maize grain yield and water use efficiency in relation to climatic factors and plant population in northern China. *Journal of Integrative Agriculture, 20*(12): 3156–3169. https://doi.org/10.1016/S2095-3119(20)63428-1

Ljubičić N, Popović V, Kostić M, Pajić M, Bude M, Gligorević K, Dražić M, Bižić M, Crnojević V (2023). Multivariate interaction analysis of *Zea mays* L. genotypes growth productivity in different environmental conditions. *Plants,* 12(11): 1-25.

Ma C, Liu C, Ye Z (2024). Influence of Genotype × environment interaction on yield stability of maize hybrids with AMMI model and GGE biplot. *Agronomy,* 14: 1-16. Doi: 10.3390/agronomy14051000

Mani JR, Issah FO, Abdussalam Z, Damisa MA (2022). Factors influencing farmer participation in maize production in Kaduna State, Nigeria. *Journal of Agriculture and Environment* 18(1): 1–11.

Mekonnen TW, van Biljon A, Ceronio G Labuschagne M (2023). Effects of planting date, environments, and their interaction on grain yield and quality traits of maize hybrids. *Heliyon, 9*(11): e21660. https://doi.org/10.1016/j.heliyon.2023.e21660

Mu̓hleisen J, Piepho H-P, Maurer H-P, Longin CFH, Reif JC (2014a). Yield stability of hybrids versus lines in wheat, barley and triticale. *Theoretical and Applied Genetics,* 127: 309–316.

Obour PB, Arthur IK, Owusu K (2022). The 2020 Maize production failure in Ghana: A case study of ejura-sekyedumase municipality. *Sustainability*, *14*(6): 3514. https://doi.org/10.3390/su14063514

Olakojo SA, Iken JE (2001). Yield performance and stability of some improved maize varieties. *Moor Journal of Agricultural Research,* 2: 21-24.

Olaoye G, Menkir A, Ajala SO, Jacob S (2009). Evaluation of local maize (*Zea mays* L.) varieties from Burkina Faso as source of tolerance to drought. *Journal of Applied Bioscience,* 17: 887-898.

Olaniyan AB (2015). Maize: Panacea for hunger in Nigeria. *African Journal of Plant Science,* 9(3): 155–174.

Onyeneke RU, Amadi MU, Anosike FC (2019). Biofortification in Nigeria: A systematic review. *AIMS Agriculture and Food, 4*(4): 892–906. https://doi.org/10.3934/agrfood.2019.4.892

Oyekunle M, Haruna A, Badu-Apraku B, Usman IS, Mani H, Ado SG, Olaoye G, Obeng-Antwi K, Abdulmalik RO, Ahmed HO (2017). Assessment of early-maturing maize hybrids and testing sites using GGE biplot analysis. *Crop Science,* 57: 2942-2950. https://doi.org/10.2135/cropsci2016.12.1014

Prasanna BM, Palacios-Rojas N, Hossain F, Muthusamy V, Menkir A, Dhliwayo T, Ndhlela T, San Vicente F, Nair SK, Vivek BS, Zhang X, Olsen M, Fan X (2020). Molecular breeding for nutritionally enriched maize: status and prospects. *Frontiers in Genetics,* 10: 1-16. https://doi.org/10.3389/fgene.2019.01392

Rahman MM, Wahed MA, Fuchs GJ, Baqui AH, Alvarez JO (2002). Synergistic effect of zinc and vitamin A on the biochemical indexes of vitamin A nutrition in children. *American Journal of Clinical Nutrition, 75*(1), 92–98. https://doi.org/10.1093/ajcn/75.1.92

Shrestha J (2013). Genotype by environment interaction and yield stability analysis of quality protein maize genotypes in the Terai region of Nepal. *International Journal of Applied Sciences and Biotechnology,* 1(2): 75–79.

Sibiya J, Tongoona P, Derera J, Rij N (2012). Genetic analysis and genotype by environment (G x E) for grey leaf spot disease resistance in elite African maize (*Zea mays* L.) germplasm. *Euphytica,* 185: 349–362.

Șimon A, Moraru PI, Ceclan A, Russu F, Chețan F, Bărdaș M, Popa A, Rusu T, Pop AI, Bogdan I (2023). The impact of climatic factors on the development stages of maize crop in the Transylvanian plain. *Agronomy*, *13*(6): 1612. https://doi.org/10.3390/agronomy13061612

Song P, Adeloye D, Li S, Zhao D, Ye X, Pan Q, Qiu Y, Zhang R, Rudan I, Global Health Epidemiology Research Group (GHERG) (2023). The prevalence of vitamin A deficiency and its public health significance in children in low- and middle-income countries: A systematic review and modelling analysis. *Journal of Global Health, 13*: 04084. https://doi.org/10.7189/jogh.13.04084

Ssentongo P, Ba DM, Ssentongo AE, Fronterre C, Whalen A, Yang Y, Ericson JE, Chinchilli VM (2020). Association of vitamin A deficiency with early childhood stunting in Uganda: A population-based cross-sectional study. *PLoS ONE, 15*(5): e0233615. https://doi.org/10.1371/journal.pone.0233615

Statista (2023). Production quantity of maize in Nigeria. Available at https://www.statista.com/statistics/1300743/production-volume-of-maize-in-nigeria/ (access date: 05.03.2025).

Stubbs CJ, Kunduru B, Bokros N, Verges V, Porter J, Cook DD, DeBolt S, McMahan C, Sekhon RS, Robertson DJ (2023). Moving toward short stature maize: The effect of plant height on maize stalk lodging resistance. *Field Crops Research, 300*:109008. https://doi.org/10.1016/j.fcr.2023.109008

Tao K, Li Y, Hu Y, Li Y, Zhang D, Li C, He G, Song Y, Shi Y, Li Y, Wang T, Lu Y, Liu X (2023). Overexpression of *ZmEXPA5* reduces anthesis-silking interval and increases grain yield under drought and well-watered conditions in maize. *Molecular Breeding, 43*(12): 84. https://doi.org/10.1007/s11032-023-01432-x

Tollenaar M, Wu J (1999). Yield improvement in temperate maize is attributable to greater stress tolerance. *Crop Science, 39*(6): 1597-1604.

Trethowan R, Crossa J, van Ginkel M, Rajaram S (2001). Relationships among bread wheat international yield testing locations in dry areas. *Crop Science 41*: 1461–1469. https://doi.org/10.2135/cropsci2001.4151461x.

Villamor E, Fawzi WW (2000). Vitamin A supplementation: Implications for morbidity and mortality in children. *The Journal of Infectious Diseases, 182*(Suppl_1): S122–S133. https://doi.org/10.1086/315921

Wirth JP, Petry N, Tanumihardjo SA, Rogers LM, McLean E, Greig A, Garrett GS, Klemm RD, Rohner F (2017). Vitamin A supplementation programs and country-level evidence of vitamin A deficiency. *Nutrients, 9*(3): 190. https://doi.org/10.3390/nu9030190

Wossen T, Menkir A, Alene A, Abdoulaye T, Ajala S, Badu-Apraku B, Gedil M, Mengesha W, Meseka S (2023). Drivers of transformation of the maize sector in Nigeria. *Global Food Security, 38*: 100713. https://doi.org/10.1016/j.gfs.2023.100713

Xue J, Ming B, Xie R, Wang K, Hou P, Li S (2020). Evaluation of maize lodging resistance based on the critical wind speed of stalk breaking during the late growth stage. *Plant Methods, 16*, 148: 1-12. https://doi.org/10.1186/s13007-020-00678-0

Yan W, Rajcan I (2002). Biplot evaluation of test sites and trait relations of soybean in Ontario. *Crop Science* 42: 11–20.

Yan W, Tinker NA, Falk D (2005). QTL identification, mega-environment classification, and strategy development for marker-based selection using biplots. *Journal of Crop Improvement* 14: 299–324.

Yan W, Tinker NA (2006). Biplot analysis of multi-environment trial data: Principles and applications. *Canadian Journal of Plant Science* 86(3): 623–645. https://doi.org/10.4141/P05-169

Yan W, Kang MS, Ma B, Woods S, Cornelius PL (2007). GGE biplot vs. AMMI analysis of genotype-by-environment data. *Crop Science* 47: 643–655.

Yan W (2014). Crop variety trials: data management and analysis. Chichester: John Wiley and Sons.

Yong H, Zhang F, Tang J, Yang Z, Zhao X, Li M, Zhang D, Hao Z, Weng J, Li X (2019). Breeding potential of inbred lines derived from five maize (*Zea mays* L.) populations. *Euphytica*, 215(1): 1–12. https://doi.org/10.1007/s10681-018-2319-8.

Zhang P, Gu S, Wang Y, Xu C, Zhao Y, Liu X, Wang P, Huang S (2023). The relationships between maize (*Zea mays* L.) lodging resistance and yield formation depend on dry matter allocation to ear and stem. *The Crop Journal, 11*(1): 258–268. https://doi.org/10.1016/j.cj.2022.04.020

APPENDIX 1. Summary of Weather Parameters for Ibadan, Eruwa, and Orin-Ekiti (2019 & 2020)

Month	**Ibadan 2019**				**Ibadan 2020**				**Eruwa 2019**				**Eruwa 2020**				**Orin-Ekiti 2019**				**Orin-Ekiti 2020**			
Parameter	**RF (mm)**	**T (°C)**	**WS (kmph)**	**RH (%)**	**RF (mm)**	**T (°C)**	**WS (kmph)**	**RH (%)**	**RF (mm)**	**T (°C)**	**WS (kmph)**	**RH (%)**	**RF (mm)**	**T (°C)**	**WS (kmph)**	**RH (%)**	**RF (mm)**	**T (°C)**	**WS (kmph)**	**RH (%)**	**RF (mm)**	**T (°C)**	**WS (kmph)**	**RH (%)**
Jan	24.00	30	5.6	50	0.90	30	5.2	51	26.10	31	6.6	49	0.50	30	5.5	51	12.80	28	5.9	41	1.60	28	5.7	36
Feb	40.14	30	6.7	55	1.50	31	5.4	59	28.58	31	8.0	51	1.00	31	6.0	58	53.61	28	6.8	50	0.90	29	5.8	45
Mar	77.97	30	7.9	63	84.71	29	8.6	72	62.3	31	9.2	59	100.90	30	9.5	69	105.77	28	8.8	67	106.98	27	9.5	73
Apr	96.11	29	8.3	68	71.49	29	8.4	76	93.63	30	9.5	64	61.32	29	9.2	73	107.03	27	9.7	75	90.69	27	9.7	79
May	166.3	28	8.2	69	150.44	27	7.3	82	143.5	29	9.0	66	135.91	28	7.6	81	251.33	26	10.4	80	168.67	26	8.3	85
Jun	216.66	25	7.3	87	186.19	25	7.3	86	245.36	26	7.7	85	187.72	26	7.7	87	268.39	24	8.6	89	199.18	24	8.6	90
Jul	226.44	24	7.0	90	197.82	24	7.7	89	252.37	25	7.4	90	204.58	24	8.0	89	279.75	23	8.1	91	235.91	22	9.0	92
Aug	230.89	24	7.6	90	60.2	24	8.1	84	217.4	25	8.2	89	41.94	24	8.5	85	214.76	23	8.7	90	83.97	22	9.7	88
Sep	276.22	25	6.5	90	245.56	24	7.0	91	288.54	25	7.2	89	171.05	24	7.4	91	371.16	24	7.1	90	393.58	22	8.1	93
Oct	348.22	25	5.8	89	93.09	26	5.3	86	381.13	25	6.0	88	97.02	26	5.8	87	380.47	23	6.1	89	205.79	24	5.8	86
Nov	40.26	27	4.6	77	9.40	28	4.7	77	36.08	28	5.1	75	10.46	28	5.3	75	53.77	26	4.9	71	9.60	27	4.6	70
Dec	1.40	29	4.3	49	3.20	28	6.0	73	2.40	29	5.1	49	1.10	29	6.7	69	1.1	28	4.4	33	1.10	27	6.4	68
Total	1774.61	326	79.80	877	1104.50	325	81.00	926	1777.39	335	89.00	854	1013.50	329	87.20	915	2099.94	308	89.50	866	1497.97	305	91.20	905
Mean	145.38	27.17	6.65	73.08	92.04	27.08	6.75	77.17	148.12	27.92	7.42	71.17	84.46	27.42	7.27	76.25	175.00	25.67	7.46	72.17	124.83	25.42	7.60	75.42

Note: RF – Rainfall (mm), T – Temperature (°C), WS – Wind Speed (kmph), RH – Relative Humidity (%)