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Analysis of Yield Performance and Disease Response of Zinc-Enriched Maize (*Zea Mays* L.) Hybrids Across Diverse Environments[A]

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Abstract: The limited yield potential of many biofortified maize varieties hampers their adoption in low-income regions like sub-Saharan Africa. This study assessed the agronomic performance, yield stability, and disease resistance of 16 zinc-enriched maize hybrids (genotypes selectively bred to accumulate higher zinc levels in the grain for improved dietary nutrition) across six environments in southwestern Nigeria during the 2021 and 2022 growing seasons. Significant genotype (G), environment (E), and genotype-by-environment (G×E) effects were observed. The average grain yield was 4.94 t ha^{-1}, with hybrid A1919-23 yielding the highest (5.78 t ha^{-1}) and showing broad adaptability (bi = 1.12; R^2 > 0.90). AMMI analysis indicated that environmental factors accounted for 68.49% of the total yield variation, while the first three principal component axes explained 89.26% of the G×E interaction. Disease severity also varied across environments, with hybrid A1919-14 exhibiting broad-spectrum resistance. Ibadan was most favorable for yield, while Omu-Aran provided optimal agroclimatic conditions. Hybrids A1919-23, A1831-3, and A1919-15 combined high yield, adaptability, and disease resistance. These results highlight the potential of zinc-enriched hybrids to improve food security and

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nutrition and inform breeding programs focused on yield resilience and micronutrient enhancement in diverse agroecological zones.

Keywords: AMMI analysis, disease resistance, food security, genotype-by-environment interaction, zinc-enriched maize, zinc biofortification.

Çinko Zenginleştirilmiş Mısır (*Zea mays* L.) Melezlerinin Farklı Ortamlarda Verim Performansi ve Hastalik Tepkisinin Analizi

Öz: Birçok biyolojik olarak zenginleştirilmiş mısır çeşidinin sınırlı verim potansiyeli, Sahra Altı Afrika gibi düşük gelirli bölgelerde benimsenmesini engellemektedir. Bu çalışma, 2021 ve 2022 yetiştirme sezonlarında güneybatı Nijerya'daki altı ortamda 16 çinko ile zenginleştirilmiş mısır melezinin tarımsal performansını, verim stabilitesini ve hastalık direncini değerlendirdi. Önemli genotip (G), ortam (E) ve genotip-çevre (G×E) etkileri gözlemlendi. Ortalama tane verimi 4.94 t ha^{-1} iken, melez A1919-23 en yüksek verimi (5.78 t ha^{-1}) verdi ve geniş bir adaptasyon yeteneği gösterdi (bi = 1,12; $R^2 > 0,90$). AMMI analizi, çevresel faktörlerin verim değişiminin % 68,49'unu oluşturduğunu ve ilk üç temel bileşenin G×E etkileşiminin % 89,26'sını açıkladığını gösterdi; hastalık şiddeti ortama göre değişti ve melez A1919-14 geniş spektrumlu direnç gösterdi. Ibadan verim için en uygun olanıydı, Omu-Aran ise optimum tarımsal iklim koşullari sağladı. Melezler A1919-23, A1831-3 ve A1919-15 yüksek verim, uyum yeteneği ve hastalik direncini bir araya getirdi. Bu sonuçlar, çinko ile zenginleştirilmiş melezlerin gıda güvenliğini ve beslenmeyi iyileştirme ve çeşitli tarımsal ekolojik bölgelerde verim dayanıklılığı ve mikro besin geliştirmeye odaklanan yetiştirme programlarını bilgilendirme potansiyelini vurgulamaktadır.

Anahtar Kelimeler: AMMI analizi, hastalık direnci, gıda güvenliği, genotip-çevre etkileşimi, çinko ile zenginleştirilmiş mısır, çinko biyofortifikasyonu.

Introduction

Maize (*Zea mays* L.) is one of the world's most significant cereal crops, providing a staple meal, animal feed, and industrial raw material (Ocwa et al., 2023). Its adaptability and high productivity underpin its critical role in food security, especially in developing regions like sub-Saharan Africa (SSA) and South Asia, where it contributes significantly to caloric intake and household income (Zhang and Wang, 2024). Despite its importance, populations dependent on maize-based diets often face nutritional challenges, notably zinc (Zn) deficiency, due to the low bioavailability of micronutrients in maize and limited access to diversified diets (Mallikarjuna et al., 2020).

Micronutrient malnutrition, or "hidden hunger," affects over two billion people globally, with Zn deficiency posing severe health risks (Zaman et al., 2018). This is predominant in low- and middle-income countries, which

is often linked to weakened immunity, impaired child growth, and cognitive deficits (Bouis and Welch, 2010). Zinc is essential for immune function, growth, and cognitive development, and its deficiency is associated with increased mortality and morbidity, particularly in children under five (Cakmak and Kutman, 2017). Addressing this issue requires sustainable solutions, with biofortification emerging as a promising strategy, and maize's dietary significance in regions vulnerable to micronutrient malnutrition makes it an ideal crop for biofortification. Biofortification enhances the nutritional quality of crops through genetic improvement, complementing dietary diversification and supplementation efforts (De Valença et al., 2017). It also offers a cost-effective, sustainable solution by enriching staple crops like maize with Zn, thereby improving public health outcomes (Mandal et al., 2024). Biofortified kernel-zinc maize has been successfully developed and adopted in several Latin American countries (Taleon et al., 2025). Similarly, ongoing breeding initiatives in Nigeria aim to develop maize lines with enhanced kernel zinc concentrations (27.2–41.6 μg g^{-1}), offering a sustainable nutritional alternative in regions where commercial maize flour fortification is not widely implemented (Matongera et al., 2023; Udo et al., 2023). Biofortified maize hybrids enriched with Zn does not only address Zn deficiency but also provide caloric energy.

Genetic variability for Zn concentration in maize provides a foundation for breeding efforts; however, achieving high Zn levels without compromising yield remains a significant challenge (Pixley et al., 2013). Genetic diversity and environmental factors affect yield components such as kernel weight, ear length, and kernel rows (Hallauer et al., 2010). Finding hybrids with wide or particular adaptability requires the use of stability analysis techniques, such as the genotype and genotype × environment (GGE) biplots and the additive main effects and multiplicative interaction (AMMI) model (Yan and Kang, 2003; Crossa et al., 1990). Furthermore, developing high-yielding, nutritionally enhanced hybrids suitable for diverse agroecological zones presents challenges due to complex genotype-environment interactions (GEI). Breeding efforts must prioritize yield performance, stability, and disease resistance to ensure adaptability and long-term adoption. Disease resistance is another cornerstone of maize breeding, particularly in disease-prone regions. It is particularly critical in mitigating yield losses from pathogens such as maize streak virus (MSV), turcicum leaf blight (TLB), rust, curvularia leaf spot (CLS), and gray leaf spot (GLS) (Akinwale and Oyelakin, 2018). These pathogens can cause significant yield losses, thereby threatening food security. Developing disease-resistant hybrids ensures yield stability and reduces dependence on chemical controls, aligning with sustainable agricultural practices (Bertram and Sagen, 2004).

Despite advancements in biofortification, limited studies have evaluated Zn-enriched hybrids comprehensively for yield, stability, and disease resistance across diverse environments. Addressing this gap is critical for maximizing the potential of biofortified maize in combating hidden hunger while ensuring agronomic sustainability. Therefore, this study aims to (i) evaluate the agronomic performance and yield components of newly developed Zn-enriched maize hybrids across diverse agroecological zones (ii) assess the stability of yield and disease resistance of these hybrids to major pathogens such as MSV, TLB, and GLS in the test locations (iii) identify hybrids that achieve an optimal balance of high yield, stability, and disease resistance for potential large-

scale adoption. The findings will provide valuable insights for breeding programs, aligning nutritional enhancement with agronomic sustainability to address food and nutritional security in vulnerable populations.

Material and Method

Field Experiments

The hybrids used for this study were developed by the International Institute of Tropical Agriculture (IITA) through systematic breeding involving the selection of genetically diverse, high-zinc parents to generate source populations and derive Zn-enriched inbred lines, which were then evaluated and crossed with suitable testers to produce testcrosses assessed for agronomic performance. A total of fourteen newly developed zinc-enriched hybrid maize varieties, along with two check varieties—a commercial hybrid (Oba Super 9) and a local farmer's variety were evaluated (Table 1).

The field experiments were conducted during the 2021 and 2022 cropping seasons at three locations in the South-West region of Nigeria: Ibadan (7.3775° N, 3.9470° E; annual rainfall: 1250–1500 mm), Ilora (7.8000° N, 3.9167° E; annual rainfall: 1000–1367 mm), and Omu-Aran (8.1333° N, 5.1000° E; annual rainfall: 1263–1634 mm). These sites represent major maize-growing agro-ecologies characterized by variations in rainfall distribution, soil type, and temperature (Appendix 1). The soils at Ibadan and Ilora are predominantly Alfisols, classified as sandy loam to loamy sand, well-drained, and moderately fertile. In contrast, the soils at Omu-Aran are mainly Ultisols, with a sandy clay loam texture, slightly acidic reaction, and moderate organic matter content.

The experiments were arranged in a randomized complete block design (RCBD) with three replications per location. Each plot consisted of four rows, 5 m in length, with inter-row and intra-row spacings of 75 cm and 50 cm, respectively, corresponding to a plant population density of approximately 53,333 plants ha^{-1}. Planting was carried out in the first week of June in both years, coinciding with the onset of the rainy season. Three seeds were sown per hill and later thinned to two healthy plants per stand at two weeks after planting (WAP) to ensure uniform stand establishment. Weed control was achieved through both chemical and manual methods. Pre- and post-emergence herbicides were applied immediately after planting (Atrazine at 2.5 kg a.i. ha^{-1} and Paraquat at 0.75 kg a.i. ha^{-1}) followed by hand weeding as needed to maintain effective weed suppression throughout the growing period. Fertilizer application was done in two splits at the recommended rate of 120 kg N, 60 kg P_2O_5, and 60 kg K_2O ha^{-1}. A basal dose of NPK 15:15:15 was applied three weeks after planting, while Urea (46% N) was top-dressed six weeks after planting to promote vigorous vegetative growth and proper grain filling. Standard agronomic practices suitable for maize production were uniformly implemented across all locations to ensure consistent crop management and minimize environmental variability.

Harvesting was carried out when the cobs reached physiological maturity and the husks were dry typically between 100 – 110 days after planting, depending on the hybrid and environmental conditions. Ears from the

two central rows of each plot were harvested to minimize border effects. The harvested ears were dried, shelled, and processed for grain yield and yield-related trait evaluation.

Table 1. List of hybrids used in this study and their origin

Code	Hybrid	Pedigree	Source
1	A1830-6	TZMI305-BB/IITATZI1296/IITATZI1861	IITA
2	A1919-17	4013-B*4/4013-BB/ATPS8-31y-BB-15-BB-B-1/KU1409-B*4	IITA
3	A1919-20	4013-B*4/(POP66SR/ACR91SUWAN1-SRC1/ACR91SUWAN1-SRC1-6X(MP420x4001xMP420)-3-1-3-1-B)S2-5-B*8/KU1409-B*4	IITA
4	A1919-23	MP420x4001xMP420)-3-1-3-1-B*10/(((KU1409/KU1414-SR/A619)-S2-2/9450/KI21-7-2-2-1-1-BB)-28-B*4-B-1/KU1409xMO17LPAxKU1409-27-3-1-1-BB/(CIM116xTZMi302xCIM116)-2-2-B*8-15-B*4	IITA
5	A1919-24	ATPS7-24y-B/4001/B73LPA/4001-9-2-1-B*4-26-B-1-B-1/(9450xCM116x9450)-5-1-3-1-B*7/KU1409xMO17LPAxKU1409-27-3-1-1-BB/(CIM116xTZMi302xCIM116)-2-2-B*8-15-B*4	IITA
6	A1919-38	4013-B*4/(POP66SR/ACR91SUWAN1-SRC1/ACR91SUWAN1-SRC1-6X(MP420x4001xMP420)-3-1-3-1-B)S2-5-B*8/(KU1409/KU1414-SR/KVI3)-S2-8-1-B*5/(KU1409/DE3/KU1409)S2-21-B*4-29-B-1-B	IITA
7	A1830-7	TZMI305-BB/IITATZI1296/IITATZI1285	IITA
8	A1831-3	CamI9P117-B/KU1409/SC55/KU1409-BB-8-B-1-B-1/ATPS6-31y-B*4/IITATZI1326	IITA
9	A1847-32	ATPS7-24y-B/4001/B73LPA/4001-9-2-1-B*4-26-B-1-B-1/IITATZI1842/IITATZI1319	IITA
10	A1918-13	CamI9P117-B*4/IITATZI1322/KU1409-B*4	IITA
11	A1918-14	ATPS8-27y-B*4/4013-B*4/KU1409-B*4	IITA
12	A1918-37	IITATZI1312/IITATZI1851/ATPS7-24y-B/4001/B73LPA/4001-9-2-1-B*4-21-B-1-B-1	IITA
13	A1919-14	(MP420x4001xMP420)-3-1-3-1-B*10/(((KU1409/KU1414-SR/A619)-S2-2/9450/KI21-7-2-2-1-1-BB)-28-B*4-B-1/4013-B/4001/KI21-3-2-1-1-1-1-B*4-33-B-2-B-1	IITA
14	A1919-15	ATPS7-24y-B/4001/B73LPA/4001-9-2-1-B*4-26-B-1-B-1/(9450xCM116x9450)-5-1-3-1-B*7/4013-B/4001/KI21-3-2-1-1-1-1-B*4-33-B-2-B-1	IITA
15	Oba Super 9	(ACR97TZLComp1–W × TZE COMP3C3)	IITA
16	Farmers Variety		

Data Collection

Data were collected on a plant and plot basis for ten quantitative traits. Plant height (cm), ear height (cm), and number of ears per plant were taken from five randomly selected plants from the middle two rows. Agronomic data such as days to anthesis (DA), days to silking (DS), and Anthesis-Silking-Interval (ASI) were taken as the difference between the days to silking and anthesis. Disease intensity of maize streak virus (MSV), rust, curvularia leaf disease, and turcicum leaf blight (TLB) was measured using a 1-5 severity scale as described by Badu-Apraku et al. (2012). Field weight was recorded from the total plot and converted to kilograms per hectare, while grain yield was calculated using the formula as described by MacRobert et al. (2014).

$$\text{Grain Yield } \left(\frac{\text{tons}}{\text{ha}}\right) = \frac{\text{field weight (Kg)} \times (100 - \text{MC}) \times 0.8 \times 10{,}000\ (m^2)}{(100 - 12.5) \times \textit{Plot Area}\ (m^2) \times 1{,}000} \quad (1)$$

Where, MC = harvest time moisture content in grains (%), 0.8 = standard shelling co-efficient, 12.5 = standard moisture content, and Plot Area = area harvested (m^2)

Statistical Analysis

Data were subjected to analysis of variance (ANOVA) procedure using a general linear model (GLM) to determine the effects of genotype, environment, and genotype × environment interaction (G×E) on the measured traits. Genotypes were treated as fixed effects, while environments, replications within environments, and error terms were treated as random effects. Significant differences among genotypes were identified using Fisher's Least Significant Difference (LSD) test at a 5% significance level. The AMMI (Additive Main Effect and Multiplicative Interaction) model was employed to analyze G×E interactions, decomposing the variability into principal component axes to explain hybrid performance across environments. Stability and adaptability of genotypes were further assessed using Eberhart and Russell's regression model, where regression coefficients and deviations from regression were used to classify genotypes based on their adaptability. Coefficients of determination were calculated to quantify the proportion of yield variability attributed to environmental effects. Disease severity data were analyzed using ANOVA to identify significant differences among genotypes and locations.

All statistical analyses were conducted using SAS 9.4 and GenStat 19th Edition. AMMI biplots and stability indices were visualized using R software version 4.4.2, enabling clear interpretation of genotype performance and interaction effects. This comprehensive approach ensured a robust evaluation of the hybrids, facilitating the identification of superior genotypes adapted to diverse agroecological zones.

Results and Discussion

The combined analysis of variance (ANOVA) for grain yield and agronomic traits across six environments revealed significant variability due to environmental factors, genotypes, and their interactions (Table 2). Locations exhibited highly significant effects ($p < 0.01$) on all measured traits except ear aspect, underscoring the substantial influence of environmental conditions on trait expression. These findings align with Azrai et al. (2023) highlighted the significant environmental influence on grain yield with the relative stability of ear aspect. Similarly, Badu-Apraku et al. (2022) observed significant environmental impacts ($p < 0.05$) on grain yield and related traits, except for ear aspect, while Badu-Apraku et al. (2020) noted that ear aspect was less affected by environmental variations compared to other traits. Year effects were highly significant ($p < 0.01$) for traits such as days to pollen shed, days to silking, anthesis-silking interval (ASI), plant and ear height, husk cover, root lodging, and grain yield while ear aspect and stalk lodging were significant at $p < 0.05$ and plant aspect was not significant. Significant genotypic differences were observed at $p < 0.01$ for traits such as plant height, ear height, grain yield, and ear aspect, reflecting substantial genetic variability in all the locations.

The genotype × location (G×L) interaction was not significant for all the traits, indicating stability and adaptability across environments. This finding aligns with Mafouasson et al. (2018), who reported non-significant G×L interactions across all traits in 80 maize hybrids evaluated under low and high nitrogen

conditions across 11 environments in Cameroon, indicating stable performance and broad adaptability. Furthermore, genotype × year (G×Y) and location × year (L×Y) interactions were significantly influenced grain yield ($p < 0.01$) and ASI ($p < 0.05$), emphasizing the dynamic influence of environmental conditions on the trait expression. Katsenios et al. (2021) also reported significant effects of environmental factors and G×E interactions on grain yield and quality traits in the different maize hybrids evaluated. In addition, Welcker et al. (2022) emphasized the sensitivity of maize performance to annual climatic variations, which is consistent with our findings in this study.

The coefficients of variation (CV) for agronomic traits highlighted ASI as the most variable trait (40.95 %), followed by root lodging at 39.59 %). Flowering time traits such as days to pollen shed (3.53 %) and days to silking (4.05 %) exhibited the least variability. These results align with Mikić et al. (2016), who reported high phenotypic variation in ASI. Oloyede-kamiyo (2019) also observed high CVs for ASI and moderate variability in other traits for different maize families. These findings highlight the inherent variability of ASI compared to other, more stable traits like flowering time.

ANOVA for disease traits (Table 3) demonstrated significant environmental and interaction effects across environments. Year effects were particularly pronounced for curvularia leaf spot (mean square = 50.00; $p < 0.01$), reflecting susceptibility to climatic variations. Significant genotypic differences ($p < 0.01$) were observed for leaf blight, but not for other diseases, indicating limited genetic variability for resistance to those diseases. The effects of location (L), year (Y), and their interaction (L×Y) were significant across all diseases, underscoring the strong influence of environmental factors on disease expression.

Table 2. Mean squares from the combined analysis of variance for grain yield and agronomic traits of the sixteen maize Genotypes evaluated across six environments.

Source	DF	Days to 50% Pollen Shed	Days to 50% Silking	ASI	Plant Height	Ear Height	Plant Asp.	Ear Asp	Grain Yield
Rep	2	8.53	20.02	4.60	567.34	468.25	0.46	1.50	5.42
L	2	3510.39**	3605.32**	186.67**	3569.55**	9693.80**	3.15**	0.18	24.69**
Year	1	320.89**	1422.22**	401.39**	10184.02**	907.74**	0.003	1.84*	415.18**
G	15	5.55	5.52	2.97	1133.17**	396.80**	0.48*	1.22**	8.04**
G × L	30	5.35	5.45	3.28	315.39	172.31	0.33	0.71	1.35
L × Y	2	467.86**	664.82**	41.84**	205.49	424.47*	14.32**	4.76**	47.43**
G × Y	15	7.40	5.37	4.18*	233.27	138.08	0.28	0.52	3.60**
G × L × Y	30	4.60	6.34	2.33	345.17	173.01	0.48**	0.53	1.41
Mean		61.27	65.03	3.78	165.11	83.13	1.60	1.67	4.94
Error	190	4.68	6.94	2.39	230.82	120.23	0.24	0.42	1.32
CV (%)		3.53	4.05	40.95	9.20	13.20	19.32	30.65	23.24

Rep= replication; DF = degree of freedom; ASI = Anthesis Silking Interval; Plant Asp. = Plant Aspect; Ear Asp. = Ear Aspect; L= Location; G = Genotype; G × L = Genotype × Location; L × Y = Location × Year; G × Y = Genotype × Year; G × L = Genotype × Location; G × L × Y = Genotype × Location × Year; CV = Coefficient of Varaition; *, **: Significant at < 0.05, < 0.01 level of probability respectively

Table 3. Mean squares from the combined analysis of variance for disease traits of the sixteen maize hybrids evaluated across six environments

Source	DF	Husk cover	Root lodging	Stalk lodging	Ear rot	Streak	Rust	Blight	Curv
Rep	2	0.22	1.76	0.09	0.68	0.11	0.34	0.61	0.22
L	2	11.28**	6.14**	4.18**	5.52**	6.92**	9.52**	6.27**	3.03**
Y	1	12.09**	3.78**	0.68*	12.09**	11.68**	10.89**	9.39**	50.00**
G	15	0.06	0.09	0.19	0.31	0.21	0.11	0.41**	0.31
G × L	30	0.08	0.11	0.09	0.29	0.16	0.09	0.24	0.20
L × Y	2	12.25**	3.14**	0.18	2.81**	6.48**	6.40**	10.34**	5.32**
G × Y	15	0.04	0.15	0.21	0.16	0.18	0.14	0.33	0.20
G × L × Y	30	0.06	0.18	0.20	0.22	0.14	0.17	0.26	0.30
Mean		1.24	1.16	1.16	1.40	1.38	1.43	1.49	1.71
Error	190	0.06	0.21	0.14	0.27	0.12	0.14	0.20	0.29
CV (%)		19.32	39.59	31.79	36.89	24.87	26.51	29.99	31.65

Rep= replication; DF = degree of freedom; Curv = Curvuaria Leaf Spot; L= Location; G = Genotype; G × L = Genotype × Location; L × Y = Location × Year; G × Y = Genotype × Year; G × L = Genotype × Location; G × L × Y = Genotype × Location × Year; CV = Coefficient of Varaition; *, **: Significant at < 0.05, < 0.01 level of probability respectively

These findings align with those of Zhu et al. (2021) and Iseghohi et al. (2024), who also reported that disease severity in maize is strongly influenced by year-specific climatic conditions. Olaoye (2009) highlighted the influence of environmental conditions on the incidence and severity of maize streak virus. The study also reported significant genotypic variation in grain yield as well as resistance to leaf blight and Curvularia leaf spot, with disease incidence ranging from 4 % to 8 %. Akinwale and Oyelakin (2018) found genotypic variability in disease resistance among maize varieties, while flowering traits such as days to silking and pollen shed were uniform across the hybrids. Zebire et al. (2024) also reported significant genotypic differences in Striga-resistant maize test crosses for most traits but noted minimal variability in flowering time.

Environmental factors significantly influenced plant height, ear height, and grain yield across the different locations (Table 4). Among the sites, Ibadan exhibited the greatest average values, with plant height at 171.93 cm, ear height at 90.31 cm, and grain yield reaching 5.46 t ha^{-1}, indicating that the conditions there were highly conducive to both vegetative growth and reproductive performance. In contrast, Omu Aran exhibited lower mean values for these traits, coinciding with the lowest grain yield (4.46 t ha^{-1}). There has been speculation of a possible linkage between plant height and yield components. Adeosun and Olawuyi (2019) and Anjorin and Ogunniyan (2014) reported positive significant relationships between plant height and yield components, indicating robust vegetative growth as a determinant of productivity.

Flowering traits, such as days to 50 % pollen shed and silking, were delayed in Ilora, suggesting stress-induced flowering delays. This is evident in the high ASI value (4.73) recorded in the location, which is an indicator of stress tolerance. These observations align with findings from Kim et al. (2021) and Lv et al. (2024), who previously reported that environmental stresses, including drought and heat, can postpone silking and lead to an increase in ASI. Omu Aran exhibited the shortest ASI (2.17 days), indicating greater adaptability in the location. Plant and ear aspect scores were favorable across locations, reflecting the genetic potential for superior plant architecture and grain quality in the evaluated genotypes.

Table 4. Mean performance of agronomic traits of sixteen maize hybrids evaluated across three locations and two years

Location	Days to 50 % Pollen Shed (days)	Days to 50 % Silking (days)	Anthesis Silking Interval (ASI)	Plant height (cm)	Ear Height (cm)	Plant Aspect (1 – 5)	Ear Aspect (1 – 5)	Grain Yield (t ha^{-1})
Ibadan	54.73^{c}	59.16^{c}	4.43^{a}	171.93^{a}	90.31^{a}	1.67^{a}	1.66^{a}	5.46^{a}
Ilora	66.66^{a}	71.39^{a}	4.73^{a}	163.22^{b}	87.43^{a}	1.74^{a}	1.72^{a}	4.90^{b}
Omu-Aran	62.42^{b}	64.56^{b}	2.17^{b}	160.19^{b}	71.65^{b}	1.40^{b}	1.64^{a}	4.46^{c}
Mean	61.27	65.03	3.78	165.11	83.13	1.60	1.67	4.94
LSD	0.62	0.75	0.44	4.33	3.12	0.14	0.18	0.32

(t ha $^{-1}$) = tonnes per hectare; cm = centimeter

Mean yield performance of the sixteen tested maize hybrids across three locations in the 2021 and 2022 growing seasons

The performance of sixteen maize genotypes was evaluated across multiple locations, revealing significant genetic variability (Table 5). Genotype A1919-23 exhibited the highest grain yield (5.78 t ha^{-1}), which may be attributed to its superior plant height (170.56 cm) and ear height (90.57 cm). Genotype A1831-3 also showed high yield potential (5.65 t ha^{-1}), comparable to A1919-23, despite minor differences in plant height and flowering traits. Both genotypes demonstrated robust vegetative growth, likely due to their adaptability and efficient resource utilization under the tested environmental conditions. In contrast, the farmers' variety recorded the lowest yield (2.84 t ha^{-1}), significantly lagging behind the improved genotypes.

In addition to its high yield, genotype A1831-3 also had the tallest plants (176.42 cm), therefore supporting earlier reports of a positive correlation between plant height, ear height, and grain yield under favorable conditions. This positive correlation is due to the ability of tall plants to have enhanced light interception ability and resource utilization, thereby contributing to their yield improvement (Peiffer et al., 2014). They also reported that the genetic architecture of maize height is strongly polygenic, with heritability exceeding 90 %. Additionally, specific quantitative trait loci (QTL) linked to plant height also influence yield performance, although their individual effects are small. Adak et al. (2021) further validated functional polymorphisms affecting plant height and their relationship with grain yield, highlighting that these associations vary across genetic backgrounds. Daemo et al. (2024) also highlighted the critical role of genotype-environment interactions in affecting plant height, ear height, and yield, underscoring the need to prioritize environmental adaptability when selecting genotypes for improved yield performance.

Stress-adaptation traits such as anthesis-silking interval (ASI) and lodging resistance are also critical traits for yield improvement. Genotypes A1830-7 (3.17) had the shortest ASI, thereby demonstrating resilience under environmental stress and thus making them promising candidates for breeding in stress-prone regions. This observation aligns with findings by Khan et al. (2022), who noted that shorter ASI contributes to improved stress adaptation. Lodging resistance was favorable across genotypes, with uniformly low root and stalk lodging

scores. Additionally, consistent husk cover ratings across genotypes ensured effective protection against pests and environmental damage, contributing to grain quality.

Table 5. Mean agronomic performance (t ha^{-1}) of sixteen hybrids of maize evaluated across the three locations between 2021 and 2022.

Genotype	Days to 50% Pollen Shed	Days to 50% Silking	ASI	Plant height (cm)	Ear height (cm)	Yield (t ha^{-1})	Root lodging (1–5)	Stalk lodging (1–5)	Husk cover (1–5)
A1830-6	60.89^{bc}	65.00^{ab}	4.11^{ab}	146.49^{g}	73.98^{e}	5.04^{abcde}	1.11	1.11^{b}	1.33^{a}
A1830-7	61.06^{bc}	64.22^{ab}	3.17^{b}	156.32^{efg}	79.43^{cde}	5.09^{abcde}	1.06	1.17^{b}	1.28^{ab}
A1831-3	61.44^{abc}	65.33^{ab}	3.89^{ab}	176.42^{a}	88.18^{ab}	5.65^{ab}	1.11	1.06^{b}	1.22^{ab}
A1847-32	60.78^{bc}	65.17^{ab}	4.39^{a}	170.00^{abc}	84.97^{abc}	4.60^{e}	1.22	1.22^{ab}	1.22^{ab}
A1918-13	61.22^{abc}	65.06^{ab}	3.83^{ab}	165.27^{bcde}	82.53^{bcd}	5.05^{abcde}	1.17	1.11^{b}	1.28^{ab}
A1918-14	62.00^{ab}	65.61^{a}	3.61^{ab}	170.31^{abc}	84.47^{abc}	4.65^{de}	1.28	1.11^{b}	1.28^{ab}
A1918-37	61.39^{abc}	65.67^{a}	4.28^{a}	167.42^{abcd}	85.48^{abc}	4.76^{cde}	1.17	1.06^{b}	1.17^{b}
A1919-14	60.61^{bc}	64.61^{ab}	4.00^{ab}	152.71^{fg}	76.98^{de}	5.37^{abcd}	1.11	1.06^{b}	1.22^{ab}
A1919-15	61.50^{abc}	64.94^{ab}	3.44^{ab}	162.60^{cdef}	79.19^{cde}	5.50^{abc}	1.11	1.17^{b}	1.17^{b}
A1919-17	61.22^{abc}	64.67^{ab}	3.44^{ab}	164.46^{bcde}	81.26^{bcd}	4.79^{cde}	1.22	1.28^{ab}	1.17^{b}
A1919-20	61.67^{ab}	64.89^{ab}	3.22^{b}	159.91^{def}	79.41^{cde}	4.77^{cde}	1.17	1.06^{b}	1.28^{ab}
A1919-23	61.44^{abc}	65.33^{ab}	4.11^{ab}	170.56^{abc}	90.57^{a}	5.78^{a}	1.11	1.17^{b}	1.17^{b}
A1919-24	61.44^{abc}	65.78^{a}	4.33^{a}	171.16^{abc}	89.77^{a}	5.39^{abc}	1.06	1.17^{b}	1.22^{ab}
A1919-38	61.05^{bc}	64.78^{ab}	3.72^{ab}	166.89^{abcd}	83.86^{abcd}	4.72^{de}	1.11	1.11^{b}	1.28^{ab}
Local check	62.50^{a}	65.72^{a}	3.22^{b}	173.63^{ab}	88.09^{ab}	2.84^{f}	1.22	1.28^{ab}	1.33^{a}
Oba Super 9	60.11^{c}	63.78^{b}	3.67^{ab}	167.67^{abcd}	81.92^{bcd}	4.97^{bcde}	1.28	1.44^{a}	1.22^{ab}
Mean	61.27	65.03	3.78	165.11	83.13	4.94	1.16	1.16	1.24
LSD	1.42	1.73	1.02	9.99	7.21	0.75	0.30	0.24	0.15
CV (%)	3.53	4.05	40.95	9.20	13.20	23.24	39.59	31.79	19.32

ASI = Anthesis Silking Interval; (t ha $^{-1}$) = tonnes per hectare; cm = centimeter

Grain yield performance and genotype × environment interaction of maize hybrids across diverse Nigerian agro-ecologies

The evaluation of sixteen maize genotypes, including local checks and zinc-enriched hybrids, across six environments in three locations—Ibadan, Ilora, and Omu-Aran over two years (2021–2022) revealed significant variability in grain yield performance influenced by both genetic and environmental factors (Table 6). The average grain yield across all environments was 4.94 t ha^{-1}. The farmer's variety consistently recorded the lowest yield at 2.84 t ha^{-1}, whereas genotype A1919-23 achieved the highest average yield of 5.78 t ha^{-1}, with stable performance across all test sites (e.g., 5.34 t ha^{-1} in Ibadan 2021 and 6.46 t ha^{-1} in Omu-Aran 2022).

The environmental conditions played a critical role in determining the yield outcomes. Ibadan 2022, which recorded the highest mean yield (6.81 t ha^{-1}) among the test environments, experienced favorable climatic conditions, including total rainfall of 1206.5 mm, mean temperature of 26.2 °C, and mean relative humidity (RH) of 76.8 % (Appendix 1). These conditions likely enhanced soil moisture availability and reduced heat stress during critical growth stages. In contrast, Ilora 2021, which had the lowest mean yield (3.09 t ha^{-1}),

received only 923.0 mm of rainfall and had the lowest RH (74.3 %), with elevated wind speeds (mean of 7.7 km ph), potentially exacerbating evapotranspiration losses and negatively impacting maize development. This result agrees with Shirley et al. (2020), who found that pre-harvest temperature and precipitation significantly impacted yield during the growing season, with optimal growth within specific ranges of these climatic factors. Furthermore, Maitah et al. (2021) studied the influence of precipitation under recent climate change on maize yield in the Czech Republic. The result is that total maize yield and yield rate increased until 2010 but began to decrease thereafter, suggesting that changes in precipitation patterns significantly affect maize productivity.

Genotypes such as A1919-15 (5.50 t ha^{-1}), A1919- 14 (5.37 t ha^{-1}), and A1831-3 (5.65 t ha^{-1}) also displayed high and stable yields. Notably, A1831-3 attained peak yields of 8.15 t ha^{-1} in Ibadan 2022 and 7.46 t ha^{-1} in Ilora 2022, coinciding with improved rainfall and humidity levels in those years. For instance, Ilora 2022 experienced a notable increase in rainfall (987.7 mm) and higher RH (72.6 %) compared to 2021, which likely contributed to better crop performance. However, the performance of A1831-3 in Ilora 2021 was substantially lower (3.52 t ha^{-1}), exemplifying a pronounced genotype × environment (G×E) interaction. The suboptimal rainfall (923.0 mm) and low RH (74.3 %) in Ilora 2021 may have imposed moisture stress, limiting yield potential. This observation aligns with Singamsetti et al. (2021), research that highlighted that certain genotypes performed consistently across different moisture regimes. Additionally, Pavlov et al. (2024) research quantified the influence of climatic factors on the G×E interaction for each vegetative and reproductive phase. Findings indicated that variables such as average maximum temperature, average minimum temperature, and relative humidity significantly influenced different growth stages, affecting overall grain yield.

Similar G×E effects were observed in genotypes such as A1830-6, which performed exceptionally in Ibadan 2021 (7.98 t ha^{-1}) a year with moderate rainfall (1038.8 mm) and relatively high RH (77.7 %) but declined sharply in Omu-Aran 2021 (4.22 t ha^{-1}), despite its higher rainfall (1440.5 mm) and RH (75.2 %). This paradox suggests that other microclimatic or soil conditions may have played a role, or that A1830-6 lacks resilience to Omu-Aran-specific stress factors. In contrast, genotypes such as A1919-23 and A1919-15 showed consistent performance across years and locations, suggesting broad adaptability to variable environmental conditions. Their stable yield in both high (Ibadan 2022) and moderate (Ilora 2021) rainfall environments indicates resilience to both moisture fluctuations and potential stress factors such as temperature and wind speed. This supports findings by Alam et al. (2022) and Supriadi et al. (2024), who emphasized the value of selecting genotypes with low sensitivity to environmental variation. Interestingly, genotype A1919-24 achieved the highest individual plot yield (8.55 t ha^{-1}) in Ilora 2022, a year characterized by improved rainfall and humidity compared to 2021. This further confirms the potential of certain hybrids to capitalize on favorable climatic windows, an observation consistent with Ideki et al. (2024), who underscored the impact of seasonal weather parameters on crop performance.

Table 6. Mean grain yield (t ha^{-1}) of sixteen hybrids of maize evaluated across three locations between 2021 and 2022.

	Environment						
Genotypes	Ibadan 2021	Ibadan 2022	Ilora 2021	Ilora 2022	Omu-Aran 2021	Omu Aran 2022	Overall Mean
A1830-6	4.44	7.98	2.46	6.64	4.22	4.51	5.04
A1830-7	4.36	6.48	3.79	6.26	3.93	5.69	5.09
A1831-3	4.98	8.15	3.52	7.46	5.10	4.69	5.65
A1847-32	4.95	4.81	3.18	6.13	3.78	4.76	4.60
A1918-13	4.54	7.27	2.60	6.50	4.65	4.71	5.05
A1918-14	4.14	5.48	3.46	4.90	5.49	4.47	4.66
A1918-37	3.78	8.27	2.42	6.87	3.18	4.02	4.76
A1919-14	3.66	7.96	3.33	7.44	3.76	6.09	5.37
A1919-15	3.65	8.39	3.24	7.66	3.97	6.11	5.50
A1919-17	3.66	7.03	3.23	7.95	3.78	3.11	4.79
A1919-20	3.85	5.88	3.11	7.08	3.96	4.72	4.76
A1919-23	5.34	7.61	3.11	7.60	4.57	6.46	5.78
A1919-24	4.22	7.14	3.00	8.55	4.34	5.07	5.39
A1919-38	3.47	6.39	3.26	7.10	3.04	5.05	4.72
Local check	2.36	3.36	2.29	3.04	2.48	3.52	2.84
Oba Super 9	4.28	6.79	3.40	6.27	3.95	5.11	4.97
Mean	4.11	6.81	3.09	6.72	4.01	4.88	4.94
LSD (0.05)	1.65	2.72	1.69	1.20	1.67	2.31	

Year-to-year yield differences were significant, with 2022 generally outperforming 2021 across locations. This trend corresponds with increased rainfall (e.g., +167.7 mm in Ibadan and +64.7 mm in Ilora from 2021 to 2022) and improved relative humidity, underscoring the importance of seasonal weather patterns. Supriadi et al. (2024) similarly emphasized that inter-annual weather variability has a profound impact on maize productivity and genotype performance stability. The commercial hybrid Oba Super 9 yielded an average of 4.97 t ha^{-1}, comparable to or slightly lower than several zinc-enriched hybrids. This further highlights the potential of genotypes like A1919-23 and A1831-3 for commercial deployment. Supporting evidence from Uberti et al. (2023) and Khan et al. (2018) demonstrates that advanced experimental hybrids can meet or exceed the performance of commercial standards, particularly when environmental adaptability is taken into account.

Assessment of disease resistance stability among maize hybrids across six environments

The evaluation of maize hybrids across two growing seasons revealed considerable variability in disease resistance to ear rot, maize streak virus (MSV), rust, blight, and Curvularia leaf disease (Table 7). This variability highlights the complex interplay between genetic and environmental factors in host response to pathogen infection. Thus, emphasizing the need for identifying hybrids with stable resistance profiles.

Ear rot severity increased moderately between 2021 and 2022, ranging from 1.00 to 1.89. Hybrids A1919-14 and A1919-20 exhibited consistently low severity across seasons, demonstrating strong resistance potential, while hybrid A1919-38 showed high susceptibility in 2021 (1.89 ± 0.31, CV = 49.13). This aligns with earlier environmental conditions that exacerbate ear rot severity by promoting pathogen proliferation (Ma et al., 2024).

The low severity expressed by varieties A1919-14 and A1919-20 to ear rot disease across the locations highlights their potential as parent materials in future breeding programs against the disease.

Table 7. Disease Severity and Coefficient of Variation (CV) in Zinc-Enriched Maize Hybrids Across Two Cropping Seasons (2021 and 2022)

Hybrids	Traits	Mean severity 2021	CV	Mean severity 2022	CV	Hybrids	Traits	Mean severity 2021	CV	Mean severity 2022	CV
A1830-6	Ear Rot	1.22±0.15	36.08	1.56±0.18	33.88	A1918-13	Ear Rot	1.22±0.15	36.08	1.78±0.28	46.88
	Streak	1.22±0.15	36.08	1.56±0.18	33.88		Streak	1.11±0.11	30.00	1.44±0.18	36.49
	Rust	1.11±0.11	30.00	1.56±0.18	33.88		Rust	1.22±0.15	36.08	1.67±0.24	42.43
	Blight	1.56±0.18	33.88	1.67±0.24	42.43		Blight	1.11±0.11	30.00	1.78±0.22	37.50
	Curv	1.22±0.15	36.08	1.89±0.20	31.81		Curv	1.33±0.24	53.03	1.89±0.26	41.39
A1830-7	Ear Rot	1.22±0.15	36.08	1.67±0.24	42.43	A1918-14	Ear Rot	1.33±0.17	37.50	1.67±0.24	42.43
	Streak	1.11±0.11	30.00	1.56±0.28	33.88		Streak	1.11±0.11	30.00	1.56±0.18	33.88
	Rust	1.22±0.15	36.08	1.67±0.17	30.00		Rust	1.11±0.11	30.00	1.67±0.17	30.00
	Blight	1.22±0.15	36.08	1.67±0.24	42.43		Blight	1.22±0.15	36.08	1.78±0.28	46.88
	Curv	1.22±0.15	36.08	2.11±0.20	28.46		Curv	1.11±0.11	30.00	1.78±0.22	37.50
A1831-3	Ear Rot	1.22±0.15	36.08	1.56±0.18	33.88	A1918-37	Ear Rot	1.22±0.15	36.08	1.89±0.31	49.13
	Streak	1.22±0.15	36.08	1.67±0.17	30.00		Streak	1.11±0.11	30.00	1.67±0.17	30.00
	Rust	1.11±0.11	30.00	1.67±0.24	42.43		Rust	1.44±0.18	36.49	1.56±0.18	33.88
	Blight	1.22±0.15	36.08	1.44±0.18	36.49		Blight	1.44±0.24	50.29	1.67±0.17	30.00
	Curv	1.22±0.15	36.08	2.22±0.22	30.00		Curv	1.44±0.24	50.29	2.22±0.22	30.00
A1847-32	Ear Rot	1.22+0.22	54.55	1.67±0.24	42.43	A1919-14	Ear Rot	1.00±0.00	0.00	1.22±0.15	36.08
	Streak	1.22±0.15	36.08	1.67±0.17	30.00		Streak	1.00±0.00	0.00	1.56±0.18	33.88
	Rust	1.11±0.11	30.00	1.78±0.22	37.50		Rust	1.11±0.11	30.00	1.56±0.18	33.88
	Blight	1.33±0.24	53.03	2.00±0.29	43.30		Blight	1.00±0.00	0.00	1.56±0.18	33.88
	Curv	1.22±0.15	36.08	2.11±0.20	28.46		Curv	1.33±0.17	37.50	2.22±0.22	30.00
A1919-15	Ear Rot	1.22±0.22	54.55	1.67±0.29	51.96	A1919-24	Ear Rot	1.22±0.11	36.08	1.33±0.24	53.03
	Streak	1.11±0.11	30.00	1.44±0.18	36.49		Streak	1.11±0.11	30.00	1.67±0.17	30.00
	Rust	1.11±0.11	30.00	1.67±0.24	42.43		Rust	1.22±0.15	36.08	1.44±0.18	36.49
	Blight	1.00±0.00	0.00	1.67±0.17	30.00		Blight	1.33±0.17	37.50	1.44±0.18	36.49
	Curv	1.33±0.17	37.50	2.22±0.15	19.84		Curv	1.33±0.17	37.50	1.89±0.20	31.81
A1919-17	Ear Rot	1.11±0.22	30.00	1.67±0.17	30.00	A1919-38	Ear Rot	1.00±0.00	0.00	1.33±0.17	37.50
	Streak	1.00±0.00	0.00	1.67±0.17	30.00		Streak	1.11±0.11	30.00	1.56±0.18	33.88
	Rust	1.33±0.17	37.50	1.44±0.18	36.49		Rust	1.33±0.17	37.50	1.67±0.17	30.00
	Blight	1.22±0.15	36.08	1.67±0.24	42.43		Blight	1.22±0.15	36.08	1.78±0.22	37.50
	Curv	1.33±0.24	53.03	2.33±0.17	21.43		Curv	1.22±0.15	36.08	2.44±0.24	29.72
A1919-20	Ear Rot	1.00±0.00	0.00	1.89±0.20	31.81	Local check	Ear Rot	1.33±0.24	53.03	1.67±0.24	42.43
	Streak	1.11±0.11	30.00	1.56±0.18	33.88		Streak	1.78±0.28	46.88	1.67±0.24	42.43
	Rust	1.22±0.15	36.08	1.78±0.22	37.50		Rust	1.33±0.17	37.50	1.67±0.24	42.43
	Blight	1.44±0.24	50.29	1.67±0.24	42.43		Blight	2.00±0.29	43.30	1.78±0.22	37.50
	Curv	1.22±0.15	36.08	2.11±0.20	28.46		Curv	1.56±0.29	56.59	2.44±0.18	21.56
A1919-23	Ear Rot	1.11±0.11	30.00	1.44±0.18	36.49	Oba Super 9	Ear Rot	1.44±0.18	36.49	1.67±0.24	42.43
	Streak	1.11±0.11	30.00	1.67±0.17	30.00		Streak	1.44±0.24	50.29	1.44±0.18	36.49
	Rust	1.22±0.15	36.08	1.56±0.18	33.88		Rust	1.56±0.18	33.88	1.67±0.17	30.00
	Blight	1.11±0.11	30.00	1.67±0.17	30.00		Blight	1.56±0.18	33.88	1.56±0.18	33.88
	Curv	1.11±0.11	30.00	2.22±0.22	30.00		Curv	1.44±0.18	36.49	1.89±0.20	31.81

The MSV severity remained relatively stable in all the genotypes, with scores ranging from 1.00 to 1.67. Hybrids A1919-14 and A1919-17 showed minimal disease expression, indicating inherent genetic resistance, while A1918-13 and A1919-38 exhibited higher severity in 2021, reflecting genotype-environment interactions

(Nyaligwa et al., 2018). Resistance to MSV is known to be governed by polygenics, with environmental factors playing a significant role. Thus, traits sensitive to environmental pressures emphasize the importance of incorporating such resistance traits into breeding programs (Mafu, 2013). The low coefficient of variation (30–36%) among resistant hybrids further indicates that the resistance is stable.

Rust severity was moderate, with scores ranging from 1.11 to 1.67. Hybrids A1919-23 and A1919-14 consistently demonstrated low severity, while A1830-6 and Oba Super 9 exhibited higher susceptibility in 2021 (1.67 ± 0.24). These findings align with studies suggesting that rust severity is significantly influenced by temperature and humidity fluctuations (Quade et al., 2021). Hybrids with lower severity also displayed less variability across locations, suggesting the presence of stable resistance mechanisms (Ren et al., 2021). Blight severity varied significantly, with hybrids such as A1919-14 and A1919-23 demonstrating high resistance across seasons, while the farmers' variety and A1919-38 were highly susceptible in 2021 (2.00 ± 0.29 and 1.78 ± 0.22, respectively). Previous research attributes this to the expression of quantitative resistance genes, which are critical under varying pathogen pressures (Ma et al., 2022; Abdelsalam et al., 2022). Curvularia leaf disease showed the highest severity and variability, with scores ranging from 1.11 to 2.44. Hybrids A1919-14 and A1919-17 demonstrated strong resistance with low scores and variability, whereas A1919-38 and the farmers' variety were highly susceptible, particularly in 2021 (2.44 ± 0.24). Previous studies (Wang et al., 2022; Wise et al., 2019) have shown that elevated humidity and extended periods of leaf wetness are key factors contributing to increased disease severity. Therefore, identification of hybrids exhibiting consistent resistance suggests they are well-suited for cultivation in regions susceptible to Curvularia outbreaks (Hou et al., 2013).

Overall, hybrid A1919-14 consistently emerged as the best performer across multiple traits, demonstrating broad-spectrum resistance and stability. In contrast, A1919-38 and the farmers' variety were among the least resistant, exhibiting high severity for multiple diseases. These findings emphasize the importance of prioritizing hybrids like A1919-14 in breeding programs to develop resilient maize varieties. However, hybrids with moderate severity may require specific management options to boost production. Furthermore, the poor performance of certain hybrids underscores the need for integrating cultural and chemical control measures to mitigate disease risks in susceptible genotypes. The dynamic nature of disease expression driven by genetic and environmental factors highlights the importance of identifying hybrids with stable resistance to be used as genetic materials to enhance maize productivity across diverse agroecological conditions.

AMMI Analysis of Zinc-Enriched Maize Hybrids

Table 8 presents the Additive Main Effects and Multiplicative Interaction (AMMI) and stability analysis results for 16 zinc-enriched maize hybrids tested across six environments. The findings revealed considerable differences in grain yield and stability among the genotypes and environments. The AMMI analysis indicated that environmental factors were the primary contributors to the variation in grain yield, accounting for 68.49 % of the total sum of squares (SS). Genotypic effects explained 14.77 %, while genotype-by-environment (G×E) interactions accounted for 16.74 %, highlighting the significant role of both genetic and environmental

influences on yield variability. These findings align with those of Bocianowski et al. (2024), who assessed 69 maize hybrids across five locations and found that environmental factors contributed 25.12 % to the total variation in grain yield, with genotypic effects accounting for 35.20 % and G×E interactions explaining 21.18 %. Similarly, Brankovic-Radojcic et al. (2018) emphasized the significance of G×E interactions in shaping maize yield and stability, highlighting the critical role of both genotypic and environmental components in yield performance.

The principal component analysis (PCA) of the genotype-by-environment (G×E) interaction indicated that the first principal component (PC1) accounted for 55.64 % of the G×E variability, with a statistically significant result ($p < 0.05$). The second principal component (PC2) explained 18.67 %, and when combined with the third principal component, the total contribution reached 89.26 %. These findings highlight that the majority of the G×E interaction effects can be effectively represented by the first few principal components, aiding in the understanding of stability and adaptability. This observation is consistent with previous research, such as the study by Ljubičić et al. (2023), where PC1 and PC2 explained 74.6 % and 21.2 % of the G×E interaction variation, respectively, covering 95.8 % of the total G×E effect. Similarly, Bocianowski et al. (2019) reported similar contributions from PC1 and PC2 in their examination of maize hybrids. These results underscore the critical role of environmental and genotypic factors, along with their interactions, in shaping grain yield variation and reinforce the value of AMMI analysis for identifying genotypes that are both stable and adaptable across varying environmental conditions.

Table 8. AMMI Analysis of Genotype x Environment Interaction and Principal Component Analysis

Parameters	df	SS	MS	F Value	P Value	PORCENT	PORCENAC
Env.	5	559.38	111.88	82.32	0	68.49	68.49
Genotype	15	120.64	8.04	5.92	0	14.77	83.26
Gen. x Env.	75	136.71	1.82	1.34	0.05699	16.74	100
PC1	19	76.07	4.00	3.04	0.00005	55.64	55.64
PC2	17	25.52	1.50	1.14	0.31815	18.67	74.31
PC3	15	20.43	1.36	1.03	0.42133	14.94	89.26
PC4	13	9.48	0.73	0.55	0.88746	6.94	96.19
Residuals	192	260.93	1.36				

df - degrees of freedom; MS - mean square error; SS - sum of squares; PORCENT - percent of the total variability explained; PORCENAC - percent of the total variability explain accumulative; P Value - value of significance of the test; F Value - test statistic.

Yield Performance and stability analysis of sixteen Maize Hybrids evaluated Across Environments Using the Eberhart and Russell Stability Model

Using the Eberhart and Russell (1966) model, sixteen maize hybrids were evaluated across three contrasting environments to assess yield stability and adaptability. The results (Table 9) revealed significant differences in performance, with an overall mean yield of 4.94 t ha^{-1}. Among the hybrids, A1919-23, A1831-3, and A1919-15 recorded the highest mean yields (> 5.5 t ha^{-1}), indicating superior genetic potential and environmental responsiveness. Their outstanding performance may be attributed to enhanced photosynthetic efficiency, kernel filling rate, and resilience to abiotic stress, traits that have been associated with high-yielding, stable maize

hybrids in multi-environment trials (Yan et al., 2021). In contrast, the farmers' variety produced the lowest yield (2.84 t ha^{-1}), highlighting the genetic improvements achieved in the experimental hybrids over existing commercial cultivars.

Their outstanding performance may be attributed to enhanced photosynthetic efficiency and canopy-level radiation-use improvements that increase biomass accumulation and carbon assimilation in modern hybrids, as shown in recent analyses of photosynthetic responses and ideotype-based Radiation Use Efficiency (RUE) improvements (Wu et al., 2024; Wang et al., 2024). Increased kernel-filling rate and greater final kernel weight documented as major contributors to genetic gain in grain yield further explain higher grain yield in experimental hybrids (Ren et al., 2022; Gambin et al., 2023). Finally, multi-environment evaluations demonstrate that hybrids bred for drought/heat/waterlogging resilience maintain higher and more stable yields across variable environments, supporting the link between abiotic-stress tolerance and yield stability (Das et al., 2025; Konate et al., 2025). In contrast, national and on-farm surveys report low average farmer-level maize productivity (≈2.8–2.9 t ha^{-1}) in several regions a benchmark frequently used to illustrate the yield gap closed by improved hybrids — highlighting the genetic and agronomic improvements achieved by the experimental hybrids over existing farmer varieties (Dhakal et al., 2021; Kulkarni et al., 2023)

Table 9. Grain Yield Performance, Stability Parameters, and Environmental Responsiveness of Sixteen Maize Hybrids Evaluated Across Multi-Environmental Trials Using the Eberhart and Russell Model

Hybrids	Mean	Sd	CV (%)	bi	S^2di	R^2
A1830-6	5.0439	1.957	38.798	1.2368	0.0069	0.9310
A1919-17	4.7928	2.1251	44.3395	1.2605	0.6922	0.8201
A1919-20	4.7678	1.4728	30.8909	0.9258	-0.109	0.9209
A1919-23	5.7828	1.7811	30.8007	1.1189	-0.0057	0.9198
A1919-24	5.3872	2.0677	38.3816	1.3131	-0.0028	0.9450
A1919-38	4.7172	1.737	36.8227	1.085	0.0181	0.9094
Farmers variety	2.8406	0.5366	18.8898	0.2605	-0.1614	0.5492
Oba Super 9	4.97	1.3416	26.9946	0.87	-0.2789	0.9801
A1830-7	5.0867	1.202	23.6299	0.7496	-0.1548	0.9065
A1831-3	5.6494	1.7755	31.4286	1.1137	0.0037	0.9169
A1847-32	4.6017	1.0213	22.1944	0.5318	0.1563	0.6319
A1918-13	5.0461	1.6444	32.5871	1.0352	-0.0656	0.9237
A1918-14	4.655	0.7955	17.0902	0.3318	0.1468	0.4053
A1918-37	4.7594	2.2936	48.1908	1.4589	0.0517	0.9429
A1919-14	5.375	2.0603	38.3313	1.304	0.0286	0.9336
A1919-15	5.5039	2.2034	40.0337	1.4045	-0.0023	0.9471
Mean	4.9362					

CV=Coefficient of variation, bi = regression coefficient, Sd = Standard deviation, S^2di = the deviations from regression, R^2 = coefficient of determination (Eberhart and Russell 1966).

The regression coefficient (bi) values varied considerably among hybrids, reflecting their differential adaptability to environmental variation. Hybrids A1919-23 (bi = 1.12) and A1831-3 (bi = 1.11) had regression coefficients close to unity, indicating broad adaptability across diverse production environments. This suggests that these

hybrids possess balanced physiological plasticity, enabling them to maintain yield stability under both favorable and suboptimal conditions (Oliveira et al., 2020; Meseka et al., 2016). Similar findings by Swapnil et al. (2024) demonstrated that maize hybrids with bi ≈ 1 often exhibit efficient assimilate partitioning and moderate stress tolerance, supporting stable yields across variable environments. Hybrids with bi > 1, including A1918-37 (1.46) and A1919-15 (1.40), were highly responsive to environmental improvements, performing best under optimal conditions. This responsiveness could be linked to high nutrient-use efficiency, superior sink strength, and accelerated grain filling under adequate moisture and nutrient availability (Ismail et al., 2023). However, their yield potential may decline in marginal environments due to higher metabolic demand and sensitivity to stress. Conversely, hybrids such as A1918-14 (bi = 0.33) and the farmers' variety (bi = 0.26) showed bi values substantially below unity, suggesting stability and tolerance under low-input or stress-prone conditions. Such stability is typically associated with conservative growth patterns, efficient water-use mechanisms, and drought-adaptive root architecture (Azrai et al., 2022).

The deviations from regression (S^2di) provided further insight into the hybrids' stability. Hybrids A1919-15 ($S^2di = -0.0023$) and A1831-3 ($S^2di = 0.0037$) exhibited minimal deviations, indicating high yield predictability and strong environmental buffering capacity. This interpretation aligns with the Eberhart and Russell (1966) model, where genotypes with low or non-significant S^2di values are considered stable, predictable performers across variable environments. Similar findings have been reported in maize and other crops, where minimal deviations from regression reflect a genotype's ability to maintain consistent performance and physiological equilibrium under fluctuating environmental conditions (Hasan et al., 2022; Pour-Aboughadareh et al., 2022; Manivannan, 2020).

According to Abd El-Latif et al. (2023), hybrids characterized by low S^2di not only demonstrate phenotypic stability but also exhibit sustained metabolic homeostasis and robust stress tolerance, indicating that genetic mechanisms contribute to environmental buffering. This is consistent with broader agronomic evidence that genotypes with low S^2di show minimal genotype × environment interaction effects and hence more reliable performance (Afzal et al., 2021). Conversely, A1919-17 ($S^2di = 0.6922$) displayed substantial deviation, implying a significant genotype × environment interaction and a greater susceptibility to environmental influences rather than inherent genetic stability. Thus, high S^2di values correspond to lower predictability, suggesting that such hybrids may require more specific environmental management to optimize yield (Changizi, 2014; Hasan et al., 2022).

The coefficient of determination (R^2) complemented the stability metrics by quantifying how well the regression model explained yield variation. Most hybrids exhibited high R^2 values (> 0.90), signifying strong predictability. Hybrids such as Oba Super 9 ($R^2 = 0.98$) and A1919-15 ($R^2 = 0.95$) demonstrated reliable yield responses, indicating a strong genotype–environment correlation and reduced unexplained variability (Ogunbodede et al., 2001; Wicaksana et al., 2022). High R^2 values have also been linked to stable metabolic responses and robust stress signaling pathways that minimize yield fluctuation under environmental perturbations (Bankole and Aboderin, 2024).

Integrating yield, adaptability, and stability metrics, A1919-23, A1831-3, and A1919-15 emerged as ideal candidates for wide adaptation across agroecological zones. These hybrids combine high productivity (effect) with broad adaptability and physiological resilience (causes), demonstrating a balance between responsiveness and stability. Similar cause-and-effect relationships were reported by Meseka et al. (2016) and Oyekale and Badu-Apraku, (2025), who noted that hybrids with efficient stress signaling and dynamic root systems maintain yield advantages across variable conditions. Conversely, hybrids with bi > 1, such as A1918-37, exhibit greater yield potential under intensive management but require favorable environments to fully express their genetic capacity. Hybrids with bi < 1, like A1830-7 and A1847-32, are better suited for low-input systems, where physiological efficiency and stress tolerance outweigh yield responsiveness.

The inferior performance of the local check reinforces the genetic gains achieved through hybrid development. These findings align with Eze et al. (2020) and Shojaei et al. (2022), who reported that improved hybrids outperform traditional varieties in both yield and stability. The present study elucidates the causal relationship between genetic composition, physiological adaptability, and yield performance, emphasizing the importance of continued selection for hybrids that concurrently express superior yield potential and enhanced environmental resilience.

Multi-environment AMMI Analysis for Yield Stability and genotype-by-environment interactions in sixteen Maize Hybrids evaluated across six environments

The AMMI analysis offered a thorough evaluation of genotype-by-environment interactions (GEI) for grain yield among 16 maize hybrids assessed across six different environments. The results showed highly significant differences attributable to environments, genotypes, and their interactions. This analysis is particularly significant for identifying stable and adaptable hybrids, a key objective in breeding programs aimed at improving productivity under varying environmental conditions.

The separation of genotypes and environments along these axes highlights the differential performance of hybrids in response to environmental conditions. The first two principal component axes (IPCA1 and IPCA2) explained a substantial proportion of the GEI variance, as illustrated in the biplot analysis (Figure 1). Hybrids A1830-6 and A1919-38 exhibited strong interactions with specific environments, suggesting their potential suitability for targeted conditions. In contrast, the farmers' variety and the commercial hybrid Oba Super 9 positioned near the origin indicate their relative stability across the different environments. Abid and Zahid (2018) in their study evaluated 26 yellow maize hybrids across eight diverse environments in Pakistan and observed highly significant differences in the GEI.

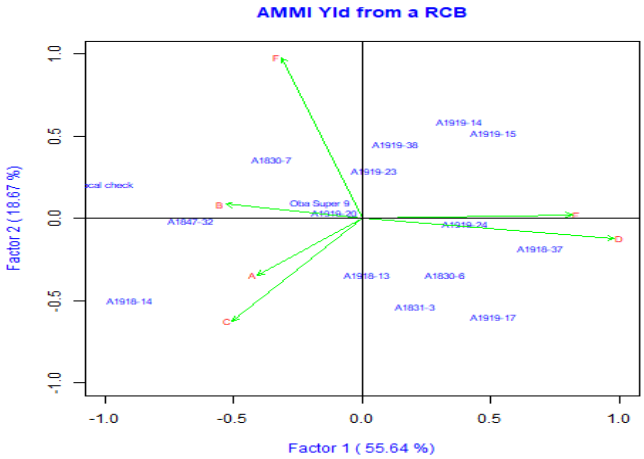

Figure 1. *Biplot of the first interaction principal component axis (IPCA1) versus the second interaction principal component axis (IPCA2) for maize hybrids. Genotype - A1830-6, A1830-7, A1831-3, A1847-32, A1918-13, A1918-14, A1918-37, A1919-14, A1919-15, A1919-17, A1919-20, A1919-23, A1919-24, A1919-38, farmers variety, and Oba Super 9 (Commercial Check). Environment – A (Ibadan 2021), B (Ibadan 2022), C (Ilora 2021), D (Ilora 2022), E (Omu-Aran 2021), and F (Omu-Aran 2022)*

The majority of the total yield variation (78 %) was attributed to environmental factors, with genotype-environment interaction also playing a role. Approximately 63 % of the variation in grain yield resulting from genotype and its interaction with the environment (GGE) was explained by the first two principal components of interaction (IPCA1 and IPCA2). Ogunniyan et al. (2021) in their research evaluated the performance of 34 maize hybrids under different nitrogen regimes and reported significant genotype × environment interaction (GEI) effects. Their findings indicated that the first two interaction principal component axes (IPCA1 and IPCA2) contributed substantially to yield variation, underscoring the critical role of GEI in the performance of maize hybrids. Similarly, Kumar et al. (2020) reported that environmental factors significantly influenced grain yield, explaining 64.7 % of the total variation, while GEI accounted for 26.6 %. Moreover, the first two IPCAs explained approximately 84 % of the variation attributable to genotype and GEI, highlighting their importance in genotype evaluation using the genotype and genotype × environment (GGE) biplot analysis.

The biplot analyses of PC1 vs. PC3 (Figure 2) and PC2 vs. PC3 (Figure 3) further confirmed the interaction patterns and revealed nuanced interactions among genotypes and environments. Hybrids A1918-14 and A1831-3 displayed considerable specific adaptations to certain environments, aligning with a narrower adaptation strategy and making them suitable for targeted cultivation under high-input or stress-specific conditions. In contrast, hybrids A1919-20 and A1919-23 showed minimal interaction effects, indicating broad adaptability and suitability as versatile candidates in breeding programs. Oyekunle et al. (2017) also reported comparable results when they evaluated the performance of 32 early-maturing maize hybrids in different locations in Nigeria and Ghana. Using genotype and genotype × environment interaction (GGE) biplot analysis, they identified hybrids exhibiting both specific and broad adaptability. Similarly, Katsenios et al. (2021) AMMI biplot analysis of maize hybrids in Greece revealed distinct interaction patterns and specific/wide adaptability, aligning with our present findings on genotype-environment relationships.

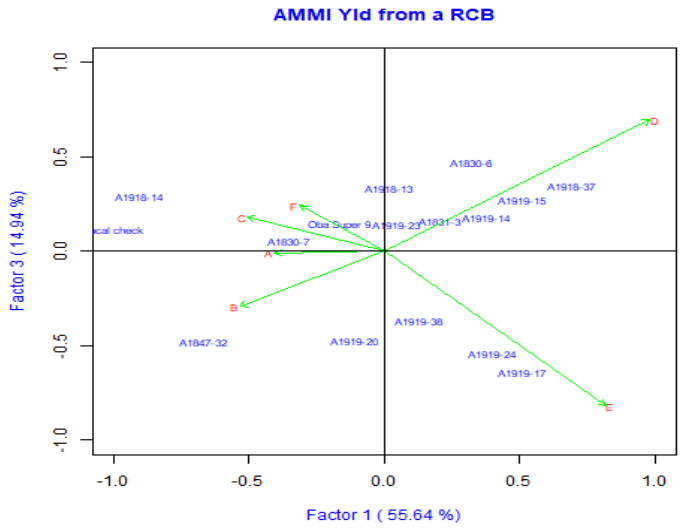

Figure 2. *Biplot PC1 vs. PC3 YLD RCB AMMI. Genotype - A1830-6, A1830-7, A1831-3, A1847-32, A1918-13, A1918-14, A1918-37, A1919-14, A1919-15, A1919-17, A1919-20, A1919-23, A1919-24, A1919-38, farmers variety, and Oba Super 9 (Commercial Check). Environment – A (Ibadan 2021), B (Ibadan 2022), C (Ilora 2021), D (Ilora 2022), E (Omu-Aran 2021), and F (Omu-Aran 2022)*

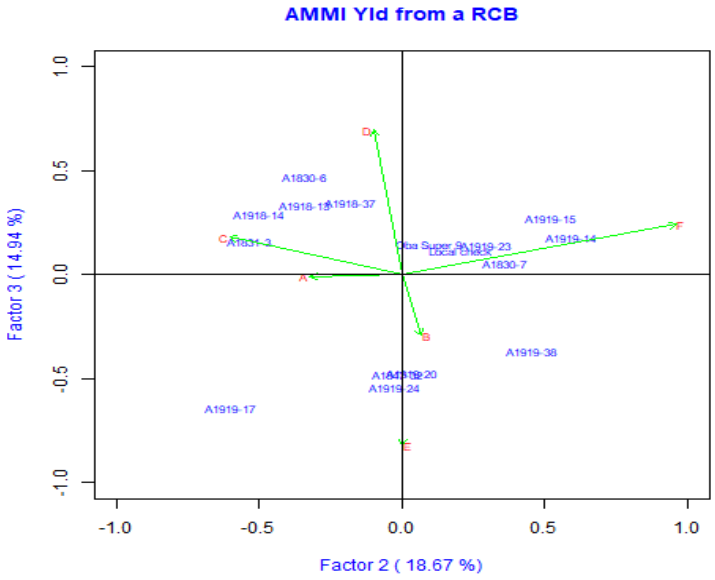

Figure 3. *Biplot PC2 vs. PC3 Yield from a RCB AMMI. Genotype - A1830-6, A1830-7, A1831-3, A1847-32, A1918-13, A1918-14, A1918-37, A1919-14, A1919-15, A1919-17, A1919-20, A1919-23, A1919-24, A1919-38, farmers variety, and Oba Super 9 (Commercial Check). Environment – A (Ibadan 2021), B (Ibadan 2022), C (Ilora 2021), D (Ilora 2022), E (Omu-Aran 2021), and F (Omu-Aran 2022)*

Environmental factors played a dominant role in determining grain yield, as evidenced by the pronounced scatter of environmental vectors in the biplots. Environment A (Ibadan 2021), for instance, had a strong

influence on genotype performance, aligning with high-yielding hybrids such as A1919-14. Meanwhile, environments D (Ilora 2022) and F (Omu-Aran 2022) were associated with genotypes exhibiting moderate yields and stability, indicating a balanced interaction profile. Several research studies corroborate the finding that environmental factors significantly influence grain yield, as demonstrated through biplot analyses. This was highlighted in the study conducted by Sesay et al. (2017), which observed that none of the environments had similar means and interaction patterns, indicating that the environments were extremely different. Similarly, Saeidnia et al. (2023) reported significant genotype × environment interactions, thereby demonstrating different genotypic responses to environmental fluctuations. This emphasizes the significant impact of environmental factors on genotype performance and highlights the necessity of multi-environment trials for assessing phenotypic stability and the influence of environmental factors on grain yield.

Figure 4 integrates the grain yield data with PCA1 scores, offering a composite view of yield stability and interaction effects. This biplot underscores the high adaptability of hybrids such as A1919-15 and A1830-7, which combined competitive yields with consistent performance across the six environments, whereas hybrids like A1847-32 and A1918-37, while high-yielding in specific environments, exhibited marked sensitivity to environmental changes, suggesting their potential for cultivation in specific environments. These findings are consistent with Abid and Zahid (2018), who reported that some hybrids exhibited high adaptability and consistent performance across different environments, while others were more sensitive to environmental changes, performing well only in specific environmental conditions.

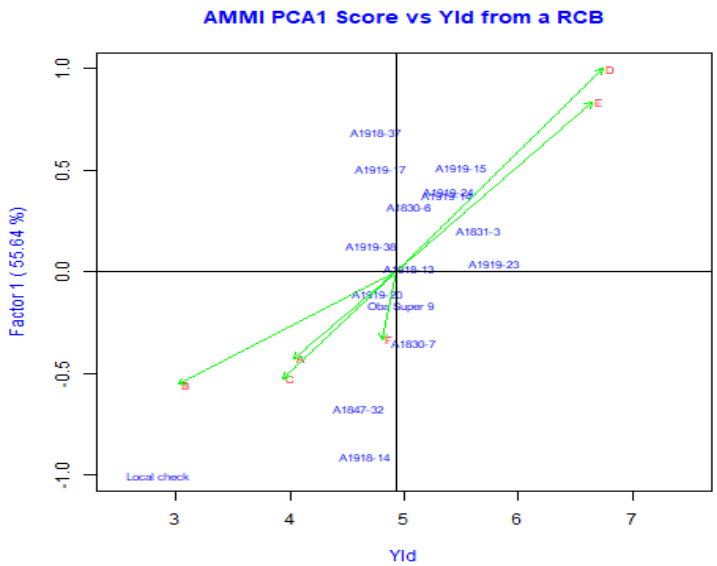

Figure 4. *Biplot analysis of GEI for the PCA1 scores and grain yield of 16 maize hybrids across six environments. Genotype - A1830-6, A1830-7, A1831-3, A1847-32, A1918-13, A1918-14, A1918-37, A1919-14, A1919-15, A1919-17, A1919-20, A1919-23, A1919-24, A1919-38, farmers variety, and Oba Super 9 (Commercial Check). Environment – A (Ibadan 2021), B (Ibadan 2022), C (Ilora 2021), D (Ilora 2022), E (Omu-Aran 2021), and F (Omu-Aran 2022)*

Conclusion

This study highlights the dual objectives of improving yield stability in zinc-enriched maize hybrids to enhance food security and nutrition in diverse growing conditions. The hybrids demonstrated significant yield potential compared to non-biofortified varieties. Hybrids A1919-23, A1831-3, and A1919-15 exhibited superior grain yield, stability, and adaptability across multiple environments, making them promising candidates for widespread adoption in maize breeding programs for addressing yield stability and nutrient enrichment. The AMMI analysis revealed a strong genotype × environment interaction, emphasizing the importance of multi-environment trials to identify hybrids with broad adaptability and environmentally specific performance. Notably, A1919-23 emerged as the most stable and high-yielding genotype, while A1830-6 showed promise for specific environments, providing valuable insights for targeted breeding strategies. The integration of zinc-enriched traits in these hybrids not only enhances their yield but also improves the productivity and nutritional value of maize while positioning biofortified maize as a sustainable solution to zinc deficiency, particularly in regions prone to malnutrition. These results underscore the need for continued breeding efforts to develop resilient, nutrient-rich hybrids suited to diverse agroecological conditions. Future research should validate these findings through multi-year trials and incorporate advanced genomic tools to optimize hybrid selection. By refining breeding strategies and enhancing adaptation to variable environments, zinc-enriched maize hybrids can play a crucial role in improving global food and nutrition security.

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This study does not require ethics committee approval. The article has been prepared in accordance with research and publication ethics. The authors were contributed jointly to the study and there was no conflict of interest between the authors.

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Appendix 1. Summary of Weather Parameters for Ibadan, Omu-Aran, and Ilora (2021 and 2022)

	Ibadan 2021				Ibadan 2022			
Month	RF (mm)	T (°C)	WS (km ph)	RH (%)	RF (mm)	T (°C)	WS (km ph)	RH (%)
January	0.8	29	6.0	64	0.4	29	5.3	54
February	3.9	30	6.7	61	2.7	29	6.3	60
March	73.5	28	8.2	72	44.8	29	9.0	70
April	65.0	29	8.5	73	77.8	27	8.4	77
May	66.8	27	8.0	80	112.7	26	7.1	83
June	123.5	26	6.6	85	215.3	25	6.6	87
July	151.2	24	7.5	87	114.4	23	7.1	89
August	252.5	24	6.9	91	247.5	23	7.5	87
September	173.2	24	5.6	90	278.6	23	5.9	92
October	112.8	25	5.6	88	92.1	25	5.4	87
November	15.2	27	5.8	80	17.2	27	5.3	75
December	0.4	28	5.0	61	3.0	28	4.9	60
Total	1038.8	321	80.4	932	1206.5	314	78.8	921
Mean	86.6	26.8	6.7	77.7	100.5	26.2	6.6	76.8
	Omu-Aran 2021				Omu-Aran 2022			
Month	RF (mm)	T (°C)	WS (km ph)	RH (%)	RF (mm)	T (°C)	WS (km ph)	RH (%)
January	0.0	28	6.6	58	0.0	27	6.5	36
February	0.0	29	6.9	55	0.0	28	6.6	50
March	72.2	28	10.4	70	15.8	28	10.1	67
April	151.9	27	10.3	73	95.9	26	10.3	76
May	148.4	26	10.6	80	134.8	25	9.1	83
June	180.9	24	8.0	85	227.1	24	8.1	87
July	167.6	23	9.8	89	162.5	23	9.4	90
August	328.7	22	8.5	92	195.8	22	9.5	90
September	269.6	23	6.4	91	252.9	22	7.5	93
October	106.8	24	6.4	87	113.3	24	5.7	84
November	14.4	26	6.6	75	1.3	26	5.8	64
December	0.0	27	5.6	47	0.0	27	5.9	43
Total	1440.5	307	96.1	902	1199.4	302	94.5	863
Mean	120.0	25.6	8.0	75.2	99.9	25.2	7.9	71.9
	Ilora 2021				Ilora 2022			
Parameter	RF (mm)	T (°C)	WS (km ph)	RH (%)	RF (mm)	T (°C)	WS (km ph)	RH (%)
January	0.3	29	6.4	59	0.1	29	5.9	43
February	0.4	30	7.2	54	1.2	29	6.3	53
March	64.3	29	9.6	68	39.8	29	10.5	65
April	82.6	29	10.0	69	61.5	28	9.9	73
May	57.8	27	9.7	78	87.4	26	8.7	81
June	139.4	26	8.0	82	160.8	25	7.9	85
July	112.0	24	9.0	85	93.9	23	8.7	88
August	235.8	23	8.1	90	253.3	23	9.0	87
September	140.2	24	6.1	90	199.0	23	6.9	92
October	76.4	25	6.4	87	73.2	25	6.0	85
November	13.8	27	6.9	76	16.0	27	5.7	69
December	0.1	28	5.4	53	1.5	28	5.4	50
Total	923.0	321	92.8	891	987.7	315	90.9	871
Mean	76.9	26.8	7.7	74.3	82.3	26.3	7.6	72.6

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