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Research Article

Genotype by environment interaction, path analysis, and yield stability of climate-resilient *DroughtTEGO* maize hybrids

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Abstract

The assessment of yield stability of climate-resilient *DroughtTEGO*® maize (*Zea mays* L.) hybrids is vital for the productivity and sustainability of maize production in Sub-Saharan Africa. This study evaluated the performance and environmental stability of *DroughtTEGO*® maize hybrids at multiple locations in Nigeria. Twenty one hybrids plus four checks were planted in an alpha lattice design with three replications for two years in nine locations. A combined analysis of variance revealed highly significant ($P < 0.01$) differences for most traits across years and locations, indicating the influence of environmental factors on the hybrid performance. Genotypic variability was observed for traits such as grain yield, plant height and flowering time, with hybrid × environment interactions significantly affecting hybrid rankings. Grain yield ranged from 3421 to 5808 kg ha^{-1}, with hybrid WE5229 outperforming commercial checks by 22.6%. Path analysis indicated that the number of ears per plant had the highest positive direct effect on yield, whereas ear aspect had the greatest negative impact. The GGE biplot analysis showed that PC1 and PC2 explained 53.41% of the total variation in grain yield, with WE9216 emerging as the most stable and highest-yielding hybrid across the locations. Ibadan and Birnin Kudu were identified as the best testing environments, whereas the other locations were useful for culling unstable hybrids. These results suggest that *DroughtTEGO*® hybrids, WE9216 and WE5229, are well-suited for commercialization in Nigeria. This study emphasizes the importance of multi-environment testing for identifying high-yielding and stable hybrids adapted to specific agro-ecologies.

1. Introduction

Maize is a major staple food and cash crop for more than 300 million smallholder farmers in Sub-Saharan Africa (SSA). Maize, in combination with rice and wheat, provides at least 30% of the food calories to more than 4.5 billion people in developing countries of the world [1]. Although maize is widely adapted to a wide range of climatic conditions, yields in the sub-region range from 1.1 to 1.7 t ha^{-1} [2], which is very low when compared with the world average yield of 4.5 t ha^{-1} [3-4]. These low yields in SSA are attributed to biotic and abiotic stresses [5-6]. Among abiotic factors, drought is one of the major factors that frequently limits maize production in the region. According to Heisey and Edmeades [7], recurrent droughts affect 20 to 25% of the world's maize production area. However, the development of varieties that are resilient to biotic and abiotic stresses is an important strategy to mitigate the constraints of maize production and productivity [1].

Nigeria is characterized by different agroecologies, ranging from rainforests to Sahel savanna. Despite the savannas of Nigeria being suitable for maize production and productivity due to high solar radiation and low disease incidence, drought, low soil nitrogen, poor adaptation to test environments, and pest infestation limit maize production [8]. In view of this, climate-resilient drought-tolerant maize hybrids trademarked *DroughtTEGO* were developed for deployment and commercialization in many African countries through a 10-year excellent breeding work by the Water Use Efficiency Maize for Africa (WEMA) Project [9-14]. An understanding of the performance of these maize hybrids in diverse growing environments in Nigeria would guide breeders in determining their suitability for narrow and wide adaptation.

The presence of genotype × environment interactions (GEI) has been identified as a key challenge in identifying superior and stable genotypes in different maize agro-ecologies [15-16]. Germplasm respond differently to different growing environments, some may be high-yielding in certain environments but low-yielding in others Thus, it is important to evaluate the new germplasm for their yield performance and stability in different growing environments before they are recommended for production, utilizing the available statistical tools [17-20].

One such tool is the genotype main effects plus genotype × environment interaction (GGE) biplot method that helps to identify the most consistently performing (stable) genotypes across diverse environments, and the most suitable test environments to guide future testing of genotypes as they are released from the breeding pipeline. Therefore, the testing environments that possess the highest ability to discriminate among genotypes and are the most representative of all test environments are the most suitable for the evaluation of new genotypes [16, 20-23].

A simple correlation may not represent the exact cause and effect relationship between yield and yield components and may result in inefficiencies in the selection strategy [24]. Path analysis is more important than correlation analysis because it partitions the correlation coefficients between two variables to evaluate whether the relationship between them is cause [25].

During the past few years, the Institute for Agricultural Research (IAR), in collaboration with the African Agricultural Technology Foundation (AATF), has extensively evaluated new climate-resilient *DroughtTEGO* maize hybrids in Nigeria. It is important to assess the performance of *DroughtTEGO* maize hybrids and testing environments to identify superior and stable hybrids, and the best test environments for hybrid evaluation to guide the recommendations for variety release to farmers. This study sought to establish and quantify genotype × environment interaction and relationships, aiming to identify indirect criteria for grain yield selection in *DroughtTEGO* maize hybrids. Therefore, this study aimed to assess the yield performance and stability of elite *DroughtTEGO* maize hybrids in major maize-growing areas of Nigeria and determine the relationship between grain yield and its related traits.

2. Materials and methods

Twenty-one medium-maturing climate-smart drought-tolerant maize hybrids trademarked *DroughtTEGO*, along with four commercial hybrid checks, were evaluated in Nigeria at six locations in 2019 and nine locations in 2020. The *DroughtTEGO* maize hybrids were developed and released for deployment and commercialization in many African countries. The experimental locations covered rain forest, southern Guinea savanna, northern Guinea savanna, and the Sudan savanna of Nigeria (Table 1). The trials were laid out in a 5 × 5 lattice design with three. replicates. In the trials, the experimental unit was a 2-row plot, 5 m long, with an inter-row spacing of 0.75 m and an intra-row spacing of 0.50 m. Three seeds were planted per hill, and the seedlings were thinned to two per hill at about 2 weeks after

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Table 1. Description of the test locations for the evaluation of *DroughtTEGO* maize hybrids in Nigeria, 2019-2020.

Location	Agro ecological zone†	Latitude	Longitude	Altitude (m ASL)	Rainfall during growing season (mm)	Year of evaluation	
						2019	2020
Zaria	NGS	12°00′N	8°22′E	640	1120	x	x
Birnin Kudu	SS	11°27'N	9°28'E	450	950	x	x
Abuja	SGS	9°16'N	7°20'E	476	1500	-	x
Minjibir	SS	6°25′N	1°06′E	500	800	-	x
Lere	SGS	9°42'N	9°20'E	260	1300	x	x
Mokwa	SGS	9°18′N	5°4′E	457	1100	x	x
Ibadan	FT	10°50'N	4°01'E	303	1700	-	x
Kachia	SGS	9°52N	7°57′E	718	1100	x	x
Kadawa	SS	12°01′N	8°19′E	520	900	x	x

† SGS = southern Guinea savanna; NGS = northern Guinea savanna; FT = forest-savanna transition zone; SS = Sudan savanna x, trial was planted; –, trial was not planted.

emergence to achieve a target plant population density of 53,333 plants ha^{-1}. A compound fertilizer (NPK, 20:10:10) was applied at a rate of 60 kg N ha^{-1} 2 weeks after planting (WAP) for all experiments. An additional 60 kg N ha^{-1} urea was top-dressed at 5 WAP. At all locations, the trials were kept weed-free using both pre- (atrazine and paraquat) and post-emergence (nicosulphuron) herbicides. In addition, manual weeding was done as necessary to ensure that the trials were weed-free.

2.1. Data collection and statistical analysis

In each experimental plot, data were collected on days to anthesis and silking, plant and ear heights, plant and ear aspects, number of ear per plant, and grain yield, as described by Oyekunle et al. [16]. A combined Analysis of Variance (ANOVA) across locations and years was done on grain yield and other measured traits with PROC GLM in SAS using the RANDOM and TEST options of SAS Institute [26]. In the combined ANOVA, location, year, hybrid, interaction, and replication were considered to be random effects. Means were separated using the least significant difference at 5% probability ($LSD_{0.05}$). The percentage contribution of each source of variation to the sum of squares was computed. The repeatability of the traits [27] was computed on a genotype-mean basis using the following formula:

$$R = \frac{\sigma_g^2}{\sigma_g^2 + \sigma_{gy}^2 / y + \sigma_{gl}^2 / l + \sigma_{gly}^2 / ly + \sigma_e^2 / re}$$

Where,

σ_g^2 is the genotypic variance,
σ_{gy}^2 is the genotype × year,
σ_{gl}^2 is the genotype × location,
σ_{gly}^2 is the genotype × location × year,
σ_e^2 is the residual variance,
l is the number of locations,
y is the number of years,
r is the number of replications per location and
e is error.

To obtain the mean grain yield of the hybrids for each location, a separate ANOVA was carried out across two-year data for each location to determine the stability of the hybrids. Thereafter, GGE biplot analysis was carried out on data on mean grain yield across replications and years for each location [19, 28-29]. The GGE biplots were built from the first two principal components (PC1 and PC2) that were derived by subjecting environment-centered grain yield means to singular-value decomposition (SVD). The options used for data analysis were no transformation (transform=0), no standardization (scale=0), and environment-centering (centering=2). The biplot was based on environment-focused singular-value partitioning (SVP=2) and was, therefore, appropriate for envisioning the relationships among locations. To determine the relationships among genotypes, biplots were based on genotype-focused singular-value partitioning (SVP=1). The following GGE biplot model was used:

$$Y_{ij} - Y_j = \lambda_1 \xi_{i1} \eta_{j1} + \lambda_2 \xi_{i2} \eta_{j2} + \varepsilon_{ij}$$

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where Y_{ij} is the mean yield of genotype i in environment j; Y_j is the mean yield across all genotypes in environment j; λ_1 and λ_2 are the singular values for PC1 and PC2, respectively; ξ_{i1} and ξ_{i2} are the PC1 and PC2 scores, respectively, for genotype i; η_{j1} and η_{j2} are the PC1 and PC2 scores, respectively, for environment j; and ε_{ij} is the residual of the model associated with genotype i in environment j.

2.2. Path analysis

Path analysis was conducted to determine the direct and indirect effects of yield-related traits on the grain yield of elite *DroughtTEGO* maize hybrids. Path analysis considered grain yield as a response/dependent variable, while all the studied traits were considered as predictive/independent variables. Estimation and fractionation of the effects of yield-related traits were performed with agricolae package version 1.3-5 [30] in R software. The direct and indirect effects of the yield-related traits were classified as negligible (0.00–0.09), low (0.1–0.19), moderate (0.2–0.29), and high (0.3–0.99), as described by Lenka and Misra [31].

3. Results

3.1. Performance of DroughtTEGO maize hybrids

The results of the combined analysis of variance showed highly significant ($P < 0.01$) differences between years and among locations for all measured traits, except for the effect of year on plant height (Table 2). Similarly, there were highly significant ($P < 0.01$) differences among hybrids for all measured traits except for anthesis-silking interval (ASI) and number of ears per plant (EPP). Furthermore, the mean square for the location × year interaction was significant ($P < 0.01$) for all measured traits, except for husk cover and EPP. Similarly, significant mean squares were observed for hybrid × location for grain yield, days to anthesis and silking, ASI, and plant and ear aspects. A significant hybrid × year effect was detected for all measured traits except for ASI, ear height, and EPP (Table 2).

The percentage contribution of location to grain yield was the highest, accounting for 35.7% of the total variation in grain yield (Table 2), followed by the year effect, which accounted for 24.2% of the total variation in grain yield. The main effect of the hybrids accounted for only 6.0% of the total variation in grain yield, whereas location × year accounted for 5.1%, hybrid × location accounted for about 16%, hybrid × year accounted for less than 2%, and hybrid × year × location accounted for 11.5%. The repeatability estimates of the hybrids ranged from 0.23 for the plant aspect to 0.77 for the husk cover characteristics (Table 2).

The grain yield of the hybrids ranged from 3421 kg ha^{-1} for P4063W to 5808 kg ha^{-1} for WE5229, with a mean of 5146 kg ha^{-1} (Table 3). The highest-yielding hybrid, WE5229, outperformed the best commercial hybrid check, Oba Super 13, by 22.6%. In addition to grain yield, hybrid WE5229 had an outstanding performance for other agronomic traits such as husk cover, plant and ear aspects (Table 3). Most hybrids attained anthesis earlier than silking, with means of 57 and 61 days, respectively. The top five *DroughtTEGO* hybrids had a yield advantage of 23 to 62% relative to the commercial checks and exhibited greater synchronization of anthesis and silking as measured by ASI, ranging from 2.3 to 2.5 days, relative to the commercial check hybrids with an ASI of 2.5 to 2.9 d. Furthermore, the top five *DroughtTEGO* hybrids had better plant and ear aspects (3.8–5.0) than the commercial check hybrids (4.6–5.3). The hybrids were shorter, with plant heights ranging from 154 to 195 cm with a mean of 171 cm. However, they had a better ear placement, than the commercial check hybrids ranging from 64-95 cm with a mean of 74 cm.

3.2. Path analysis

All the studied yield-related traits were considered as first-order predictors, and grain yield as a response variable. The direct and indirect effects of the yield-related traits are shown in Table 4. Generally, the indirect effects had lower magnitude compared to the direct effects ($\alpha \leq 0.05$). The number of ears per plant recorded the highest positive direct effect on grain yield of 93.714, followed by days to silk (49.762), and ear height (1.563). Ear aspect had the highest negative direct effect on yield of -112.435, followed by husk cover (-57.786), ASI (-46.140), plant aspect (-45.138), days to anthesis (-43.432), and plant height (-0.057).

3.3. Grain yield and environmental stability of droughtTEGO maize hybrids

The GGE biplot presented in Figs. 1–3 shows that PC1

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Table 2. Mean squares for grain yield and other agronomic traits and percentage contribution of various sources of variation for grain yield of *DroughtTEGO* maize hybrids evaluated across nine locations in Nigeria, 2019 and 2020.

Source	df	Grain yield kg ha-1	Contribution (%)	Days to anthesis	Days to silk	ASI†	Plant height, cm
Rep (Loc × Year)	30	3932487**		24.6**	24.0**	2.2**	8245.0
Block (Rep × Loc × Year)	180	1860790**		6.4	5.8	1.0*	11732.1**
Loc	8	96223237**	35.7	1068.1**	1334.6**	158.2**	214068.7**
Year	1	520696777**	24.2	1699.0**	2218.6**	26.9**	4315.9
Loc × Year	5	21901394**	5.1	986.2**	767.7**	24.8**	222859.8**
Hybrid	24	5379085**	6.0	32.7**	36.1**	0.9	14421.5**
Loc × Hybrid	192	1790094**	15.9	13.3**	14.1**	0.8*	5761.9
Year × Hybrid	24	1446231**	1.6	14.7**	13.4**	0.9	10898.4*
Loc × Year × Hybrid	120	2069394**	11.5	4.7	5.0	0.8	9120.1*
Error	651	1094876		5.0	5.0	0.7	6953.7
Repeatability		0.67		0.64	0.69	0.24	0.62

Table 2. *(continued)*

Source	EH	Husk cover (1-5) ‡	Plant aspect (1-9) §	Ear aspect (1-9) ¶	EPP#
Rep (Loc × Year)	726.0**	0.6*	2.9**	3.1**	0.08*
Block (Rep × Loc × Year)	299.7	0.4	0.9**	1.3**	0.05
Loc	35846.2**	9.0**	32.8**	28.3**	0.21**
Year	21457.5**	305.6**	5.1**	6.2**	0.40**
Loc × Year	60756.8**	3.1	11.5**	10.7**	0.05
Hybrid	576.4**	2.8**	0.9**	1.8**	0.03
Loc × Hybrid	270.4	0.4	0.7**	0.8*	0.1
Year × Hybrid	347.4	0.8**	0.9**	1.2**	0.01
Loc × Year × Hybrid	317.0**	0.3	0.6*	1.0*	0.01
Error	249.6	0.3	0.5	0.7	0.05
Repeatability	0.65	0.77	0.23	0.38	0.46

*, **, Significant at 0.05 and 0.01 probability level, respectively. †ASI, Anthesis-silking interval; ‡Husk cover (scale 1-5), where 1= husk tightly arranged and extended beyond the ear tip and 5 = ear tips exposed. §Plant aspect (scale 1-9), where 1 = excellent plant type and 9 = poor plant type. ¶Ear aspect (scale 1-9), where 1 = clean, uniform, large, and well-filled ears and 9 = ears with undesirable features. #EPP, number of ears per plant

accounted for 38.62% of the total variation, whereas PC2 accounted for 14.79% of the variation in grain yield. Thus, the two axes accounted for 53.41% of the total variation in grain yield. In the polygon view of the biplot, the vertex hybrids in each sector represented the highest-yielding hybrid in the location that fell within that sector. Thus, based on this information, Entry 12 (WE6205) was the highest-yielding hybrid at Zaria, Lere, and Minjibir locations; Entry 21 (WE9216) was the highest-yielding hybrid at Birnin Kudu, Ibadan and Kadawa locations; and Entry 10 (WE5229) was the vertex hybrid at Abuja, Kachia, and Mokwa (Fig. 1). However, no environment fell into the sector where two of the commercial check hybrids Entries 24 (SC719) and 25 (P4063W), were vertex hybrids, indicating that these hybrids were the lowest-yielding hybrids at some or all locations. The four hybrids (Entries 2 [WE1259], 8 [WE5210], 11 [E6204], and 23 [Oba Super 13] located close to the origin of the polygon, were less responsive to those locations than the vertex hybrids.

In the biplot of Fig. 2, the hybrids were ranked along the average-tester axis, with the arrow pointing to a greater value based on their mean performance across all locations. The double-arrowed line separated entries with below-average mean yield from those

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Table 3. Grain yield and other agronomic traits of *DroughtTEGO* maize hybrids were evaluated across nine locations in Nigeria in 2019 and 2020.

Entry	Hybrid	Grain yield, kg ha^{-1}	Days to anthesis	Days to silk	ASI†	Plant height (cm)	Ear height (cm)	Husk cover (1-5) ‡	Plant aspect (1-5) §	Ear aspect (1-5) ¶	EPP#
1	WE1254	4985	56	60	2.6	168	74	3.3	5.1	5.0	0.9
2	WE1259	5483	57	61	2.5	162	69	2.2	4.8	4.4	1.0
3	WE3205	4899	58	62	3.6	162	65	2.4	5.3	4.8	1.0
4	WE3210	5168	58	62	2.7	189	76	2.5	4.9	4.6	0.9
5	WE4207	5487	58	63	2.9	170	74	2.2	4.5	4.8	1.0
6	WE4208	5086	56	60	2.7	162	69	2.4	5.1	4.5	1.0
7	WE5202	5251	58	63	3.2	165	75	2.4	5.0	4.5	1.0
8	WE5210	4899	58	62	2.5	172	73	2.8	5.0	4.8	1.0
9	WE5215	5479	56	60	2.8	180	81	2.6	4.9	4.6	0.9
10	WE5229	5808	57	60	2.3	177	83	2.4	4.7	3.8	1.0
11	WE6204	5326	56	60	2.6	168	75	2.2	5.1	4.6	0.9
12	WE6205	5236	56	60	2.5	169	73	2.3	5.2	4.8	1.0
13	WE7202	5102	55	58	2.2	165	72	2.3	5.1	4.8	0.9
14	WE7208	5735	56	59	2.5	171	76	3.0	5.0	4.6	1.0
15	WE7211	4632	56	60	2.8	166	72	2.1	5.1	4.9	1.0
16	WE8204	5172	55	59	2.3	171	70	2.4	5.0	4.5	1.0
17	WE8206	5403	56	60	3.0	171	64	2.4	4.9	4.1	1.0
18	WE8216	5368	56	60	2.1	178	78	2.1	5.2	4.6	0.9
19	WE9202	5698	55	59	2.5	165	71	2.6	4.9	4.3	1.0
20	WE9214	5502	55	59	2.5	157	68	2.4	4.9	4.2	0.9
21	WE9216	5648	56	59	2.4	154	75	2.3	5.0	4.4	1.0
22	Oba Super 9	4567	58	63	2.7	178	82	2.5	5.3	4.9	0.9
23	Oba Super 13	4737	57	62	2.6	181	77	2.8	5.1	4.8	0.9
24	SC719	4559	61	66	2.9	195	95	1.6	4.7	4.6	0.9
25	P4063W	3421	61	66	2.5	174	70	2.2	5.2	5.1	0.9
	Mean	5146	57	61	2.6	171	74	2.4	5.0	4.6	1.0
	LSD	786	3	3	0.8	16	11	0.4	0.5	0.6	0.1
	CV	23	4	4	28.7	13	16	25.1	14.8	18.0	11.3
	Min	3421	55	58	2.1	154	64	1.6	4.5	3.8	0.9
	Max	5808	61	66	3.6	195	95	3.3	5.3	5.1	1.0

†ASI, Anthesis-silking interval; ‡Husk cover (scale 1-5), where 1= husk tightly arranged and extended beyond the ear tip and 5 = ear tips exposed. §Plant aspect (scale 1-9), where 1 = excellent plant type and 9 = poor plant type. ¶Ear aspect (scale 1-9), where 1 = clean, uniform, large, and well-filled ears and 9 = ears with undesirable features. #EPP, number of ears per plant.

Table 4. Estimates of direct and indirect effects of the different traits on grain yield of maize hybrids tested at nine locations in 2019 and 2020.

Response Trait	Estimate	Std. Err	z-value	P(>|z|)	Std. lv	Std. all
Days to anthesis	-43.432	21.385	-2.031	0.042	-43.432	-0.789
Days to silk	49.762	21.257	2.341	0.019	49.762	0.934
Anthesis-silking interval	-46.14	22.185	-2.08	0.038	-46.14	-0.251
Plant height	-0.057	0.072	-0.801	0.423	-0.057	-0.022
Ear height	1.563	0.256	6.106	0.000	1.563	0.173
Husk cover	-57.786	7.755	-7.452	0.000	-57.786	-0.181
Plant aspect	-45.138	7.545	-5.983	0.000	-45.138	-0.164
Ear aspect	-112.435	7.224	-15.565	0.000	-112.435	-0.451
Number of ears per plant	93.714	28.77	3.257	0.001	93.714	0.079

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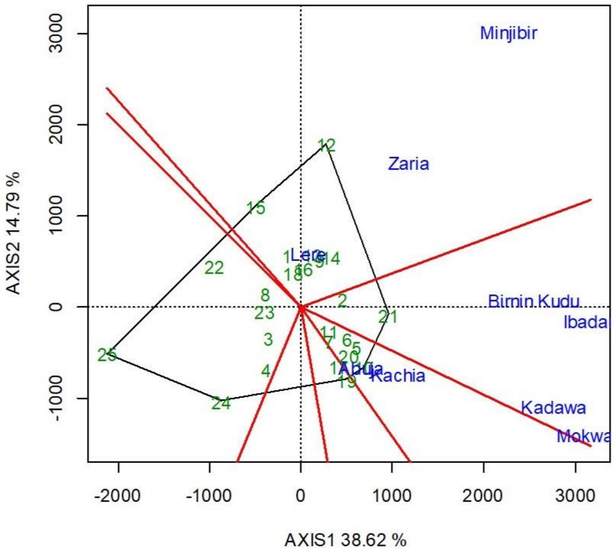

Figure 1. A 'which-won-where' or 'which-is-best-at-what' based on a genotype × environment yield data of 25 *DroughtTEGO* maize hybrids evaluated across nine locations in Nigeria, 2019 and 2020. See Table 3 for the hybrid's legend.

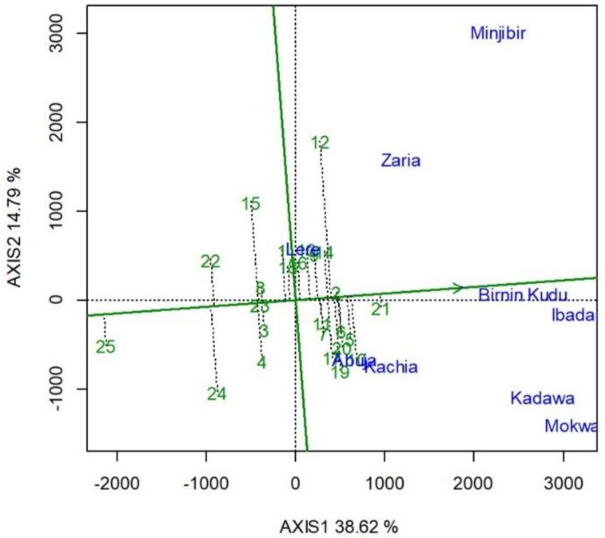

Figure 2. The 'mean v. stability' view of the GGE biplot based on genotype × environment yield data of 25 *DroughtTEGO* maize hybrids evaluated across nine locations in Nigeria, 2019 and 2020. See Table 3 for the hybrid's legend.

with above-average mean yield. The mean yield of the hybrids was approximated by the projections of their markers on the average-tester axis. The stability of the hybrids was measured by their projection onto the double-arrow line (average-tester coordinate [ATC] y-axis). The greater the absolute length of a hybrid projection the less stable the hybrid. Thus, Entry 21 (WE9216) exhibited outstanding yield performance and was the most stable hybrid across all testing environments. Conversely, Entry 25 (P4063W) was the lowest-yielding, although it was a stable hybrid.

3.4. Discriminating power and representativeness of test environments

The discriminating power vs. representativeness view of the GGE biplot analysis is presented in Fig. 3. The short-vector locations, i.e., Lere, Abuja, and Kachia, may be regarded as independent testing locations and treated as unique locations. It is interesting to note that the two most contrasting locations, Ibadan in the derived savanna agro-ecology and Birnin Kudu in the Sudan savanna agroecology, were identified as the best testing locations in Nigeria. The other locations with long vectors but large angles with the AEC, such as Zaria, Kadawa, and Mokwa, cannot be used to select superior hybrids but may be useful in culling unstable hybrids in a pool of germplasm during the preliminary stages of evaluation.

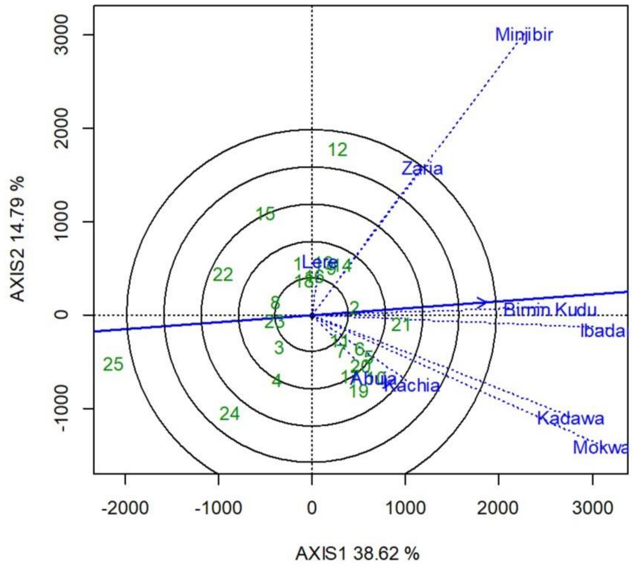

Figure 3. The 'discriminating power and representativeness' view of GGE biplot based on a genotype × environment yield data of 25 *DroughtTEGO* maize hybrids evaluated across nine locations in Nigeria, 2019 and 2020. See Table 3 for the hybrid's legend.

4. Discussion

4.1. Performance of DroughtTEGO maize hybrids

The presence of significant differences between years and locations for most traits indicated the uniqueness of the testing environments in assessing the hybrid

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performance. This suggests the possibility of identifying the best testing location(s) for evaluating climate-smart *DroughtTEGO* maize hybrids in Nigeria. The significant mean squares obtained for the genotypic effect for all measured traits except ASI and EPP, showed the existence of genetic variability amongst the hybrids for the traits as previously reported [16, 32-33]. This suggests a high possibility of identifying high-yielding maize hybrid(s) with narrow or broad adaptation in Nigeria.

The presence of significant hybrid × year indicated differences in the ranking of the hybrids in the two-year evaluation, suggesting the need for extensive evaluation of the hybrids for more than one year before recommending genotypes for deployment and commercialization to farmers. Significant hybrid × location × year effect was also observed for grain yield, plant and ear heights, and plant and ear aspects, indicating that the ranking of the hybrids was not consistent in the different locations and years. The differential responses of genotypes with varying years and locations complicate the identification and selection of outstanding maize hybrids for commercialization. The results suggest the need for extensive testing of *DroughtTEGO* maize hybrids in multiple locations across years to guide hybrid recommendations to farmers in Nigeria, as previously reported [16, 34]. The existence of a significant hybrid × location × year interaction for grain yield prompted the use of the GGE biplot to explain the nature of G + G × E interaction in determining the best high-yielding and most stable maize hybrids as well as to identify the best testing locations in Nigeria.

The percentage contributions by the main effects and their interactions were within the limits previously reported by Badu-Apraku et al. [15, 35] and Oyekunle et al. [16]. The large proportion of the contribution of the location and year effects to the total sum of squares for grain yield observed in the present study was expected because the hybrids were evaluated in diverse locations covering different agro-ecologies spread across the country with varying weather conditions from year to year. Interactions involving years tend to be less predictable, whereas those involving locations related to soil and elevation are more predictable [36]. Conversely, the low proportion of the genotypic main effect to the total sum of squares for grain yield observed in this study was expected because the hybrids evaluated were the top-yielding hybrids developed and released for deployment and commercialization in East and Southern Africa through the 10-year breeding work by the WEMA Project [9, 10, 13-14]. This result is consistent with the finding that the largest proportion of total variation in multi-location trials was mostly attributed to the environments, whereas G and G × E sources of variation were relatively smaller [16, 35, 37].

The moderately high repeatability estimates in this study for grain yield and most of the other traits, except ASI, plant, and ear aspects, imply that the expression of these traits was consistent in the test environments; and that there was a possibility of predicting the performance of the newly developed maize hybrids in future studies in the same environments. This indicates that the hybrids had a better ability to adapt to varying environmental conditions such as nitrogen and moisture stress [33].

4.2. Path analysis

Path analysis is a statistical method used to evaluate the direct and indirect relationships between multiple variables, allowing researchers to understand how different traits contribute to a response variable, in this case, grain yield in maize. To make sound breeding and management decisions to improve grain yield, plant breeders must have a clear understanding of the different yield-related traits in maize and their influences on yield. By considering all yield-related traits as first-order predictors and grain yield as the response variable, the path analysis provides insights into the dynamics of trait interactions. According to the results, the direct effects of the yield-related traits on grain yield were generally greater in magnitude compared to their indirect effects ($\alpha \leq 0.05$). This suggests that the traits exert a more immediate influence on yield, highlighting the importance of focusing on these direct contributors when aiming to improve maize yield.

The number of ears per plant trait recorded the highest positive direct effect on grain yield, with a value of 93.714. This finding aligns with numerous studies that emphasize the critical role of ear number in determining maize yield. For instance, Nielsen [38]

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indicated that an increase in the number of ears directly correlates with higher grain production, as each ear can contribute significantly to the total yield. Days to silking had a substantial positive direct effect of 49.762 days on grain yield. The timing of silking is essential for successful pollination, and studies such as those by Bolaños and Edmeades [39] have shown that earlier silk dates can enhance yield by improving flower synchronization. Although, the positive direct effect of ear height was relatively low at 1.563, it-was still significant. Research indicates that ear height can influence harvest ability and exposure to external factors, such as rodents, which may affect the overall yield [40].

In contrast to the positive effects, certain traits exhibited negative direct effects on yield, with the highest negative direct effect of -112.435, the ear aspect highlights the detrimental impact that poor ear morphology can have on grain yield. Beyer et al. [41] noted that suboptimal ear characteristics, such as small size or poor filling, directly lead to reduced yield potential. The husk cover trait was followed by a negative direct effect of -57.786, indicating that inadequate husk coverage may expose kernels to environmental factors, which can lead to yield losses, as explained by Tollenaar and Lee [42]. Other traits, such as plant aspect, ASI, days to anthesis, and plant height, also demonstrated negative effects, underscoring the complex interplay between various traits and their combined impact on yield. For instance, Edmeades et al. [43] highlighted the significance of synchrony between flowering and silking, with a delay in these events potentially reducing yield. The path analysis results indicated that while certain traits, such as EPP and days to silk, positively influenced grain yield, other traits, such as poor ear aspect and husk cover significantly detracted from yield potential. Understanding these direct and indirect effects can guide breeding strategies aimed at improving maize productivity, ultimately contributing to food security.

4.3. Grain yield and environmental stability of droughtTEGO maize hybrids

The identification of the highest-yielding hybrids at different locations implied that these hybrids were more adaptable to those locations or agro-ecologies and could be recommended for release and commercialization in those specific environments where they were more adapted.

The identification of Entry 21 (WE9216) as the highest-yielding and most stable hybrid indicated that Entry 21 was the best hybrid across the maize-growing agro-ecology; thus, it should be promoted for adoption and commercialization in Nigeria.

4.4. Discriminating power and representativeness of test environments

The identification of the best testing locations is crucial for effective selection of superior hybrids in any hybrid breeding program. An ideal testing location should possess two characteristics, most discriminating of the genotypes and representative of all environments [21]. The short-vector locations, that is Lere, Abuja, and Kachia, may be regarded as independent testing locations and treated as unique locations. This implies that these locations provide little or no information on the genotypes and, therefore, should not be used as test environments in future evaluations [20]. However, the long-vector locations, i.e., Zaria, Birnin Kudu, Ibadan, Kadawa, Minjibir, and Mokwa, were more effective in discriminating among the maize hybrids. Locations with long vectors and small angles with the AEC abscissa are the best for selecting superior genotypes, [16, 29]. The Ibadan and Birnin Kudu locations had a long vector (high discriminating power) and formed a small angle with the AEC abscissa (most representative), therefore, they were the most discriminating and representative testing locations.

It is interesting to note that the two most contrasting locations, Ibadan in the derived savanna agroecology and Birnin Kudu in the Sudan savanna agroecology, were identified as the best testing locations in Nigeria. This results could be due to the favourable environmental factors, such as adequate sunshine, low pest and disease pressure and good edaphic conditions at the two sites. The other locations with long vectors but large angles with the AEC, i.e., Zaria, Kadawa, and Mokwa, cannot be used to select superior hybrids but may be useful in culling unstable hybrids in a pool of germplasm during the preliminary stages of evaluation [20]. The results of this study on medium maturing drought-tolerant

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maize hybrids contrast with the findings of Badu-Apraku et al. [35] and Oyekunle et al. [16]. Badu-Apraku et al. [35] reported that Zaria location in the northern Guinea savanna characterized by moderately high rainfall, which was the most representative and highly discriminating of the test environments and, therefore, the best location for their studies on 12 extra-early maturing maize cultivars. In contrast, Oyekunle et al. [16] reported that Minjibir in the Sudan savanna represented the ideal test location in Nigeria for the evaluation of early-maturing maize hybrids used in their study. The differences in the results of the current study and earlier studies [16, 35] could be attributed to the type of cultivars (hybrids or open-pollinated cultivars), maturity groups (extra-early, early, and medium), and the magnitude of the location used in the evaluation, which might have influenced the identification of the best testing locations.

5. Conclusions

The performance of *DroughtTEGO* maize hybrids demonstrated considerable genetic variability and environmental interactions, confirming the adaptability of these hybrids to varying agro-ecological conditions in Nigeria. The top five performing *DroughtTEGO* hybrids (WE5229, WE7208, WE9205, WE9214 and WE9216) had 23 to 62% greater yield relative to the commercial check hybrids (3421–4737 kg ha^{-1}). Significant genotype × environment interactions, particularly for grain yield, days to flowering, and plant height, highlight the importance of multi-environment testing in breeding programs to ensure the selection of high-yielding and stable hybrids. The GGE biplot analysis identified specific hybrids, such as WE9216 and WE5229, that exhibited superior yield performance and stability across multiple locations, making them strong candidates for commercialization. These hybrids have great potential to enhance maize production in Nigeria, thereby contributing to food security and climate resilience. Moreover, the study identified Ibadan and Birnin Kudu as the most discriminating and representative testing environments, reinforcing their importance in future breeding trials in Nigeria. The path analysis underlined the critical role of yield-related traits, such as the number of ears per plant and days to silking in enhancing grain yield, whereas poor ear aspect and husk cover detracted from yield potential.

Authors' contributions

Formal analysis, M.O., J.P.S.; resources, M.O., E.N., Y.B., S.O.O.; data curation, M.O.; J.P.S.; writing – original draft preparation, M.O.; visualization, M.O.; supervision, M.O., R.S.A.; project administration, S.O.O.; funding acquisition, S.O.O.

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Availability of data and materials

All data will be made available on request according to the journal policy.

Conflicts of interest

The authors have no relevant financial or non-financial interests to disclose.

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