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# Assessment of Early-Maturing Maize Hybrids and Testing Sites Using GGE Biplot Analysis

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## ABSTRACT

Identification of outstanding maize (*Zea mays* L.) hybrids for target environments is complicated by genotype × environment interactions. Thirty-two early-maturity maize hybrids were evaluated at eight locations in Nigeria and six locations in Ghana for 2 yr to (i) identify high-yielding, stable hybrids across locations and/or hybrids specifically adapted to different locations, and (ii) identify ideal test sites for selection of superior hybrids in the two countries. Genotype, country, year, location (country), and their interactive effects were significant ($P < 0{\cdot}01$) for grain yield, days to anthesis and silking, anthesis-silking interval, plant and ear aspects, and ears per plant. Mean grain yield of the hybrids ranged from 3177 kg ha$^{-1}$ for EWH-5 to 4596 kg ha$^{-1}$ for EWH-29. The genotype main effects plus genotype × environment interaction (GGE) biplot analysis revealed that EWH-29, EWH-8, and EWH-30 did not differ significantly in grain yield and were the most stable hybrids in both countries, whereas EWH-26 and EWH-32 were the most stable hybrids only in Ghana. The GGE biplot analysis identified Samaru, Kafin Soli, and Minjibir in Nigeria and Nyankpala, Damongo, and Fumesua in Ghana as the most discriminating locations. Minjibir (Nigeria) and Nyankpala (Ghana), being most discriminating and representative locations, were considered the ideal testing sites for the respective countries. The type of cultivars evaluated determined the most suitable locations for multilocation testing within Ghana and Nigeria. Whereas hybrids EWH-29, EWH-8, and EWH-30 should be suitable for production in Nigeria, EWH-26 and EWH-32 should be promoted for production in Ghana.

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**Abbreviations:** AEA, average-environment axis; AEC, average environment coordinate; AMMI, additive main effects and multiplicative interaction; ASI, anthesis-silking interval; E, environment; EPP, ears per plant; G, genotype; GGE, genotype main effects plus genotype × environment interaction; L, location; PC, principal component; WA, West Africa; Y, year.

Maize (*Zea mays* L.) is an important staple crop for rural and urban dwellers of West Africa (WA). Savanna agroecological zones of the subregion have the highest potential for increased maize production and productivity because of high solar radiation, low night temperatures, and low incidence of diseases. Despite the immense potential of maize in the savannas of WA, its production is greatly constrained by biotic and abiotic factors, such as *Striga hermonthica* (Delile) Benth., recurrent drought, and low soil fertility, especially low soil nitrogen (N) (Badu-Apraku et al., 2003). In view of this, international and national maize breeding programs have developed several early-, extra-early-, intermediate-, and late-maturing white- and yellow-endosperm source populations, open-pollinated varieties, and hybrids, which combine tolerance to drought and low soil N and resistance to *Striga*. The early (90- to 95-d maturity) maize hybrids are capable of contributing significantly to food security, especially in marginal rainfall areas of WA

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(Badu-Apraku et al., 2013). To promote rapid adoption and commercialization of maize in the savannas of WA, there is a need for developing early-maturity maize hybrids that are resistant or tolerant to *Striga* infestation, drought, and low soil N. The early-maturing and extra-early-maturing genotypes afford farmers the opportunity to market the early crop as green maize at a premium price, as well as to use such genotypes for intercropping (IITA, 1992; Badu-Apraku et al., 2011).

The presence of genotype (G) × environment (E) interaction complicates identification of superior cultivars in multilocation trials (Yates and Cochran, 1938; Comstock and Moll, 1963; Fakorede and Adeyemo, 1986; Badu-Apraku et al., 2008; Badu-Apraku et al., 2011). In multilocation trials, some cultivars may be high yielding in some environments and low yielding in other environments. Therefore, it is important to assess the early-maturing maize hybrids to identify high-yielding and stable hybrids and also to identify ideal testing sites in WA. The identification of ideal testing sites could reduce cost of testing and enhance efficiency of selection of high-yielding and stable, early-maturing hybrids for commercialization in the countries of WA.

Several statistical methods have been used for the analysis and interpretation of multienvironment trial data (Yates and Cochran, 1938; Crossa and Cornelius, 1997; Gauch and Zobel, 1997; Yan et al., 2000, 2007). Of these statistical tools, the two most frequently used are the additive main effects and multiplicative interaction (AMMI) model (Gauch, 1988; Zobel et al., 1988; Gauch and Zobel, 1997) and the genotype main effect plus G × E interaction (GGE) biplot methodology proposed by Yan et al. (2000). Several reviews have compared and contrasted AMMI and GGE biplot methods with respect to their suitability for G × E analysis (Gauch, 2006; Yan et al., 2007; Gauch et al., 2008; Yang et al., 2009, Badu-Apraku et al., 2011). Badu-Apraku et al. (2011) reported that the AMMI and GGE biplots provided similar results relative to stability and performance of the cultivars but concluded that the GGE biplot was more versatile and flexible and provided a better understanding of G × E interaction than the AMMI method. The GGE biplot is considered effective in identifying the best-performing genotype(s) in a given environment (specific adaptation) and the most suitable environment(s) for each genotype, and for comparing pairs of genotypes in individual environments (Yan and Kang, 2003; Yan and Tinker, 2006; Yan et al., 2007; Yan, 2014). In addition, the GGE biplot method helps identify the most consistently performing (stable) genotypes and the most suitable test environments (i.e., those that possess the highest ability to discriminate among genotypes and are most representative of all test environments) (Yan and Kang, 2003; Yan and Tinker, 2006; Yan et al., 2007; Yan, 2014). Badu-Apraku et al. (2008) and Badu-Apraku and Lum (2010) used the GGE biplot analysis to obtain information on the early-maturing maize cultivars that were suitable for *Striga*-infested and *Striga*-free environments and to determine stability of cultivars across environments. However, GGE biplot methodology has not been used to assess the performance of early-maturing maize hybrids and to identify ideal test locations in WA.

During the past decade, the International Institute of Tropical Agriculture (IITA), in collaboration with national scientists in Nigeria and Ghana, has been involved in extensive testing of early-maturing maize hybrids, with funding support from the Drought Tolerant Maize for Africa Project. However, information on target environments and ideal test environments within each country is lacking. Therefore, the objectives of this study were (i) to identify high-yielding, stable, and specifically adapted maize hybrids in and across Ghana and Nigeria, and (ii) to identify ideal testing sites within each country for selection of superior maize hybrids.

## MATERIALS AND METHODS

Thirty-two early-maturity, white-endosperm, drought-tolerant maize hybrids identified from a number of preliminary hybrid trials conducted from 2008 to 2012 were evaluated in regional hybrid trials at eight locations in Nigeria and six locations in Ghana in 2013 and 2014. The description of the experimental sites is presented in Table 1. All hybrids came from the Drought Tolerant Maize for Africa program of the IITA. All trials were conducted under rainfed conditions and were planted when rains at each site had become fully established. The trials were conducted at all sites using an eight-by-four randomized incomplete block design with three replications. A plot consisted of two 5-m-long rows, with inter-row spacing of 0.75 m and intra-row spacing of 0.4 m. Three seeds were planted per hill, and later the stand was thinned to two plants per hill, giving a final population density of ~66,666 plants ha$^{-1}$. A compound fertilizer (N-P-K 15:15:15) was applied at the rate of 60 kg N ha$^{-1}$, 60 kg P ha$^{-1}$, and 60 kg K ha$^{-1}$ 2 wk after planting at all locations. An additional 30 and 60 kg N ha$^{-1}$ urea was topdressed 3 wk later in Ghana and Nigeria, respectively. The trials were kept weed free by applying 5 L ha$^{-1}$ each of a mixture of paraquat as a foliar contact herbicide and atrazine as a preemergence herbicide. Subsequently, manual weeding was done as necessary to keep the trials weed free.

Data were recorded from each plot on days to 50% anthesis and silking as the number of days from planting to when 50% of the plants had shed pollen and had silk emergence, respectively. Anthesis-silking interval (ASI) was determined as the difference between days to 50% silking and days to 50% anthesis. Plant and ear heights were measured as the distance from the base of the plant to the height of the first tassel branch and the node bearing the upper ear, respectively. Husk cover was rated on a scale of 1 to 5 (where 1 = tight husk, extending beyond the ear tip, and 5 = ear tips exposed). Plant aspect was recorded on a scale of 1 to 5 according to plant and ear heights, uniformity of plants, ear size, lodging, disease, and insect damage (where 1 = excellent plant type, and 5 = poor plant type). Ear aspect was recorded on a scale

Table 1. Description of the test locations for the evaluation of early-maturity maize hybrids in Ghana and Nigeria in 2013 and 2014.

| Country | Location | Code | Agroecological zone† | Latitude | Longitude | Altitude | Rainfall during growing season |
|---|---|---|---|---|---|---|---|
| | | | | | | m asl | mm |
| Ghana | Damongo | DM | NGS | 9°50′ N | 1°49′ W | 252 | 1050 |
| Ghana | Ejura | EJ | FT | 7°38′ N | 1°37′ E | 90 | 1460 |
| Ghana | Fumesua | FU | FT | 6°41′ N | 1°28′ W | 150 | 1345 |
| Ghana | Manga | MA | SS | 11°01′ N | 0°16′ W | 270 | 1000 |
| Ghana | Nyankpala | NY | NGS | 9°25′ N | 0°58′ E | 340 | 1090 |
| Ghana | Pokuase | PO | NGS | 6°43′ N | 1°36′ W | 287 | 1100 |
| Nigeria | Samaru | SA | NGS | 12°00′ N | 8°22′ E | 640 | 1120 |
| Nigeria | Batsari | BA | SS | 12°45′ N | 7°14′ E | 608 | 950 |
| Nigeria | Kafin-Soli | KS | SS | 12°31′ N | 7°43′ E | 598 | 900 |
| Nigeria | Minjibir | MJ | SS | 6°25′ N | 1°06′ E | 500 | 800 |
| Nigeria | Talata Mafara | TM | SS | 12°33′ N | 6°40′ E | 319 | 780 |
| Nigeria | Mokwa | MK | SGS | 9°18′ N | 5°40′ E | 457 | 1100 |
| Nigeria | Lapai | LA | SGS | 9°40′ N | 6°43′ E | 263 | 1100 |
| Nigeria | Ilorin | IL | SGS | 8°30′ N | 4°32′ E | 289 | 1200 |

† SGS, southern Guinea savanna; NGS, northern Guinea savanna; FT, forest-savanna transition zone; SS, Sudan savanna.

of 1 to 5 (where 1 = clean, uniform, large, and well-filled ears, and 5 = ears with undesirable features). Number of ears per plant (EPP) was obtained by dividing the total number of ears per plot by the number of plants harvested. Grain yield was calculated on the basis of 80% (800 g grain kg$^{-1}$ ear weight) shelling percentage and adjusted to 150 g kg$^{-1}$ moisture content.

Combined ANOVA across locations was performed on plot means for grain yield and other measured traits with PROC GLM in SAS using the RANDOM and TEST options (SAS Institute, 2002) to determine interactions of genotypes with locations, countries, and years. In the combined ANOVA, locations, years, interactions, and replications were considered random effects, whereas genotypes and countries were considered fixed effects. Means were separated using the LSD. The percentage contribution of each source of variation was computed for grain yield on the basis of sum of squares. To obtain mean grain yield of the hybrids for each location, ANOVA was performed across 2 yr for each location to determine the stability of hybrids within each country and across countries. Subsequently, data on mean grain yield across replications were subjected to GGE biplot analysis (Yan, 2001, 2014; Yan et al., 2000, 2010) across test locations within each country and across the two countries.

The GGE biplots were constructed from the first two principal components (PC1 and PC2) that were derived by subjecting environment-centered grain yield means to singular-value decomposition. 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 visualizing the relationships among locations. When relationships among genotypes were desired, the biplots were based on genotype-focused singular-value partitioning (SVP = 1). The following GGE biplot model was used (Yan and Kang, 2003):

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

where $Y_{ij}$ is the mean yield of genotype $i$ in environment $j$; $\overline{Y}_j$ is the mean yield across all genotypes in environment $j$; $\lambda_1$ and $\lambda_2$ are the singular values for PC1 and PC2, respectively; $\xi_{i1}$ and $\xi_{i2}$ are the PC1 and PC2 scores, respectively, for genotype $i$; $\eta_{j1}$ and $\eta_{j2}$ are the PC1 and PC2 scores, respectively, for environment $j$; and $\varepsilon_{ij}$ is the residual of the model associated with genotype $i$ in environment $j$.

# RESULTS AND DISCUSSION

## ANOVA and Performance of Early-Maturing Maize Hybrids

The results of combined ANOVA across sites and years for the 32 genotypes revealed that there were significant ($P < 0.01$) differences between the two countries for all traits, except husk cover and plant and ear aspects, and among genotypes for all traits, except husk cover and ear aspect (Table 2). The presence of significant differences between countries for grain yield, days to anthesis and silking, ASI, plant height, and EPP suggested uniqueness of the two countries in assessing the performance of the genotypes with respect to these traits and the possibility of identifying consistently performing (stable), high-yielding genotypes for each country. Genotypes differed significantly for grain yield, days to anthesis and silking, ASI, plant height, plant aspect, and EPP. However, country × G, year (Y) × G, and country × Y × G interactions were all significant for grain yield. Thus, selection of genotypes cannot be made on the basis of overall mean grain yield of genotypes. Rather, genotypes specifically adapted to a country must be identified. The significant Y × G interaction implied that one must not rely on single-year data to identify superior genotypes. The significant effect observed for G × Y × L (country) interaction for grain yield and days to anthesis and 50% silking indicated that the ranking of the hybrids was not consistent in different years and at different locations within a country. This implied that there is a need to identify specific hybrids within each year for a specific location within each country. The presence

Table 2. Mean squares for grain yield and other agronomic traits and percentage contribution of various sources of variation based on sum of squares for grain yield of early-maturity white hybrids evaluated at 14 locations across Nigeria and Ghana in 2013 and 2014.

| Source | df | Grain yield | Contribution | Days to anthesis | Days to silk | ASI† | Plant height | Husk cover‡ | Plant aspect§ | Ear aspect¶ | EPP# |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | kg ha$^{-1}$ | % | | d | | cm | | 1–5 score | | |
| Block (location × country × replication) | 126 | 1,138,436** | | 3.9** | 3.7** | 1.4** | 380.5** | 2.3** | 0.5 | 1.1 | 0.1 |
| Replication (location × country) | 28 | 2,020,520** | | 9.7** | 11.9** | 2.0** | 928.6** | 1.2 | 0.7 | 1.8** | 0.2** |
| Country | 1 | 10,939,5978** | 3.6 | 788.0** | 1,489.2** | 121.5** | 5,870.5** | 0.7 | 2.4 | 1.7 | 0.9** |
| Year | 1 | 10,165,296** | 0.3 | 120.2** | 523.9** | 144.0** | 13,652.6** | 5.7 | 6.6** | 7.6** | 0.0 |
| Years × Country | 1 | 151,897,910** | 5.0 | 794.0** | 232.9** | 169.2** | 43,053.4** | 35.7** | 59.2** | 84.8** | 1.6** |
| Location (country) | 12 | 119,781,287** | 47.3 | 728.1** | 688.9** | 335.0** | 62,254.9** | 38.7** | 41.2** | 12.7** | 1.3** |
| Genotype | 31 | 6,045,246** | 6.2 | 20.1** | 20.1** | 1.4** | 1,921.6** | 1.0 | 0.8* | 0.9 | 0.3** |
| Country × genotype | 31 | 1,830,301** | 1.9 | 7.2** | 5.2** | 1.5** | 224.4 | 1.1 | 0.5 | 0.5 | 0.3** |
| Year × genotypes | 31 | 8,143,896** | 8.3 | 8.5** | 6.6** | 1.0** | 714.4** | 6.3 | 1.5** | 1.9** | 0.2** |
| Year × country × genotype | 31 | 2,092,412** | 2.1 | 5.9** | 5.1** | 1.0** | 369.5** | 6.2** | 1.1** | 2.5** | 0.2** |
| Year × location (country) | 12 | 15,186,818** | 3.0 | 75.5** | 45.1** | 14.0** | 9,483.9** | 49.4** | 7.2 | 8.1** | 0.1 |
| Genotype × location (country) | 372 | 1,220,223** | 14.9 | 3.2** | 2.8** | 1.4** | 348.3** | 1.7** | 0.5 | 1.0 | 0.1 |
| Genotype × year × location (country) | 372 | 1,192,327** | 7.3 | 4.0** | 4.4** | 0.7 | 302.5 | 1.8 | 0.6 | 1.0 | 0.1 |
| Error | 1,732 | 794,046 | | 2.6 | 2.2 | 1.1 | 287.5 | 1.7 | 0.5 | 1.0 | 0.1 |

*, ** Significant at the 0.05 and 0.01 probability levels, 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 1–5), where 1 = excellent plant type, and 5 = poor plant type.

¶ Ear aspect (scale 1–5), where 1 = clean, uniform, large, and well-filled ears, and 5 = ears with undesirable features.

# EPP, number of ears per plant.

of significant G × L × Y interaction for grain yield relative to the early-maturing maize hybrids in this study suggested the need for testing in multiple locations across years before making genotype recommendations in the two countries. Such has also been suggested previously (Badu-Apraku et al., 1995; Sabaghnia et al., 2008; Moghaddam and Pourdad, 2009; Badu-Apraku et al., 2011, 2015).

The significant G × L interaction for grain yield necessitated the use of the GGE biplot to decompose the G + G × L interaction to determine the yield potential and stability of the early hybrids and to identify the ideal test locations in the two countries. Furthermore, the presence of significant country × G interaction for grain yield justified separate GGE biplot analysis for the two countries to identify highest-performing cultivar(s) for each country.

Location (country) had the highest impact on grain yield, accounting for 47.3% of the total variation (sum of squares) in grain yield (Table 2), followed by G × L (country) interaction that accounted for 14.9% of the variation in grain yield. The large proportion of the contribution of the location (country) and G × L (country) effects indicated that the performance of the hybrids varied greatly in the different locations within country and that there is a need to test the hybrids extensively in the target countries over years to identify the most stable and high-yielding genotypes in the different countries. This implied that there is a need to identify the most suitable sites within each country for testing elite genotypes for the purpose of identifying the most promising hybrids for release. Furthermore, the low proportion (6.2%) of the genotypic main effect to the total sum of squares for grain yield observed in the present study was expected, because the hybrids evaluated were the top-yielding hybrids selected from several preliminary observation trials that gave them competitive yield levels. Grain yield of the hybrids ranged from 3085 kg ha$^{-1}$ for EWH-4 to 4596 kg ha$^{-1}$ for EWH-29 (Table 3). The highest-yielding hybrid, EWH-29, outyielded the reference commercial hybrid check by 30%.

Table 3. Grain yield and other agronomic traits of early-maturing maize hybrids evaluated at 14 locations across Nigeria and Ghana, 2013 and 2014.

| Code | Hybrid | Pedigree | Grain yield | Days to anthesis | Days to silk | ASI† | Plant height | Ear height | Husk cover‡ | Plant aspect§ | Ear aspect¶ | EPP# |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | kg ha$^{-1}$ | d | | | cm | | 1–5 score | | | |
| 1 | EWH 1 | (TZEI 2 × TZEI 108) × TZEI 63 | 3583 | 51 | 53 | 2.4 | 148 | 67 | 2.0 | 2.3 | 2.4 | 0.9 |
| 2 | EWH 2 | (TZEI 59 × TZEI 108) × TZEI 63 | 3920 | 50 | 53 | 2.5 | 146 | 68 | 1.9 | 2.2 | 2.3 | 0.9 |
| 3 | EWH 36 | TZE-W Pop DT C2 STR × ENT 3 | 4015 | 51 | 53 | 2.4 | 149 | 69 | 2.3 | 2.2 | 2.5 | 1.0 |
| 4 | EWH 18 | (TZEI 63 × TZEI 87) × TZEI 59 | 3902 | 50 | 53 | 2.4 | 145 | 66 | 1.9 | 2.2 | 2.4 | 1.0 |
| 5 | EWH 37 | DTE-W STR SYN C1 × ENT 12 | 4440 | 51 | 53 | 2.7 | 151 | 66 | 2.3 | 2.0 | 2.2 | 1.0 |
| 6 | EWH 3 | (TZEI-63 × TZEI-108) (TZEI-59 × TZEI-87) | 3632 | 50 | 52 | 2.8 | 148 | 68 | 1.9 | 2.3 | 2.4 | 0.9 |
| 7 | EWH 4 | (TZEI 63 × TZEI 59) × (TZEI 108 × TZEI 87) | 3085 | 50 | 53 | 2.6 | 144 | 62 | 2.0 | 2.5 | 2.5 | 0.9 |
| 8 | EWH 21 | (TZEI 63 × TZEI 87) × (TZEI 59 × TZEI 108) | 3503 | 50 | 52 | 2.6 | 144 | 66 | 1.9 | 2.3 | 2.4 | 0.9 |
| 9 | EWH 22 | (TZEI-2 × TZEI-63) (TZEI-108 × TZEI-87) | 3773 | 50 | 52 | 2.5 | 150 | 67 | 2.0 | 2.2 | 2.4 | 1.0 |
| 10 | EWH 23 | (TZEI 2 × TZEI 63) × (TZEI 59 × TZEI 87) | 3841 | 50 | 53 | 2.8 | 146 | 66 | 2.0 | 2.3 | 2.4 | 0.9 |
| 11 | EWH 5 | TZE W Pop DT STR C4 × TZEI 4 | 3178 | 52 | 55 | 2.8 | 156 | 66 | 2.0 | 2.3 | 2.3 | 0.9 |
| 12 | EWH 6 | TZE-W Pop DT STR C4 × TZEI 22 | 4098 | 51 | 54 | 2.5 | 157 | 71 | 2.0 | 2.2 | 2.2 | 0.9 |
| 13 | EWH 7 | TZE-W Pop DT STR C4 × TZEI 7 | 4039 | 51 | 53 | 2.5 | 151 | 69 | 1.8 | 2.1 | 2.4 | 1.0 |
| 14 | EWH 24 | TZE-W Pop DT STR C4 × TZEI 19 | 3930 | 51 | 54 | 2.8 | 157 | 72 | 1.9 | 2.1 | 2.5 | 0.9 |
| 15 | EWH 38 | TZE-W Pop DT C2 STR × ENT 20 | 4234 | 50 | 54 | 3.3 | 154 | 71 | 1.9 | 2.0 | 2.0 | 0.9 |
| 16 | EWH 8 | TZEI 5 × TZEI 98 | 4371 | 51 | 54 | 2.5 | 148 | 69 | 2.2 | 2.0 | 2.0 | 1.0 |
| 17 | EWH 39 | TZEI 32 × TZEI 56 | 3846 | 50 | 53 | 2.5 | 149 | 68 | 2.1 | 2.2 | 2.4 | 1.0 |
| 18 | EWH 12 | TZEI 4 × TZEI 7 | 4448 | 50 | 53 | 2.7 | 158 | 72 | 2.4 | 2.0 | 2.3 | 0.9 |
| 19 | EWH 40 | ENT 12 × TZEI 89 | 4335 | 51 | 54 | 2.7 | 155 | 66 | 2.0 | 2.1 | 2.3 | 1.0 |
| 20 | EWH 41 | TZEI 63 × TZEI 48 | 4011 | 50 | 53 | 2.6 | 148 | 72 | 1.8 | 2.3 | 2.7 | 1.0 |
| 21 | EWH 42 | ENT 11 × TZEI 22 | 4263 | 51 | 54 | 2.7 | 154 | 71 | 2.1 | 2.0 | 2.2 | 1.0 |
| 22 | EWH 16 | TZEI 1 × TZEI 3 | 3685 | 51 | 54 | 2.5 | 149 | 63 | 2.0 | 2.2 | 2.3 | 0.9 |
| 23 | EWH 26 | TZEI 188 × TZEI 98 | 4375 | 50 | 53 | 2.6 | 150 | 72 | 2.1 | 2.2 | 2.2 | 0.9 |
| 24 | EWH 27 | TZEI 5 × TZEI 60 | 4141 | 52 | 54 | 2.4 | 165 | 75 | 1.9 | 2.0 | 2.1 | 1.2 |
| 25 | EWH 28 | TZEI 31 × TZEI 18 | 3784 | 50 | 53 | 2.6 | 153 | 66 | 2.0 | 2.3 | 2.4 | 0.9 |
| 26 | EWH 29 | TZEI 60 × TZEI 86 | 4596 | 51 | 53 | 2.7 | 160 | 76 | 2.0 | 2.3 | 2.1 | 1.0 |
| 27 | EWH 30 | TZEI 83 × TZEI 60 | 4414 | 51 | 53 | 2.3 | 157 | 73 | 2.0 | 2.0 | 2.2 | 0.9 |
| 28 | EWH 32 | ENT 12 × TZEI 48 | 4252 | 51 | 53 | 2.7 | 155 | 70 | 1.9 | 1.9 | 2.2 | 1.0 |
| 29 | EWH 33 | ENT 10 × TZEI 82 | 3941 | 51 | 53 | 2.7 | 156 | 68 | 2.1 | 2.3 | 2.4 | 0.9 |
| 30 | EWH 34 | ENT 3 × TZEI 65 | 4567 | 50 | 53 | 2.5 | 153 | 73 | 2.0 | 2.1 | 2.1 | 1.0 |
| 31 | EWH 35 | ENT 7 × TZEI 60 | 4002 | 51 | 54 | 2.7 | 167 | 73 | 2.0 | 2.0 | 2.3 | 1.1 |
| 32 | CHECK | TZE COMP3 DT C1 F2 (RE) | 3537 | 51 | 54 | 2.7 | 151 | 69 | 2.0 | 2.3 | 2.3 | 0.9 |
| | Mean | | 4372 | 51 | 53 | 2.5 | 154 | 70 | 2.0 | 2.2 | 2.2 | 1.0 |
| | LSD | | 2153 | 4 | 4 | 2 | 43 | 27 | 2.4 | 1.4 | 1.8 | 0.6 |
| | CV | | 21 | 5 | 5 | 23.0 | 17 | 24 | 27.0 | 24.0 | 26.0 | 24.0 |

†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 1–5), where 1 = excellent plant type, and 5 = poor plant type.

¶ Ear aspect (scale 1–5), where 1 = clean, uniform, large, and well-filled ears, and 5 = ears with undesirable features.

# EPP, number of ears per plant.

## GGE Biplot Analysis of Grain Yield and Stability of Early-Maturity Hybrids

In the GGE biplot, the PC1 explained 44.7% of total variation, whereas PC2 explained 15.1% of the variation for grain yield. Thus, the two axes together accounted for 59.8% of the total variation for grain yield (Fig. 1–3). The polygon view of the biplot showed which genotype performed best in which location (Fig. 1). Yan et al. (2000) pointed out that the vertex hybrids in each sector represented the highest-yielding hybrid in the location that fell within that particular sector. Given this information, Entry 5 (EWH 37) was the highest-yielding hybrid at Kafin-Soli, Mokwa, Batsari, Talata Mafara, Pokuase, Lapai, and Ejura; Entry 30 (EWH 34) was the highest-yielding hybrid at Manga, Fumesua, Damongo, Nyankpala, and Minjibir; and Entry 31 (EWH 35) was the highest-yielding hybrid at Samaru and Ilorin. No environment fell into the sector where Entries 7 (EWH 4), 11 (EWH 35), 32 (Check), and 22 (EWH 16) were the vertex hybrids, indicating that these hybrids were the lowest-yielding hybrids at some or all locations. Hybrids located close to the origin of the polygon (i.e., Entries 3 [EWH 36], 22 [EWH 16], 10 [EWH 23], and 2 [EWH 2]) were more adapted to low-yielding locations than the vertex hybrids.

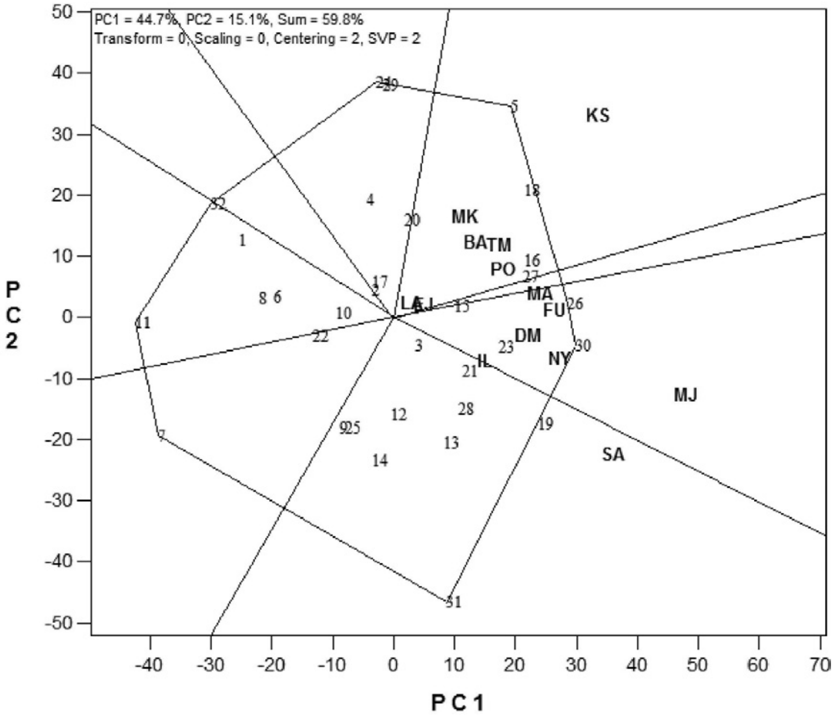

Fig. 1. A "which-won-where" or "which-is-best-at-what" based on genotype × environment yield data of 32 early-maturing maize hybrids evaluated in 14 locations across Nigeria and Ghana in 2013 and 2014. See Tables 1 and 3 for the legends. PC, principal component.

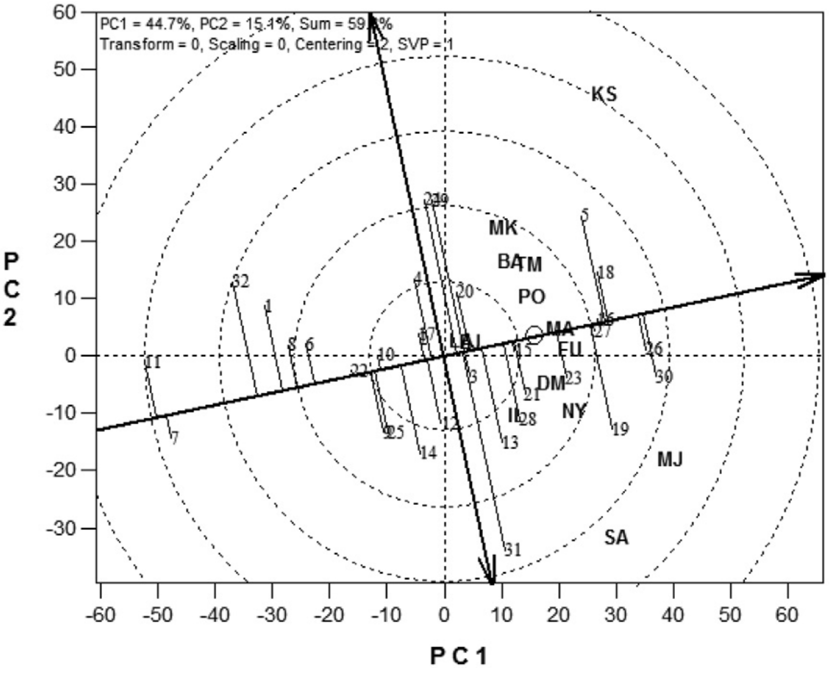

Fig. 2. The "mean vs. stability" view of the genotype main effects plus genotype × environment interaction (GGE) biplot based on genotype × environment yield data of 32 early-maturing maize hybrids evaluated in 14 locations across Nigeria and Ghana in 2013 and 2014. See Tables 1 and 3 for the legends. PC, principal component.

In Fig. 2, the genotypes were ranked along the average-tester axis, with the arrow pointing to a greater value according to their mean performance across all environments. The double-arrowed line separated entries with below-average grain yield from those with above-average grain 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 *y*-axis). The greater the absolute length of the projection of a hybrid, the less stable the hybrid. Thus, Entries 7 (EWH 4) and 11 (EWH 5) were the lowest-yielding but most stable hybrids. On the other hand, Entries 30 (EWH 34), 26 (EWH 29), 27 (EWH 30), 16 (EWH 8), and 18 (EWH 12) were the highest-yielding and most stable hybrids and were hence identified as the ideal hybrids across locations in both countries. Entries 5 (EWH 37) and 19 (EWH 40) were high yielding but the most unstable across locations, whereas Entries 32 (Check) and 1 (EWH 1) were not only low yielding but also among the least stable hybrids.

In the separate analysis conducted for each country, the PC1 and PC2 together accounted for 73.9% of the total variation in grain yield for Ghana and 67.4% for Nigeria (Fig. 4). Entries 7 (EWH 4) and 11 (EWH 5)

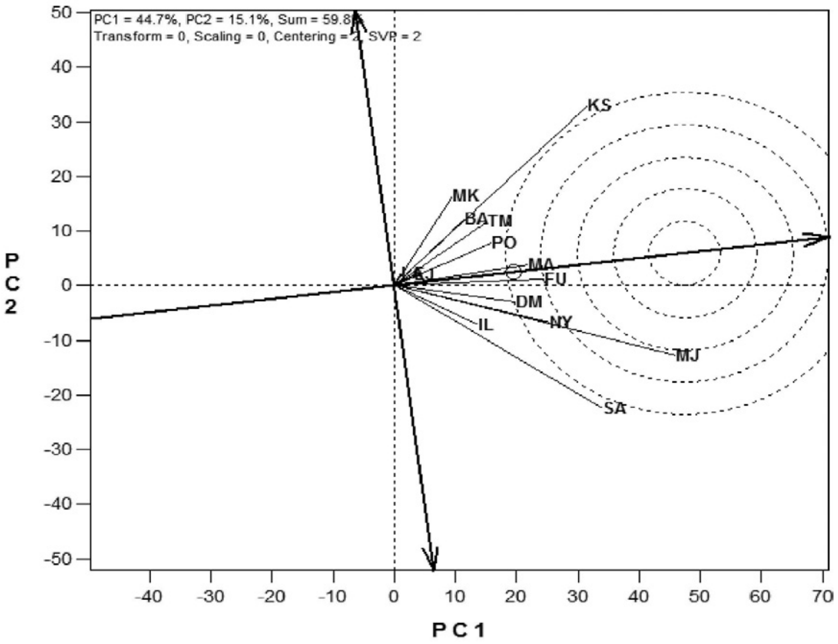

Fig. 3. The "discriminating power and representativeness" view of the genotype main effects plus genotype × environment interaction (GGE) biplot based on genotype × environment yield data of 32 early-maturing white maize hybrids evaluated at 14 locations across Nigeria and Ghana in 2013 and 2014. See Table 1 for the legend. PC, principal component.

were the lowest yielding in both countries. On the other hand, Entries 30 (EWH 34), 26 (EWH 29), 27 (EWH 30), 16 (EWH 8), and 18 (EWH 12) were the highest-yielding and most stable hybrids and hence the closest to the ideal hybrids across locations in Nigeria. Entries 23 (EWH 26), 6 (EWH 3), 26 (EWH 29), 30 (EWH 34), 27 (EWH 30), and 28 (EWH 32) were the highest-yielding and most stable in Ghana. Note that similar results were obtained when comparing the results obtained for Nigeria and across both countries. This could be attributed to the high discriminating power of some locations in Nigeria. The identification of different high-yielding hybrids for the two countries further supported the need for testing in multiple locations across years in each country before making hybrid recommendations.

## Discriminating Power and Representativeness of the Test Environments

Identification of ideal test sites for effective selection of superior genotypes is an important breeding strategy. An ideal test environment should be both the most discriminating of the genotypes and representative of all environments (Yan and Kang, 2003). The discriminating power of an environment or location refers to its ability to differentiate genotypes, whereas representativeness refers to the ability of a test location to be representative of other test locations (Yan et al., 2007). The discriminating power vs. representativeness view of the GGE biplot analysis is presented in Fig. 3. The cosine of the angle between any environment vector and the average environment axis approximates the correlation coefficient between the genotype values in that environment and the genotype means across the environment (Yan et al., 2007). Because the average environment coordinate (AEC) abscissa is the average-environment axis (AEA), test environments making small angles with the AEA are more representative of all environments than those making large angles. The small circle is the average environment and the arrow pointing to it is used to indicate the direction of the AEA. The length of the vector approximates the standard deviation (the discriminating ability) of the test location. The vector length of a test environment measures the magnitude (discriminating power) of its ability to differentiate genotypes in the test environments. According to Yan et al. (2010), shorter environmental vectors indicate that the specific environments are not strongly correlated with environments with longer vectors and that they were probably not strongly correlated with one another either. Based on this, the short-vector locations (i.e., Mokwa, Batsari, Talata Mafara, Pokuase, Fumesua, Damongo, Nyankpala, Ilorin, Lapai, and Ejura) may be regarded as independent research locations and could probably be treated as unique locations. However, the long-vector locations (i.e., Kafin-Soli, Minjibir, and Samaru) were more powerful in discriminating among the hybrids. Environments or locations with long vectors and small angles with the AEC abscissa are ideal for selecting superior genotypes. Minjibir had a long vector and made a relatively small angle with the AEC abscissa and was therefore the most discriminating and representative test location.

In the separate biplot analysis conducted for each country, a similar trend observed in the across countries biplot analysis was observed for Nigeria. Nyankpala, Damongo, and Fumesua had long vectors (data not shown) and were therefore the most discriminating locations in Ghana. However, in addition to having good discriminating ability, Nyankpala made a relatively small angle with the AEC abscissa and was therefore the most representative test location in Ghana.

According to the discriminating power and representativeness of test locations, three types of environments were described by Yan et al. (2007). Type 1 environments are those that have short vectors, provide little or no information on the genotypes, and therefore should not be used as test environments. Type 2 environments have long vectors, made small angles with the AEC abscissa, and are ideal for selecting superior genotypes. Type 3 environments have long vectors and large angles with the AEC abscissa and cannot be used in selecting superior genotypes, but such environments should be useful in

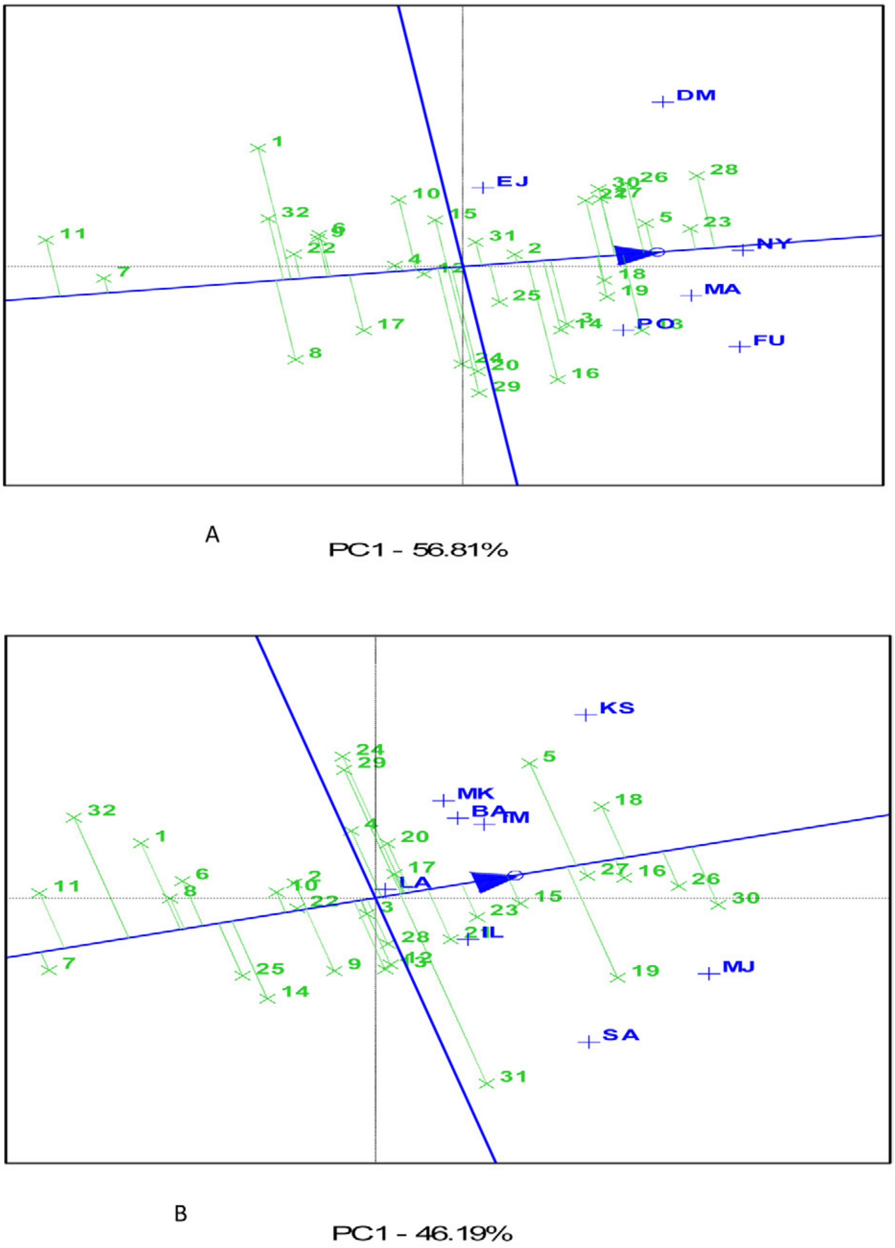

Fig. 4. The “mean vs. stability” view of the genotype main effects plus genotype × environment interaction (GGE) biplot based on genotype × environment yield data of 32 early-maturing maize hybrids evaluated at (A) six locations in Ghana and (B) eight locations in Nigeria in 2013 and 2014. See Tables 1 and 3 for the legends. PC, principal component.

culling unstable genotypes. According to this classification, Mokwa, Batsari, Talata Mafara, Pokuase, Fumesua, Damongo, Nyankpala, Ilorin, Lapai, and Ejura were Type 1 environments (short vectors). They provided little or no information on the genotypes and therefore should not be used as test environments. The implication is that some of these locations were redundant and could be dropped to reduce costs of field testing without loss of information. The GGE biplot identified Minjibir and Nyankpala as the ideal environments (Type 2 environments), which would be appropriate for selecting superior genotypes because of their high discriminating power and representativeness. Type 3 environments included Kafin-Soli, Damongo, Fumesua, and Samaru, which should not be used in selecting superior genotypes but could be useful in culling unstable genotypes. The results of this study are contrary to the findings of Badu-Apraku et al. (2011). The authors conducted a similar study involving 12 extra-early-maturing, open-pollinated maize cultivars evaluated at 17 locations in four countries of WA (Nigeria, Ghana, Mali, and Benin Republic) between 2006 and 2009 and reported that Ikenne and Ilorin locations had long vectors and large angles with the AEC abscissa and could therefore not be used in selecting superior genotypes but could be effectively used in culling unstable genotypes. In addition, they reported that Zaria, in the northern Guinea savanna characterized by moderately high rainfall (1120 mm of rainfall), was identified as the most representative and highly discriminating of the test environments, indicating that it represented the ideal test location for the 12 extra-early-maturing cultivars. Furthermore, Zaria, Minjibir, Ilorin, Ikenne, Mokwa, Kita, and Ejura had the longest vector lengths and were identified as the most discriminating locations for the extra-early cultivars, whereas Bagauda, Fumesua, Bagou, Nyankpala, Katiboukou, Babile, Ina, Manga, Angaredebou, and Samaru had shorter vector lengths and thus provided little or no information about the genotypes and could not be used as test environments. The authors concluded that Zaria (northern Guinea savanna), Ikenne (forest-savanna transition zone), and Ilorin (southern Guinea savanna), all in Nigeria, constituted a minimum set of core test environments in the four countries for the open-pollinated cultivars. In contrast, in the present study, Minjibir (Nigeria) and Nyankpala (Ghana) were identified as ideal test sites for the hybrids in the two countries. The implications of this study are that the type of cultivars (hybrids or open-pollinated cultivars) evaluated determined the most suitable locations for multilocation testing according to the discriminating power and representativeness of the test locations.

In conclusion, the results of this study demonstrated the existence of G × E interaction relative to hybrid performance across different environments. The GGE biplot analysis revealed that EWH-29, EWH-8, and EWH-30 were the highest-yielding and most stable hybrids in Nigeria and across both countries. Hybrids EWH-26 and EWH-32 were identified as the highest-yielding and most stable hybrids in Ghana. Minjibir (Nigeria) and Nyankpala (Ghana) were identified as ideal test sites. The ideal test sites identified in this study should facilitate the identification of stable and high-yielding maize hybrids for the two countries. The identified hybrids could be promoted for commercial production.

## Conflict of Interest

The authors declare that there is no conflict of interest.

## Acknowledgments

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