Heliyon 9 (2023) e21659

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Agronomic performance and yield stability of extra-early maturing maize hybrids in multiple environments in the Sahel

Laban Konate [a], Baffour Badu-Apraku [b], Mamadou Coulibaly [a], Abebe Menkir [b], M. Nasser Laouali [c], Silvestro Meseka [b,*], Wende Mengesha [b]

[a] *Institut d'Economie Rurale, PB 258, Sotuba, Bamako, Mali*
[b] *International Institute of Tropical Agriculture, PMB 5320, Oyo Road, Ibadan, Nigeria*
[c] *Institut National de la Recherche Agronomique du Niger, BP 240, Maradi, Niger*

ARTICLE INFO

Keywords:
Drought
Heat stress
Maize hybrid
Yield stability
Multiple stress

ABSTRACT

Frequent occurrence of drought, heat, low soil fertility and *Striga* infestation are the main stress factors reducing maize yield in the Sahel. Adoption of stable multiple stress tolerant maize cultivars in the region is crucial for achieving food security. However, selection of a stable high yielding cultivar is complicated by genotype × environment interaction (GEI) due to differential responses to growing conditions. Eleven extra-early maturing multiple-stress tolerant maize hybrids and two checks arranged in a randomized complete block design was evaluated across nine locations for two years in Mali and Niger. The objectives of this study were to identify (i) stable and high-yielding maize hybrids, and (ii) suitable test locations for selecting promising extra-early maize hybrids. GGE biplot was used for graphical analysis. Significant genotype, location and GEI effects were detected for grain yield and number of ears per plant. EEWQH-13 produced the highest grain yield (3860 kg ha^{-1}) while EEYQH-1 had the poorest yield (2663 kg ha^{-1}) with trial mean of 3395 kg ha^{-1} for all hybrids. GGE biplot explained 69.6 % of the total variation in grain yield among the hybrids. The polygon view identified EEWQH-13 as the best hybrid across six of the nine test locations. EEPVAH-58 was identified as the most stable high yielding hybrid across the nine test locations followed by EEWQH-16 and EEWQH-13. The nine locations were clustered under two mega-environments (ME1, ME2). Among the nine test locations, Tara and Aderaoua clustered in ME1 were the most suitable ones for selecting promising extra-early maize hybrids for wider adaptation. The three hybrids, EEPVAH-58, EEWQH-16, and EEWQH-13, identified in this study could be recommended for on-farm evaluation to confirm the consistency of their yield performance for possible release and commercialization in Mali and Niger.

1. Introduction

Maize (*Zea mays* L.) is a staple food crop cultivated and consumed by majority of the rural populations in West and Central Africa (WCA). It has gained wider acceptability over other traditional cereal crops such as sorghum (*Sorghum bicolor* L.) and Pear millet (*Pennisetum glaucum* (L.R. Br.) due to its high yield potential and wide adaptability to different agro-ecological zones. In addition to its high yield potential, maize is more responsive to fertilizer application than the traditional staple cereal crops in the savanna

---

[*] Corresponding author.
E-mail address: s.meseka@cgiar.org (S. Meseka).

https://doi.org/10.1016/j.heliyon.2023.e21659
Received 11 April 2023; Received in revised form 5 October 2023; Accepted 25 October 2023
Available online 2 November 2023
2405-8440/© 2023 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

agroecosystem [1] including the Sahel region. The Sahel, is a vast semi-arid region of West Africa separating the Sahara desert to the north and the tropical savannas to the south. This region is faced with short duration of rainfall, poor soil fertility, frequent occurrence of drought, heat stress as well as *Striga hermonthica,* which significantly reduce maize yield potentials in farmers' fields [1–3]. Extra-early maturing maize cultivars with tolerance to multiple stresses can thus play an important role for food security in filling the hunger gap in July, especially in Mali and Niger, when all food reserves are depleted after the long dry season. The earliness of extra-early maize makes them drought-avoiding genotypes [1,3,4], fitting well in the short duration of rainfall conditions in the Sahel region. The most important advantage of the extra-early maturing cultivars is that they provide farmers, in various maize growing areas, with flexibility in the date of planting [1,5]. However, drought-avoiding character may not be sufficient to fit the arid and semi-arid conditions, where drought and other stresses like heat that simultaneously occur in the farmer's field at any of the crop's development stages. The newly developed extra-early maize hybrids used in this study have good levels of tolerance to drought and heat stresses. Some of the hybrids have been improved for quality protein (lysine and tryptophan) and provitamin A, which are important attributes for producing maize for food and nutritional security in the Sahel region.

The stress factors constraining maize production and productivity in the Sahel region of WCA are well documented. Edmeades et al. [6] reported an annual yield loss of 15 % in maize production due to drought in WCA. Maize yield loss due to the combination of drought and heat stress could be much higher if this occurs during the flowering and grain filling stages. Infestation of farmers' maize fields by *S. hermonthica* is estimated to cause an annual yield loss ranging from 20 to 100 % [3,4], while soil nitrogen (low N) can reduce maize yield by 10–50 % [4,5,7]. Thus, host plant resistance/tolerance to these multiple stress factors has been recommended as the most economical and sustainable approach to mitigate their effects on maize yield in Sub-Saharan Africa (SSA). The Climate Smart Agricultural Technologies (CSAT) project being implemented in Mali and Niger focus on incorporating several stress-tolerant adaptive traits and nutritional values as well as complementary best agronomic practices for increased productivity in the farmer's fields [8]. With the expansion of maize production into new frontiers and marginal areas like the Sahel region, introduction and extensive testing of multiple stress tolerant maize hybrids in multiple environments (location x year) for release and commercialization is critical. Adoption and utilization of the resilient maize hybrids would improve productivity and sustain maize production in the region. Therefore, maize hybrids targeted for Sahel region should be tolerant to drought and low N as well as heat stress with good levels of resistance to *S. hermonthica.* The International Institute of Tropical Agriculture (IITA) in collaboration with partners have developed many stress resilient extra-early maturing maize hybrids being extensively tested in the Sahel region. Selection, release and commercialization of promising resilient extra-early maize hybrids for this region would increase productivity and bridge the hunger gap between the long dry season and the next harvest.

Improved maize varieties to be recommended for production in target environments should be evaluated in representative environments to identify consistently high-yielding and stable varieties and areas of their specific adaptation [6,8,9]. Multi-environment trials are being used by breeders to identify superior genotypes which are broadly adapted or those which are adapted to specific environments [10–13]. The identification of extra-early multiple-stress tolerant maize hybrids that show high and stable performance over a wide range of environmental conditions across years would be useful to farmers. Usually, the selection of stable and high yielding genotypes is complicated by the occurrence of genotype by environment interaction (GEI). Several statistical tools including the additive main effects and multiplicative interaction [14]) and the genotype, genotype by environment (GGE) interactions have been used by breeders to reveal patterns of GEI in multilocation yield trials. It provides an easy and comprehensive solution to the complex GEI data analysis [15], which has been a challenge to plant breeders. In this study, we used GGE biplot to identify stable high yielding hybrids and suitable test environments that have implications for maize breeding in the Sahel, especially for Mali and Niger. The objectives of this study were, therefore, to identify (i) high-yielding and stable maize hybrids for commercialization in the Sahel region, and (ii) suitable environments for testing extra-early maize hybrids in the region.

Table 1

Extra-early maturing maize hybrids evaluated in Mali and Niger in 2019 and 2020.

N°	Hybrid Name	Type	Grain colour	Source
1	EEPVAH-67	Provitamine A maize	Orange	IITA
2	EEPVAH-58	Provitamine A maize	Orange	IITA
3	EEYQH-1	Quality protein maize	Yellow	IITA
4	EEYQH-2	Quality protein maize	Yellow	IITA
5	EEYH-42	Normal maize[a]	Yellow	IITA
6	EEYH-60	Normal maize	Yellow	IITA
7	EEYH-61	Normal maize	Yellow	IITA
8	EEWQH-13	Quality protein maize	White	IITA
9	EEWQH-16	Quality protein maize	White	IITA
10	EEWH-57	Normal maize	White	IITA
11	EEWH-75	Normal maize	White	IITA
12	LOCAL CHECK1	Normal maize	White	NARS
13	LOCAL CHECK2	Normal maize	Yellow	NARS

[a] Normal maize is not biofortified.

2. Materials and methods

2.1. Genetic materials and sites

Eleven extra-early maturing maize hybrids comprising of two provitamin A, four quality protein maize (QPM), three yellow and four white normal maize hybrids developed at IITA (Table 1). These hybrids were selected from regional trials evaluated with partners in West Africa in 2018. In this study, the 11 hybrids together with two local checks were evaluated for two years at 9 locations across four diverse agro-ecologies in Mali and Niger (Table 2).

Four of the nine locations were in Mali and five in Niger across four agro-ecologies of the Sahel region. The rainfall in these agro-ecologies varied from 450 mm for dry Savanna in Niger to 1100 mm in the north-guinea Savanna in Mali. The minimum air temperatures ranged from 18 °C to 23.5 °C while the maximum varied from 31.5 °C to 36.5 °C during the growing season (June to October). Generally, the maximum temperatures were higher in Niger than in Mali.

2.2. Field layout and experimental management

The field trial was designed as single factor and laid out in a randomized complete block design with three replications. The trial was evaluated during the rainy season in 2019 and 2020. Each entry was planted in a two-row plot of 5 m long with 0.75 m spacing between rows and 0.40 m between hills within the rows. Three seeds were planted per hole and thinned to two plants per hill at two weeks after planting (WAP) to give a final population density of 66,000 plants/ha. The trial received 100 kg ha^{-1} of NPK (17-17-17) chemical fertilizers with additional 50 kg ha^{-1} of urea (46 %N) at planting. Additional N fertilizer was supplied by applying 100 kg ha^{-1} of urea as top dressing at four WAP. The weeds were controlled by hand-weeding at three and five WAP to keep the trial free of weeds.

2.3. Data collection

Data were collected in each plot on grain yield and agronomic traits. Days to anthesis was recorded as the number of days from planting to the time when 50 % of the plants had tassels shedding pollen grains, whereas days to silking were recorded as the number of days from planting to the time when 50 % of plants had emerged silks. Anthesis-silking interval (ASI) was computed as the difference between days to silking and anthesis. Plant aspect was scored based on the overall plant appeal considering plant height uniformity, earl placement, disease reactions and lodging on a scale of 1–5, where 1 = excellent plant type with large and similar ears, low ear placement, shorter plants, resistance to foliar diseases, and no or little stalk and root lodging, and 5 = plants with small and variable ears, tall plants with high ear placement, susceptible to foliar diseases as well as stalk and root lodging. Ear aspect was scored considering factors such as ear size, uniformity, disease and insect damage, on a scale of 1–5, where 1 = clean, uniform, large, and well-filled ears, and 5 = rotten, variable, small, and partially filled ears. Number of ears per plant (EPP) was computed as the ratio of the number of ears harvested to the number of plants harvested. Harvested ears were shelled, and a sample of grain was measured for moisture content using a portable Dickey-John moisture tester. The grain weight and moisture content were used to compute grain yield adjusted to 15 % moisture content.

2.4. Statical analysis

Analyses of variance (ANOVA) were performed across locations with general linear model procedure (PROC GLM) of Statistical Analysis System (SAS) using RANDOM statement with the TEST option [16]. Locations (L), and replications were considered as random factors while the genotypes were considered as fixed effects. Means were separated using the least significant difference (LSD) and standard deviation (SD). The statistical model [17] presented in Equation (1) was used for the combined analysis.

$$Yijkg = u + Ei + Rj(i) + Bk(ij) + G\,g + EGig + \varepsilon ijkg \qquad (1)$$

where Y_{ijkg} is the observed measurement for the gth genotype grown in environment i, in block k in replicate j; u is the grand mean; E_i is

Table 2
Description of the nine test locations used for evaluation of the extra-early maturing hybrids, 2019 and 2020.

Country	Location	Code	Coordinates	Agroecological zone	Rainfall (mm)	Temperature[a] (°C)
Mali	Sotuba	S1	12.66°N, 7.91° W	Sudan-savanna	800	23.5–32.3
Mali	Katibougou	K	12.93°N, 7.53° W	Sudan-savanna	700	23.5–33.4
Mali	Bougouni	B1	11.42°N, 7.47° W	South Sudan-savanna	1000	22.8–32.0
Mali	Sikasso	S2	13.41°N, 6.39° W	North-guinea savanna	1100	22.6–31.5
Niger	Aderaoua	S3	14.88°N, 5.27° E	Savanna	500	18.0–33.5
Niger	Tama	P	7.35°N, 8.61°E	Savanna	450	19.0–35.0
Niger	Bengou	B2	11.59°N, 3.35° E	South Sudan-Savana	1000	22.5–36.5
Niger	Tara	T	14.47°N, 0.80° E	Sudan-Savanna	900	20.5–36.5
Niger	Maradi	M	13.50°N, 7.10° E	Savanna	550	21.0–35.0

[a] Temperature means during the growing season from June to October.

the main effect of the environment; $R_{j(i)}$ is the effect of the replicate nested within the environment; $Bk_{(ij)}$ is the effect of the block nested within the replicate j by environment i; G_g is the effect of genotypes (hybrids and checks); EG_{ig} is the interaction effect between genotype and environment, and ε_{ijkg} the error term.

Out of all the observations recorded in our experiment, this paper focused more on yield stability. Grain yield data was further analyzed using the GGE biplot to identify stable and high-yielding hybrids across test locations as well as identify mega-environments/locations for testing extra-early maize hybrids in the semi-arid Sahel region. The GGE biplot model for graphical analysis according to Ref. [18] is presented in Equation (2) as shown below:

$$Yij - \beta_j = \alpha_1 \acute{E}_{i1} n_{j1} + \alpha_2 \acute{E}_{i2} n_{j2} + E_{ij} \tag{2}$$

where Y_{ij} is the average yield of genotype i in environment j, α_1 and α_2 are singular values for PC1 and PC2, respectively, $\acute{E}_{i1}$ and $\acute{E}_{i2}$ are the PC1and PC2 scores, respectively, for genotype *i*, n_{j1} and n_{j2} are PC1 and PC2 scores, respectively, for environment *j*, E_{ij} is the residual of the model associated with the genotype *i* in environment *j*.

The analyses were performed using GGE biplot, a Windows application, that fully automates biplot analysis [18]. The GGE biplot is the single most informative tool for both genotype and environment evaluation [14], allowing visualization of any crossover GEI, which is usually essential to a breeding program [15].

3. Results

3.1. *Performance of the hybrids across environment*

The combined analysis of variance across test locations (Equation (1)) showed significant G, E, and GEI mean squares for grain yield and EPP (Table 3). Also, significant G and E mean squares were detected among the hybrids for plant aspect, days to 50 % silking, ASI, and ear aspect scores.

The hybrids showed highly significant ($P < 0.001$) differences and wide range of yield performance across the test locations. The mean grain yield of hybrids was 3395 kg ha^{-1} with the best hybrid, EEWQH-13 producing grain yield of 3860 kg ha^{-1} while the lowest-yielding hybrid, EEYQH-2 produced grain yield of 2663 kg ha^{-1} (Table 3). The grain yield of the best local check (Check 1) was 2776 kg ha^{-1}. Six of the eleven multiple-stress tolerant hybrids (EEWQH-13, EEPVAH-58, EEWQH-16, EEYH-42, EEWH-75, EEYH-60) produced grain yield which were above the average trial mean of 3395 kg ha^{-1}. These hybrids outyielded the best local check by 24–39 %. The top performing hybrids were EEWQH-13, EEPVAH-58, and EEWQH-16 which produced high grain yields of 3860, 3726 and 3627 kg ha^{-1}, respectively. The best hybrid combining high grain yield performance with good plant (2.4) and ear aspect (2.3) was EEPVAH-58, and EEWQH-13 combined high grain yield excellent ear aspect (2.1) demonstrating their adaptation to the test locations.

3.2. *Hybrids adaptation to test location*

The results of the GGE biplot analysis showed that the two principal components (PC1 and PC2) together accounted for 69.6 % of the total variation in the sum of squares of grain yield of multiple stress extra-early hybrids, indicating that the two principal

Table 3

Yield performance and other agronomic traits of extra-early maturing maize hybrids evaluated across nine locations in Mali and Niger, 2019 and 2020.

Entry	Hybrids	Grain Yield	Ears per Plant	Plant aspect (1–5)	Days to silking	Anthesis-silking interval	Ear aspect (1–5)
8	EEWQH-13	3860	1	2.9	55	2	2.1
2	EEPVAH-58	3726	1	2.4	55	2	2.3
9	EEWQH-16	3627	1	3.0	55	2	2.5
6	EEYH-60	3518	1	2.9	53	2	2.2
11	EEWH-75	3478	1	3.0	53	1	2.4
5	EEYH-42	3441	1	2.9	53	2	2.2
1	EEPVAH-67	3375	1	2.1	55	2	2.3
10	EEWH-57	3348	1	2.6	54	2	2.5
7	EEYH-61	3008	1	3.4	53	2	2.5
4	EEYQH-2	2881	1	3.0	57	3	2.5
12	LOCAL CHECK1	2776	1	3.4	53	2	3.6
13	LOCAL CHECK2	2664	1	3.5	54	2	3.5
3	EEYQH-1	2663	1	3.2	57	3	2.9
	Means	3395	1	2.9	54.3	2	2.5
	CV	27.2	13	36.9	5.0	85	76.2
	LSD	430.3	0.1	0.5	1.3	1	0.0
	SD	422.6	0.04	0.4	1.4	0.4	0.5
	Genotype (P<)	**	**	**	**	**	*
	Location (P<)	**	**	**	**	**	**
	Gen x Loc (P<)	*	*	NS	NS	NS	NS

*,** Significant F-test at probability levels of 0.05, 0.01, respectively. NS = not significant.

components adequately approximated the multiple-location data of yield performance. The GGE biplot polygon view "which won where" grouped the genotypes into five sectors (Fig. 1).

The vertex genotype in each sector is the best genotype in location whose markers fell into the respective sectors, while the genotypes within the polygon were less responsive to location than the corner genotypes. Based on this principle, hybrid EEWQH-13 was the highest yielding hybrid across six locations, S1 (Sotuba), S2 (Sikasso), and K (Katibougou) in Mali; S3 (Aderaoua), T (Tara), and B2 (Bengou) in Niger, indicating its broad adaptation. Hybrid EEYH-42 was the highest yielding multiple stress tolerant extra-early hybrid at M (Maradi) in Niger and B1 (Bougouni) in Mali, while EEWH-75 was the highest yielding hybrid at P (Tama) in Niger, suggesting that these hybrids are adapted to specific locations. The two other corner cultivars (EEYQH-1, Local check 2) were located far away from the markers of all locations suggesting that they had poor grain yield across the nine test locations.

3.3. *Mean performance vs. stability*

In the GGE biplot, the single arrowed line is the average environment coordination (AEC) axis and points in the direction of higher mean grain yield, while the other line without an arrow represents the stability of the genotypes. The line without an arrow separates the hybrids with below-average mean grain yield from those with above-average mean grain yield (Fig. 2).

The average grain yield of the hybrids is approximated by the projection of their markers on the average axis. The stability of the hybrids is measured by their projections onto the average-tester coordinate axis single-row line. EEWQH-13 was the highest-yielding hybrid and produced a higher grain yield than the mean grain yield while EEYQH-1 produced the lowest grain yield. Although EEWQH-13 had the highest mean grain yield, it was less stable compared to EEPVAH-58 and EEWQH-16. Considering the yield performance and stability of the hybrids, EEPVAH-58 was high yielding and stable followed by EEWQH-16.

3.4. *Ranking of ideal genotypes*

An ideal genotype, which is located at the center of concentric circle, has both high mean grain yield and stability. Our results of ranking the 11 hybrids by mean grain yield and stability showed that EEPVAH-58 was the most ideal hybrid followed by EEWQH-16 (Fig. 3).

Although EEWQH-13 was the highest yielding hybrid it was in the third concentric circle and can be considered as relatively stable, suggesting that it is adapted to most of the test locations across the two countries. EEYQH-1 and the two local checks (1 and 2) were located out of the concentric circles indicating that they were the most unstable genotypes across the test locations.

3.5. *Discriminativeness vs. representativeness of test environments*

GGE biplot determines the relationships between test environments by both the length of their vectors and the cosine of the angle between them. Accordingly, the angle between Sikasso and Tama is > 90° suggesting the lack of relationship between the two test

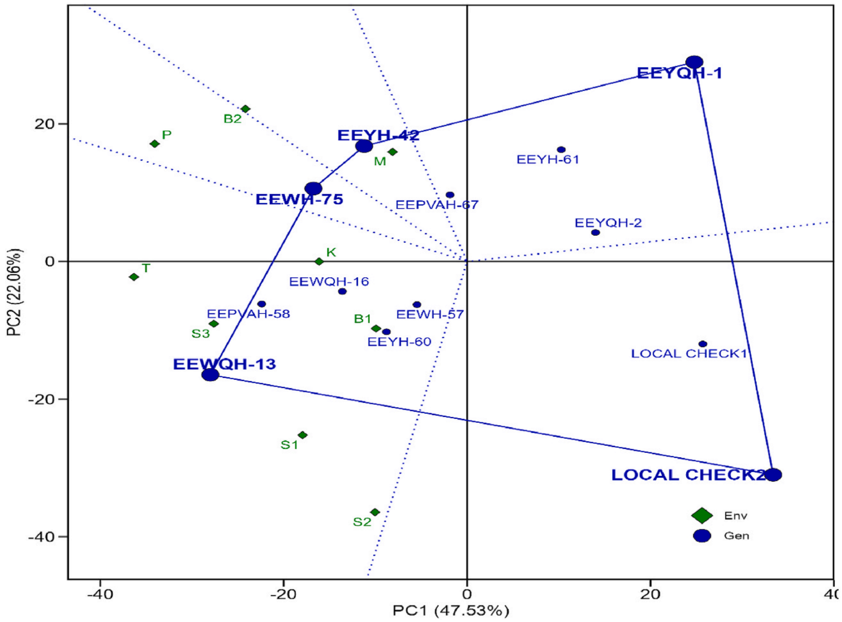

Fig. 1. A "which won where" based on genotype x environment yield data of 13 extra-early maturing hybrids evaluated across nine environments in Mali and Niger. S1=Sotuba, S2= Sikasso, S3 = Aderaoua, T = Tara, K= Katibougou, B1= Bougouni, B2= Bengou, M = Maradi, P= Tama.

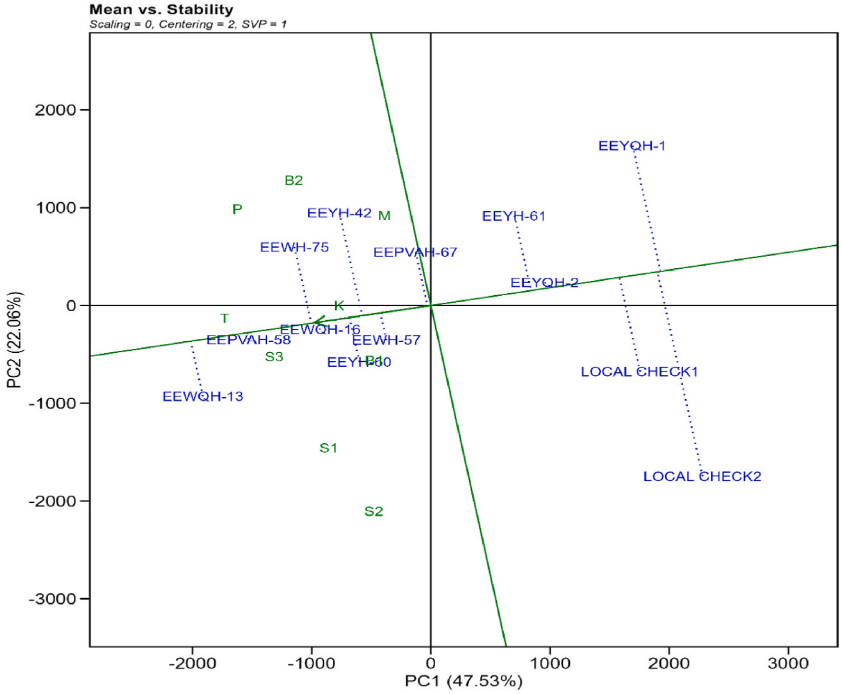

Fig. 2. The "mean vs. stability" view of genotype × environment interaction of 13 extra-early maturing maize hybrids evaluated under multiple stress environments in 2019 and 2020 in Mali and Niger. S1=Sotuba, S2= Sikasso, S3 = Aderaoua, T = Tara, K= Katibougou, B1= Bougouni, B2= Bengou, M = Maradi, P= Tama.

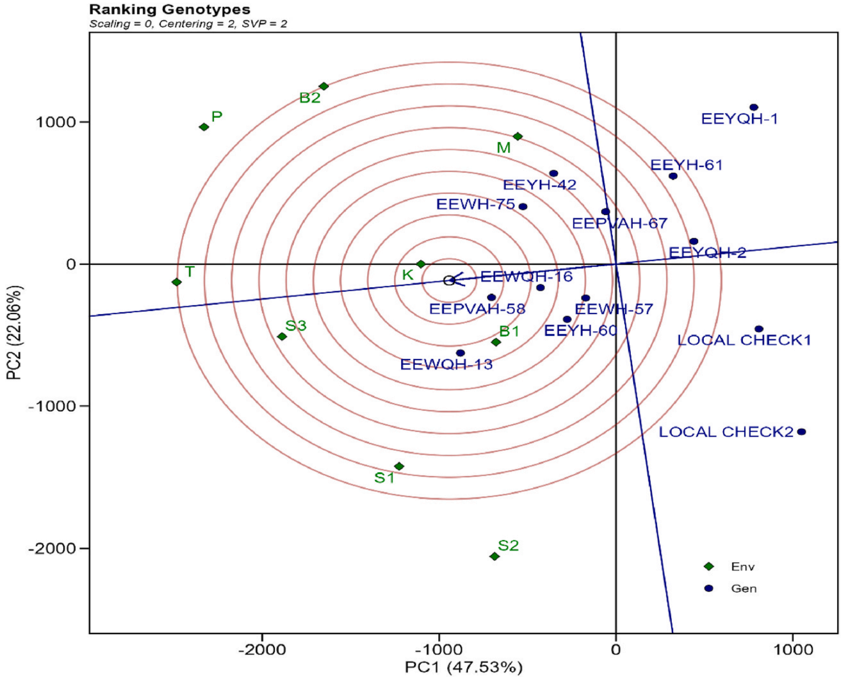

Fig. 3. Ranking of 13 extra-early maturing maize hybrids relative to an ideal genotype. S1=Sotuba, S2= Sikasso, S3 = Aderaoua, T = Tara, K= Katibougou, B1= Bougouni, B2= Bengou, M = Maradi, P= Tama.

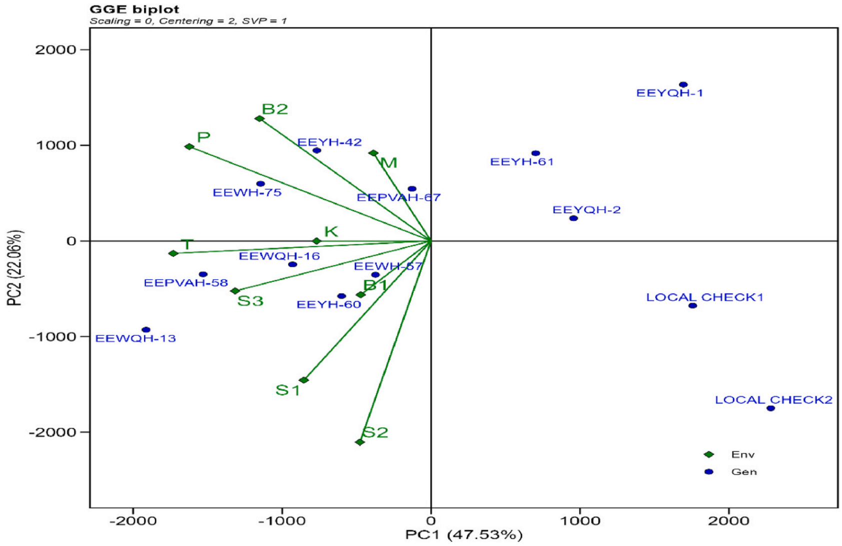

Fig. 4. The environmental vector view of the GGE biplot showing similarities among test environments for extra-early maize hybrids tested at nine locations. S1=Sotuba, S2= Sikasso, S3 = Aderaoua, T = Tara, K= Katibougou, B1= Bougouni, B2= Bengou, M = Maradi, P= Tama.

environments (Fig. 4).

Six test locations (Sotuba, Sikasso, Aderaoua, Bougouni, Katibougou, Tara) had <90° between them, indicating that these locations were strongly correlated and constitute a mega-environment (ME1). The second group of locations which comprised Bengou, Maradi and Tama had <90° between them and constituted another mega-environment (ME2). Considering the length of environment vector, Bougouni and Katibougou in ME1 and Maradi in ME2 had short vectors, suggesting that they had little discriminative power and are not as such helpful in selecting stable and high yielding hybrids. While Bengou and Tama in ME2 were only discriminative and useful for culling unstable genotypes; Sotuba, Sikasso, Aderaoua, and Tara (all in ME1) were both discriminative and representative test environments. These results suggested that testing the extra-early maize hybrids in few locations in ME1 would be sufficient for identifying the best hybrids that could be recommended for production within ME1 in Niger and Mali.

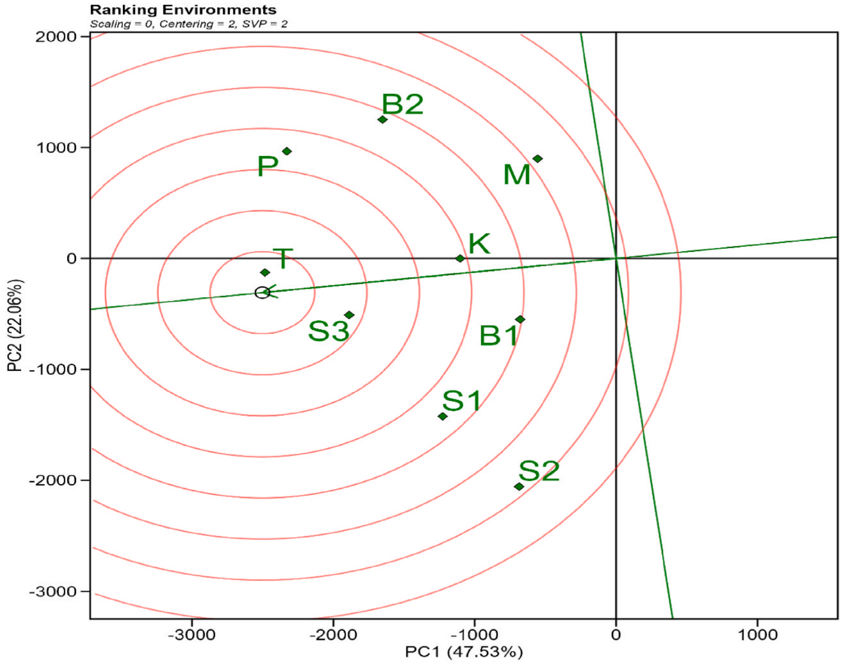

Fig. 5. GGE-biplot view for comparison of environments with the ideal environment. S1=Sotuba, S2= Sikasso, S3 = Aderaoua, T = Tara, K= Katibougou, B1= Bougouni, B2= Bengou, M = Maradi, P= Tama.

3.6. Ideal environments for testing extra-early hybrids

The GGE biplot graphical analysis showed that rankings based on the discriminating ability and representativeness of the test environments revealed that Tara and Aderaoua in Niger were closest to the ideal test environment (Fig. 5).

While Katibougou in Mali and Tama in Niger could also be considered as favorable environments for selection. However, Bengou and Maradi in Niger and Bougouni, Sotuba and Sikasso in Mali were poor locations for selecting extra-early maize hybrids for stable and high grain yield. The two ideal sites (Tara and Aderaoua) for selection of extra-early maize hybrids in this study have significant differences in terms of rainfall and agro-ecologies. Tara is located in Sudan-Savanna with annual rainfall of while 900 mm while Aderaoua is in Savanna agro-ecology receiving average annual rainfall of 500 mm (Table 2).

4. Discussion

Climate change is expected to increase the frequency and severity of drought, pest and disease outbreaks as well as the geographical distribution of parasitic weeds in the Sahel region [8]. Based on this projection, the CSAT project being implemented in Mali and Niger has been testing maize cultivars combining tolerance to heat and drought stress with resistance to *S. hermonthica* to increase the resilience of the production systems of smallholder farmers. The 11 extra-early maize hybrids reported in this study were part of the multiple stress tolerant maize hybrids being evaluated in this project.

The significant genotype and environment mean squares observed for grain yield and other agronomic traits indicated the presence of adequate genetic variance among the extra-early hybrids to facilitate progress from selection for the measured traits under the contrasting research environments. Similar results were reported by several researchers [12,19,20]. The lack of significant GEI for plant and ear aspect, day to silking and ASI indicated that these traits were stable and not significantly affected by the hybrids × environments interaction effects. In contrast, significant mean squares of GEI detected for grain yield and EPP indicated that the ranking of the extra-early maize hybrids varied in terms of grain yield performance and EPP across the environments in Mali and Niger. This result confirmed that GEI had a remarkable effect on hybrid performance across different environments [21–23]. This justified the need for the deployment of GGE biplot for further analysis of grain yield to identify high yielding and stable hybrids and the mega-environments for selecting productive extra-early maturing maize hybrids [3,18,24] in the Sahel region.

The results of ANOVA for individual years (2019 and 2020) consistently ranked EEWQH-13 and EEWQH-16 as the top two hybrids followed by EEPVAH-58. However, in the combined ANOVA EEPVAH-58 ranked second to EEWQH-13 in terms of yield performance. The superior performance of the top three hybrids (EEWQH-13, EEPVAH-58, and EEWQH-16) across environments in the two countries indicated the effectiveness of the breeding method used to incorporate favorable alleles for high yield and multiple-stress tolerance traits. These results showed that the three hybrids selected based on the *per se* performance in the regional trials in West Africa are adapted to several locations in Mali and Niger. With the yield advantages of 30–39 % over the best check, these hybrids can be of major interest to farmers growing maize under stressful environments in the Sahel region. Our results agreed with Badu-Apraku et al. [3,24] who identified several tropical early-maturing maize hybrids in WCA for areas where drought, *Striga*, and low soil nutrient deficiencies are common in farmers' fields.

Decomposition of the GEI using GGE biplot is important for identifying genotypes with broad or specific adaptation to test environments. The polygon view of the "which-won-where" clearly identified EEWQH-13 as the highest yielding hybrid across six locations (Sikasso, Sotuba, Katibougou, Aderaoua, Tara, and Bengou), suggesting that it is the best performing hybrid across locations in Mali and Niger. These locations fall into the Sudan-savanna, South Sudan-savanna and North guinea-savanna agroecological zones which are prone to multiple stress factors present in the Sahel region. Thus, these results should encourage maize breeders in L'Institut d'Economie Rurale (IER) in Mali and Institut National de la Recherche Agronomique (INRAN) in Niger to promote the release and commercialization of EEWQH-13 in the two countries. Our findings agree with Yan et al. [25] who reported that the vertex genotype in each mega-environment represents the highest-yielding genotype in the locations that fall within the polygon. Similar results were reported in other studies [24,26–28].

The results of the GGE biplot analysis for average grain yield performance and stability identified EEPVAH-58 as the most stable hybrid followed by EEWQH-13 and EEWQH-16 in that order. Although EEWQH-13 was the best hybrid across six of the nine test locations, it was relatively stable in the remaining three locations limiting its outstanding performance to those six locations across Mali and Niger. The consistent ranking of EEPVAH-58 across environments suggested a crossover type of GEI for general adaptation [29,30], confirming its wide adaptability across Mali and Niger. In addition to tolerance to multiple stress, this hybrid combined high yield performance with good plant (2.4) and ear aspect (2.3) which are desirable agronomic traits. It ranked second to EEWQH-13, in terms of average grain yield performance across diverse environments, further demonstrating its potential to tolerate multiple stress factors in farmers' fields. EEWQH-13 and EEWQH-16 also displayed high yield potential but were relatively stable than EEPVAH-58 across the test locations. The two hybrids demonstrated good adaptation across six of the nine test locations (polygon view "which-won-where") and could be targeted for release for major maize production areas of Sikasso, Sotuba, and Katibougou in Mali, and Aderaoua, Tara, and Bengou in Niger. Because these hybrids have additional nice-to-have attributes of high-quality proteins (EEWQH-13, EEWQH-16) and enhanced provitamin A (EEPVAH-58), they should be recommended for release to contribute to food and nutrition security in the Sahel. Konate et al. [31] reported that food security and malnutrition are common among the rural populations in the Sahel region. Because of the unique attributes of these hybrids, they are most likely to be adopted by farmers to mitigate the adverse effects of climate change [24,25,32,33] and malnutrition in the Sahel.

The mega-environment is a group of environments that consistently share the best set of genotypes across years [33–35]. In this study, ME1 that comprised six of the nine test locations (Sotuba, Sikasso, Aderaoua, Bougouni, Katibougou and Tara) cut across the four major agro-ecologies of the Sahel region. Considering selection of stable high yielding extra-early hybrids in ME1, one or a few test locations would be sufficient to identify the best hybrid that can be recommended for production within ME1 in Niger and Mali. We observed that most of the high yielding hybrids including EEWQH-13, EEPVAH-58 and EEWQH-16 were found in this mega-environment, confirming their adaptation and suitability for the Sahel region. While in ME2, Bengou and Maradi were discriminative and useful for selecting against unstable hybrids, whereas Tama (in Niger) provided little information on the differences among the hybrids is not useful for selecting stable high yielding extra-early maize hybrids [1,3,4,24,35,36]. Our results agree with other researchers [34,37] who proposed that the best way to achieve reliable selection of the broadly adopted high yielding genotypes is to conduct multiple location trials.

In multiple location trials, some testing locations may be better than others for hybrid evaluation, suggesting that the genotypes may be evaluated at fewer but in better and representative locations [20,34–37]. In our study, the ranking based on discriminating ability and representativeness of the test locations revealed that Tara and Aderaoua (all in Niger) were closest to the ideal test environment. The two locations could be considered as the best test locations based on their suitability and presence in ME1 for testing extra-early maturing maize hybrids. Katibougou and Tama also have good potential for selecting extra-early maize hybrids in Mali and Niger. Interestingly, Tara and Katibougou are located in the Sudan-Savanna while Tama and Aderaoua are in the savanna agroecological zones of the Sahel region. However, the number of locations and hybrids tested in this study were few to provide full picture of suitable testing locations for selecting stable high yielding extra-early maize hybrids in the Sahel region. Further studies would be needed to evaluate a significant number of hybrids in increased number of locations to recommend suitable test sites in the Sahel region.

5. Conclusion

The results of this study have demonstrated that GEI had significant effect on yield performance of extra-early maturing maize hybrids tested across nine locations in Mali and Niger. The GGE biplot explained 69.6 % of the total variability for grain yield. The polygon view “which-win-where” identified EEWQH-13 as the winning hybrid with wider adaptation across six locations (Sikasso, Sotuba, Katibougou, Aderaoua, Tara, and Bengou) cutting across Mali and Niger. While EEYH-42 was specifically adapted to Maradi in Niger and Bougouni in Mali, EEWH-75 was adapted to Tama in Niger. The mean vs stability analysis ranked EEPVAH-58 as the most stable and high yielding hybrid followed by EEWQH-16 and EEWQH-13. Our study identified two mega-environments, ME1 and ME2; ME1 provided more information on hybrid performance than ME2. We found Tara and Aderaoua within ME1 as the suitable locations for selecting promising stable extra-early maize hybrids for wider adaptation. The three hybrids, EEPVAH-58, EEWQH-16, and EEWQH-13 identified in this study have shown resilience to stress factors common in farmers’ maize fields. They could be recommended for on-farm evaluation to confirm the consistency of their yield performance for commercialization in Mali and Niger. Further evaluation of the resilient maize cultivars in multiple locations would be needed to identify more suitable test locations for selecting productive maize hybrids for the Sahel region.

Data availability

Data associated with this study has not been deposited into a publicly available repository. The data will be made available on request.

CRediT authorship contribution statement

Laban Konate: Data curation, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Baffour Badu-Apraku:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Mamadou Coulibaly:** Data curation, Formal analysis, Methodology, Writing – original draft. **Abebe Menkir:** Funding acquisition, Project administration, Resources, Writing – review & editing. **M. Nasser Laouali:** Data curation, Investigation, Methodology, Writing – original draft. **Silvestro Meseka:** Data curation, Formal analysis, Methodology, Supervision, Writing – review & editing, Formal analysis, Methodology, Supervision, Writing – review & editing. **Wende Mengesha:** Methodology, Resources, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was conducted under the “Climate Smart Agricultural Technologies for improved Rural Livelihoods and Food Security in Mali and Niger” project. The authors acknowledge the financial support provided by Royal Norwegian Embassy in Mali (MFA NER-17/0005 and MLI 17/0008 grants). The immense support of the maize improvement program of IITA, the contributions of technical staff members of IER and INRAN are greatly acknowledged.

References

[1] B. Badu-Apraku, M. Oyekunle, K. Obeng-Antwi, A.S. Osuman, S.G. Ado, N. Coulibaly, C.G. Yallou, M. Abdulai, A. G, Boakyewaa, A. Didjeira, Performance of extra-early maize cultivars based on GGE biplot and AMMI analysis, J. Agric. Sci. 150 (2012) 473–483.

[2] J.G. Kling, J.M. Fajemisin, B. Badu-Apraku, A. Diallo, A. Menkir, A. Melake-Berhan, Striga resistance breeding in maize, in: B.I.G. Haussmann, et al. (Eds.), Breeding for Striga Resistance in Cereals. Proceed. Workshop Held at IITA, Ibadan, Nigeria, 2000, 103–118, 28 May - 2 June 1995 (Ibadan, Nigeria).

[3] B. Badu-Apraku, A. Menkir, S.O. Ajala, R.O. Akinwale, M. Oyekunle, K. Obeng-Antwi, K, Performance of tropical early-maturing maize cultivars in multiple stress environments, Can. J. Plant Sci. 90 (6) (2010) 831–852.

[4] B. Badu-Apraku, M.A.B. Fakorede, A.O. Talabi, M. Adekunle, M. Aderounmu, A.F. Lum, P.F. Ribeiro, G.B. Adu, J.O. Toyinbo, Genetic studies of extra-early provitamin-A maize inbred lines and their hybrids in multiple environments, Crop Sci. (2019) 1–51.

[5] G.O. Edmeades, M. Banzinger, S.C. Chapman, J. M Ribaut, J. Bolanos, Recent advances in breeding for drought tolerance in maize, in: B. Badu-Apraku, M. O. Akoroda, M. Ouedraogo, F.M. Quin (Eds.), Contributing to Food Self-Sufficiency – Maize Research and Development in West and Central Africa: Proceed, Regional Maize Workshop, 1995, pp. 24–41. May 1995 (IITA-Cotonou, Benin Republic).

[6] G. Mulugeta, D. Yigzaw, Genotype by environment interaction analysis for tuber yield of potato (Solanum tuberosum L.) using a GGE biplot method in Amhara Region, Ethiopia, Agric. Sci. 5 (2014) 239–249. https://doi:0.4236/as.2014.54027.

[7] M. Balestre, J.C. de Souza, R.G.V. Pinho, R.L. de Oliveira, J.M.V. Paes, Yield stability and adaptability of maize hybrids based on GGE biplot analysis characteristics, Crop Breed. Appl. Biotech. 9 (2009) 219–228, https://doi.org/10.12702/1984-7033.v09n03a03.

[8] CSAT, Climate Smart Agricultural Technologies for Improved Rural Livelihoods and Food Security in Mali and Niger, A project proposal submitted to the Royal Norwegian Embassy, Bamako, Mali, 2018 (2018), May 2018.

[9] P.S. Setimela, C. Magorokosho, R. Lunduka, E. Gasura, D. Makumbi, A. Tarekegne, J. Cairns, T. Ndhlela, O. Erenstein, W. Mwangi, On-farm yield gains with stress-tolerant maize in eastern and southern Africa, Agron. J. 109 (2) (2017) 406–417, https://doi.org/10.2134/agronj2015.0540.

[10] L. Musundire, J. Derera, S. Dari, A. Lagat, P. Tongoona, Stability assessment of single-cross maize hybrids using GGE-Biplot analysis, J. Agric. Sci. 13 (2) (2021) 78.

[11] Y. Kaya, M. Akçura, S. Taner, GGE-Biplot analysis of multi-environment yield trials in bread wheat, Turk. J. Agric. For. 30 (5) (2006) 325–337.

[12] E.M. Mehareb, M.A.M. Osman, A.E. Attia, M.A. Bekheet, F. M Fouz, A. Elenen, Stability assessment for selection of elite sugarcane clones across multi-environment based on AMMI and GGE-biplot models, Euphytica 218 (2022) 95, https://doi.org/10.1007/s10681-022-03025-9.

[13] W. Yan, GGE biplot: a window application for graphical analysisof multi-environment trial data and other types of two-way data, Agron. J. 93 (5) (2001) 1111–1118. https://doi:10.2134/agronj2001.9351111x.

[14] H.G. Gauch, Statistical Analysis of Regional Yield Trials: AMMI Analysis of Factorial Designs, Elsevier, Amsterdam, The Netherlands, 1992.

[15] W. Yan, N.A. Tinker, Biplot analysis of multi-environment trial data: principles and applications, Can. J. Plant Sci. 86 (3) (2006) 623–645. https://dio:10.4141/P05-169.

[16] SAS Institute Inc, Base SAS 9.3. Procedures Guide, SAS Institute Inc, Cary, NC, 2011.

[17] W. Yan, L.A. Hunt, O. Sheng, Z. Szlavnics, Cultivar evaluation and mega-environment investigation based on the GGE Biplot, Crop Sci. 40 (3) (2000) 597–605, https://doi.org/10.2135/cropsci2000.403597x.

[18] W. Yan, Singular value partitioning in biplot analysis of multienvironment trial data, Agron. J. 94 (5) (2002) 990–996. https://doi:10.2134/agronj2002.0990.

[19] M. Oyekunle, A. Haruna, B. Badu-Apraku, I.S. Usman, H. Mani, S.G. Ado, G. Olaoye, K. Obeng-Antwi, R.O. Abdulmalik, H.O. Ahmed, Assessment of early maturing maize hybrids and testing sites using GGE biplot analysis, Crop Sci. 57 (6) (2017) 2942–2950, https://doi.org/10.2135/cropsci2016.12.1014.

[20] Y. Oladosu, M.Y. Rafii, U. Magaji, N. Abdullah, A. Ramli, G. Hussin, Assessing the representative and discriminative ability of test environments for rice breeding in Malaysia using GGE Biplot, Intern. J. Sci. Tech. Resch. 6 (11) (2017) 2277–8616.

[21] M. Ding, B. Tier, W. Yan, H.X. Wu, M.B. Powell, T.A. McRAE, Application of GGE biplot analysis to evaluate Genotype (G), Environment (E), and G×E interaction on Pinus radiata: a case study, N. Z. J. For. Sci. 38 (1) (2008) 132–142.

[22] Y. Goa, H. Mohammed, W. Worku, E. Urage, Genotype by environment interaction and yield stability of cowpea (Vigna unguiculata (L.) Walp.) genotypes in moisture limited areas of Southern Ethiopia, Heliyon 8 (2022), e09013, https://doi.org/10.1016/j.heliyon.2022.e09013.

[23] K.C. Bishwas, M.R. Poudel, D. Regmi, AMMI and GGE biplot analysis of yield of different elite wheat line under terminal heat stress and irrigated environments, Heliyon 7 (2021), e07206, https://doi.org/10.1016/j.heliyon.2021.e07206.

[24] B. Badu-Apraku, M.A.B. Fakorede, M. Gedil, A.O. Talabi, B. Annor, M. Oyekunle, R.O. Akinwale, T.Y. Fasanmade, I.C. Akaogu, M. Aderounmu, Heterotic Responses Among Crosses of IITA and CIMMYT Early White Maize Inbred Lines under Multiple Stress Environments, Euphytica, 2015, pp. 245–262. https://dio:10.1007/s10681-015-1506-0.

[25] W. Yan, J. Fregeau-Reid, D. Pageau, R. Martin, J. Mitchell-Fetch, M. Etienne, J. Rowsell, P. Scott, M. Price, B. de Haan, A. Cummiskey, J. Lajeunesse, J. Durand, E. Sparry, Identifying essential test locations for oat breeding in Eastern Canada, Crop Sci. 50 (2010) 504–515. https://doi:10.2135/cropsci2009.03.0133.

[26] M.S. Araújo, W.F.L. de Aragao, S.P. dos Santos, T.K.T. Freitas, V.C. Saraiva, K.J. Damasceno-Silva, L.A.S. Dias, M.M. Rocha, Evaluation of adaptability and stability for iron, zinc and protein content in cowpea genotypes using GGE biplot approach, Heliyon 8 (2022), e11832, https://doi.org/10.1016/j.heliyon.2022.e11832.

[27] A. Karuniawan, H. Maulana, D. Ustari, S. Dewayani, E. Solihin, M.A. Solihin, S. Amien, M. Arifin, Yield stability analysis of orange - fleshed sweet potato in Indonesia using AMMI and GGE biplot, Heliyon 7 (2021), e06881, https://doi.org/10.1016/j.heliyon.2021.e06881.

[28] D. Ruswandi, M. Syafii, H. Maulana, M. Ariyanti, N.P. Indriani, Y. Yuwariah, GGE biplot analysis for stability and adaptability of maize hybrids in western region of Indonesia, Interna. J. Agron. (2021) 161–170, https://doi.org/10.1155/2021/2166022.

[29] J. Memon, R. Patel, D.J. Parmar, S. Kumar, N.A. Patel, B.N. Patel, D.A. Patel, P. Katba, Deployment of AMMI, GGE-biplot and MTSI to select elite genotypes of castor (Ricinus communis L.), Heliyon 9 (2023), e13515, https://doi.org/10.1016/j.heliyon.2023.e13515.

[30] M.A. Matus-Cádiz, P. Hucl, C.E. Perron, R.T. Tyler, Genotype x environment interaction for grain color in hard white spring wheat, Crop Sci. 43 (1) (2003) 219–226. https://doi:10.2135/cropsci2003.2190.

[31] L. Konate, B. Badu-Apraku, D. Traore, Combining ability and heterotic grouping of early maturing provitamin A maize inbreds across Striga infested and optimal growing environments, J. Agric. Environ. intern. Develop. 111 (1) (2017) 141–157.

[32] C. Debdali, A. Bharadwaj, V.K. Sehgal, Mega-environment concept in Agriculture: a review, Intern. J. Curr. Microbio Appl. Sci. 8 (1) (2019) 2147–2152.

[33] R.N. Raj, M. Sofiya, J. Gokulakrishnan, Assessment of G x E interactions in maize (Zea mays L.) hybrids for yield using AMMI and GGE models, Indian J. Agric. Res. (2021), https://doi.org/10.18805/IJARe.A-5637.

[34] B. Badu-Apraku, R.O. Akinwale, Biplot analysis of line x tester data of maize (Zea may L.) inbred lines under stress and nonstress environments, Cereal Res. Common. 47 (3) (2019) 518–530. https://dio:10.1556/0806.47.2019.25.

[35] W. Yan, S.K. Manjit, M. Baoluo, W. Sheila, L.C. Paul, GGE Biplot vs. AMMI Analysis of genotype by environment data, Crop Sci. 47 (2) (2007) 641–653.

[36] W. Yan, J.B. Holland, Aheritability-adjusted GGE biplot for test environment evaluation, Euphytica 171 (3) (2010) 355–369. https://dio.10.1007/s10681-009-0030.5.

[37] M. Mushayi, H. Shimelis, J. Derera, A.I.T. Shayanowako, I. Mathew, multi-environmental evaluation of maize hybrids developed from tropical and temperate lines, Euphytica 216 (5) (2020) 84, https://doi.org/10.1007/s10681-020-02618-6, 216.