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ASSESSMENT OF YIELD PERFORMANCE AND STABILITY OF MAIZE HYBRIDS ACROSS ENVIRONMENTS USING AMMI AND GGE BIPLOT ANALYSIS

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ABSTRACT

Maize hybrids perform differently in different locations. So, selection of suitable hybrids in diverse locations is essential. The objectives of this study were to estimate the productivity of new maize hybrids under different locations to identify the will-adapted and stable maize hybrids and suitable locations for testing maize hybrids. This study included ten promising white maize hybrids and two commercial hybrids evaluated under five locations in Egypt using a randomized complete block design with three replications. The mean squares due to locations, hybrids and their interaction were highly significant for grain yield. The highest hybrid for superiority percentage relative to cheeks for grain yield was SC-Sk176 followed by SC-Sk183 and SC-Sk179. The first two principal components IPCA1 and IPCA2 explained 81.04% of interaction between locations and hybrids. Based on AMMI analysis, the hybrids; SC-Sk178, SC-Sk179, SC-Sk180, SC-Sk183 and SC-Sk185 gave high grain yield and low scores of IPCA1, indicating that these hybrids are high yielding and stable across different environments. Meanwhile, the SC-Sk176 had the highest grain yield and high scores of IPCA1, indicating that this hybrid is suitable for specific environments. Also, the highest location for IPCA1 showing greater discriminating ability and ease of selection of hybrids was Sids location followed by Nubaria, Sakha and Mallawi. Meanwhile, the poor discriminating ability was shown by location Gemmeiza. The GGE biplot analysis showed that the hybrid SC-Sk176 was optimal in Sakha, Gemmeiza and Nubaria and the hybrid SC-Sk183 was optimal in Sids and Mallawi. The ranking of GGE biplot analysis showed that the hybrid SC-Sk179 followed by SC-Sk183 and SC-Sk185 were the most ideal hybrids because they had high grain yield and stability. Also, Sakha location was more discriminating among hybrids and more representatives of all environments, hence it was considered the ideal testing site for selection. Therefore, the AMMI model and GGE biplot can be used to complement each other for a comprehensive evaluation of maize hybrids yield. Also, selected maize hybrids with high yield and stability can be promoted in maize hybrids breeding program.

Kay words: ***Zea mays, Stability, Grain yield, G×E interaction, Discriminativeness and Representativeness***

INTRODUTION

Maize (*Zea mays* L.) is a multiple uses crop and has a diverse genetic background, also can be planted in different agro-ecological zones. Identifying high yielding hybrids in diverse environments is a constant goal for plant breeder. The overarching goal of any breeding program is to breed elite genotypes in relation to a particular environment, but the genotype × environment interaction (GEI) makes selection more complicated (Gauch 2013). Maize yield is a complex quantitative trait, influenced by multiple genes by genotype (G), environments (E) and G×E interaction among other factors (Kandus *et al* 2010 and Singamsetti *et al* 2021). The understanding of (GEI) effect has significant implication for the yield and stability of maize hybrids (Mafouasson *et al* 2018 and Owusu *et al* 2018). In multi environments trials, often due to GEI, variety selection is inefficient and the relative ranking of varieties varies according to the environment. So, it is necessary to analyze the interaction caused by GEI effect on yield (Mafouasson *et al* 2018). The genotypes are considered stable if their variation among environments are small, which is called statistical stability. Several statistical methods have been developed and deployed to measure GEI and stability. There are two types of stability measures; parametric (multivariate and univariate) and non-parametric stability measures. The non-parametric and univariate stability statistics cannot provide a real picture of the complete response pattern as the genotype response is of multivariate nature in different environments (Lin *et al* 1986 and Akpan and Udoh 2017). Multivariate analysis such as the additive main effects and multiplicative interaction model (AMMI) (Gauch and Zobel 1996) and genotype + genotype × environment (GGE) biplot (Yan *et al* 2000), interpret GEI effects through principal component analysis (PCA) for graphical depiction. The AMMI ANOVA and GGE biplots can provide the robust evaluation of genotypes when GEI is significant and are easy to read interpret graphical tools (Yan and Kang 2002). In addition to the GGE biplots, some indices like AMMI stability value (ASV) and genotype selection index (GSI) aids in identifying the stable and high yielding genotypes across all the environments, respectively approach (Pour-Aboughadareh *et al* 2022). The AMMI model is effective in analyzing the primary effects of genotypes and the environment, along with GEI effects. GGE biplots is a graphical visualization of genotypes and environments based on principal components (first two principal components with large variation). Also, GGE biplots aids in visualizing the winning genotypes in corresponding environments, ranking of genotypes and environment, discriminativeness *vs* representatives of environment (Bos and Caligari 1995, Fan *et al* 2007, Dia *et al* 2016 and Zaid *et al* 2022). AMMI model separates the additive effects for genotype and environment from the multiplicative effect for G×E interaction by applying principal component analysis (PCA) (Pacheco *et al* 2015). GGE biplot is a linear bilinear model that removes the environmental main effect and considers the genotype plus the G×E interaction. This model is powerful in depicting which won where (WWW) pattern and easily identify stable and ideal hybrids as well environments with representativeness effect and discriminating ability of the environments (Bankole *et al* 2023, Matongera *et al* 2023 and Engida *et al* 2024). The objectives of this study were therefore, to identify the high yielding and stable maize hybrids and identify the suitable environments for testing maize hybrids.

MATERIALS AND METHODS

This study was included ten promising white maize hybrids, *i.e.* SC-Sk176, SC-Sk177, SC-Sk178, SC-Sk179, SC-Sk180, SC-Sk181, SC-Sk182, SC-Sk183, SC-Sk184 and SC-Sk185. These hybrids were released by Sakha Maize Research Department at Agricultural Research Center, Egypt. Ten new hybrids along with two commercial hybrids, *i.e.* SC10 and SC128 evaluated in a randomized complete block design with four replications at five Research Stations, *i.e.* Sakha (Sk), Gemmeiza (Gm), Sids (Sd), Mallawi (Mall) and Nubaria (Nub). Each plot consisted of four rows 6 m in length, with a spacing of 0.8 m between the rows and 0.25 m between hills. All agricultural practices were carried out according to the recommendations to give the highest yield. The data recorded on grain yield in ardab per feddan (ard/fed) adjusted on 15.5% grain moisture (ardab = 140 kg and feddan = 4200 m^2). The statistical analysis was done at each location and the combined analysis across five locations was performed after the homogeneity test according to Snedecor and Cochran (1989) by using computer application of Statistical Analysis System (SAS 2008). Stability analysis of the 12 maize genotypes was carried out for grain yield across five locations and then genotype × environment interaction was divided according to the additive main effects and multiplicative interaction (AMMI) model Gauch and Zoble (1996) and genotype + genotype × environment model GGE biplots model (Yan *et al* 2000). AMMI and GGE biplot models were computed using the GEA-R Software Version 4.1 (Pacheco *et al* 2015).

RESULTS AND DISCUSSION

The mean squares due to locations, hybrids and their interaction for grain yield are presented in Table 1. Mean squares due to locations (L) were highly significant for grain yield, indicating that a significant environment effects, highlighting the diversity of the tested environments, which included variation in soil type, climate conditions and other factors influencing grain yield. The mean squares due to hybrids (H) were highly significant, indicating that the hybrids had different grain yield responses from one to another. The mean squares due to H×L interaction was highly significant, suggesting that the grain yield of hybrids were affected by change locations; also, significance of interaction H×L indicates the validity of stability analysis. Similar results were reported by Supriadi *et al* (2024), Thapa and Rawal (2024) and Mosa *et al* (2025).

Table 1. Mean squares due to locations, hybrids and their interactions for grain yield.

SOV	df	Grain yield (ard/fed)
Locations (L)	**4**	**1379.15****
Rep/L	**15**	**5.82**
Hybrids (H)	**11**	**22.21****
H × L	**44**	**23.90****
Error	**165**	**5.56**

**** Indicate significant at 0.01 level of probability.**

Mean performance and superiority percentage relative to the two checks hybrids of ten new hybrids for grain yield across five locations are presented in Table 2. The mean performance of ten new hybrids ranged from 22.89 ard/fed for SC-Sk177 to 26.02 ard/fed for SC-Sk176 with an average of 24.23 ard/fed. Superiority percentage relative to checks SC128 and SC10 showed that four and three hybrids were significant, respectively. The highest hybrid in superiority percentage for grain yield was SC-Sk176 followed by SC-Sk183 and SC-Sk179. These three hybrids are promoted to the next stage of hybrid evaluation program in Egypt.

Table 2. Mean performance and superiority percentage relative to the two checks hybrids of the 10 new white hybrids for grain yield across environments.

Hybrid		Grain yield (ard/fed)	Superiority relative to check (%)	
			SC128	SC10
SC Sk-176	(1)	26.02	13.58*	9.87*
SC Sk-177	(2)	22.89	-0.07	-3.33
SC Sk-178	(3)	24.33	6.21	2.74
SC Sk-179	(4)	25.15	9.80*	6.21*
SC Sk-180	(5)	24.35	6.32	2.84
SC Sk-181	(6)	23.63	3.15	-0.21
SC Sk-182	(7)	23.52	2.69	-0.66
SC Sk-183	(8)	25.83	12.75*	9.07*
SC Sk-184	(9)	23.59	2.96	-0.40
SC Sk-185	(10)	24.92	8.78*	5.23
SC128	(11)	22.91	-	-
SC10	(12)	23.68	-	-
Mean		24.23	-	-
$LSD_{0.05}$		1.47	-	-

*** Indicate significant at 0.05 level of probability.**

The AMMI model analysis of 12 hybrids for grain yield across five locations is presented in Table 3. The results showed the grain yield was significantly affected by the locations (L), hybrids (H) and their interactions (H×L), indicating that the hybrids response were influenced by locations differences, requiring further stability analysis to understand the H×L effect. The H×L was divided into four interaction principal component axes (IPCA's). The first three IPCA's were significant, where IPCA1 accounted for 64.57%, IPCA2 accounted for 16.47%, IPCA3 accounted for 13.52% and IPCA4 accounted for 5.44%. Hence, the interaction effect was concentrated in the first two IPCA's scores (81.04%) explaining the magnitude of interaction effect on grain yield. The remaining IPCA axes contributed only (18.96%) to H × L interaction. Because, the greater percentage of genotype by environment (GEI) due to the first two principal components (IPCA1 and IPCA2), therefore it will be used in GGE biplot analysis. Several authors reported that the first two IPCA's were used in GGE biplot analysis because the greater percentage of genotype × environment interaction in most cases were explained by the first IPCA (Al-Naggar *et al* 2020, Bishwas *et al* 2021 and Thapa and Rawal 2024).

Table 3. Analysis of variance for the additive main effects and multiplicative interaction model (AMMI) of 12 maize hybrids for grain yield across five locations.

SOV	df	SS	MS	Proportions to H×L%
Locations (L)	4	5516.61	1379.15**	-
Rep/L	15	87.30	5.82	-
Hybrids (H)	11	244.32	22.21**	-
H×L	44	1051.70	23.90**	-
IPCA1	14	679.10	48.51**	64.57
IPCA2	12	173.20	14.43**	16.47
IPCA3	10	142.17	14.22**	13.52
IPCA4	8	57.22	7.15	5.44
Error	165	917.40	5.56	-

**** Indicate significant at 0.01 level of probability.**

The relationship between grain yield (ard/fed) and IPCA1 of 12 hybrids evaluated in five locations is shown in Figure 1, where the average grain yield is the x-axis and the IPCA1 is the y-axis when hybrids or locations located on the right-hand side midpoint of the axis main effects have higher grain yields than those on the left-hand side (Ngeve and Boukamp 1993). However, the desirable hybrids on the AMMI biplot are those representing high values on the x-axis (right position) combined with the low estimation of the IPCA1 y-axis (near to zero). Hance, in this study the hybrids no.1 (SC-Sk176), 3 (SC-Sk178), 4 (SC-Sk179), 5 (SC-Sk180), 8 (SC-Sk183) and 10 (SC-Sk185) were high grain yielding. They were placed on right hand side of midpoint representing grand mean. Similarly, locations; Sakha (Sk) and Nubaria (Nub) were higher for grain yield. However, the hybrids no.3 (SC-Sk178), 4 (SC-Sk179), 5 (SC-Sk180) and 10 (SC-Sk185) had high yield (over grand mean) and low score of IPCA1, indicating that these hybrids were high-yielding stable across different conditions, also the hybrid no.8 (SC-Sk183) had high grain yield and moderate score of IPCA1, indicating that this hybrid had moderate stability. Meanwhile, the hybrid no.1 (SC-Sk176) had high grain yield and high score of IPCA1, indicating that this hybrid had significant involvement in the interaction effects, signaling instability and suitability for specific environments. Tena *et al* (2019), Katsenios *et al* (2021), Daemo *et al* (2024) and Ma *et al* (2024) demonstrated that genotypes with an IPCA1 score value close to zero; indicate little or no interaction, suggesting stability performance across environments. Moreover, they identified stable and high yielding superior genotypes through their AMMI biplot analysis. This approach is crucial for breeder to select genotypes with broad adaptability and stability, ensuring reliable yields in various agro-ecological setting.

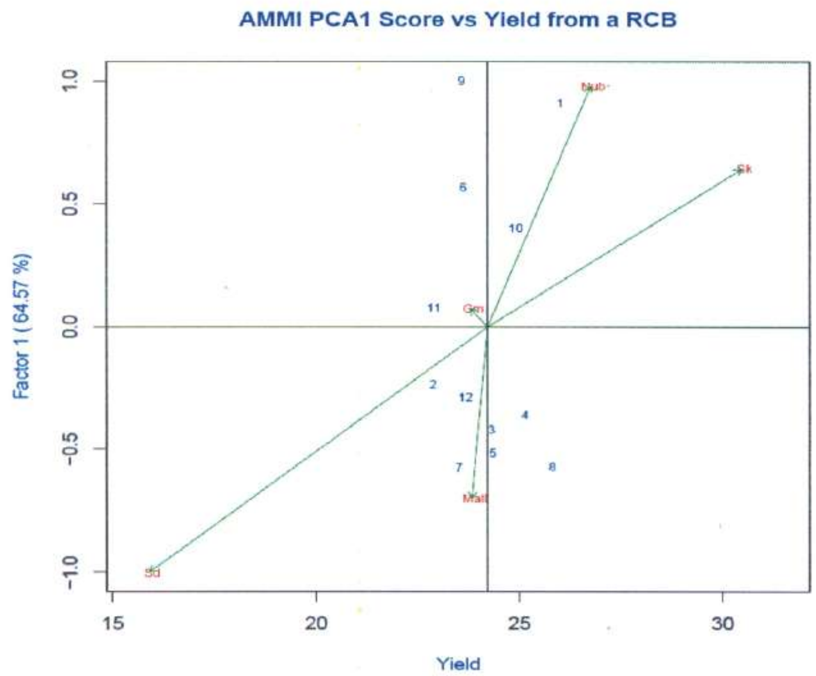

Fig. 1. The ralationship between grain yield (ard/fed) and IPCA1 of 12 hybrids evaluated under five locations.

The analysis based on AMMI model for the two IPCA scores (IPCA1 and IPCA2) which explained 81.04% of hybrids × locations interaction for grain yield was presented in Figure 2. Locations with a small angle between them are highly positively correlated and they provide similar information on hybrids. Based on that, locations Sids (Sd) with Mallawi (Mall) and Nubaria (Nub) with Gemmeiza (Gm) considered to be similar as they had small angle between them and they provide similar information on hybrids. In contrast, the locations (Nub) with (Sd) and locations (Sk) with (Mall) were dissimilar as they had big angle between them and they provide different information on hybrids. The location with higher IPCA1 shows greater discriminating ability. Hence, the results showed that the location

(Sd) followed by (Nub) and (Sk) gave more information on the tested hybrids than the other locations. Meanwhile, (Gm) location was least location for IPCA1, indicating that this location is the most representative environment and poor discriminating ability. Esan *et al* (2023) and Li *et al* (2023) stated that the AMMI model helps to better understand the effects of genotypes × environments interaction, optimal genotypes and suitable environments on improving genotype yield.

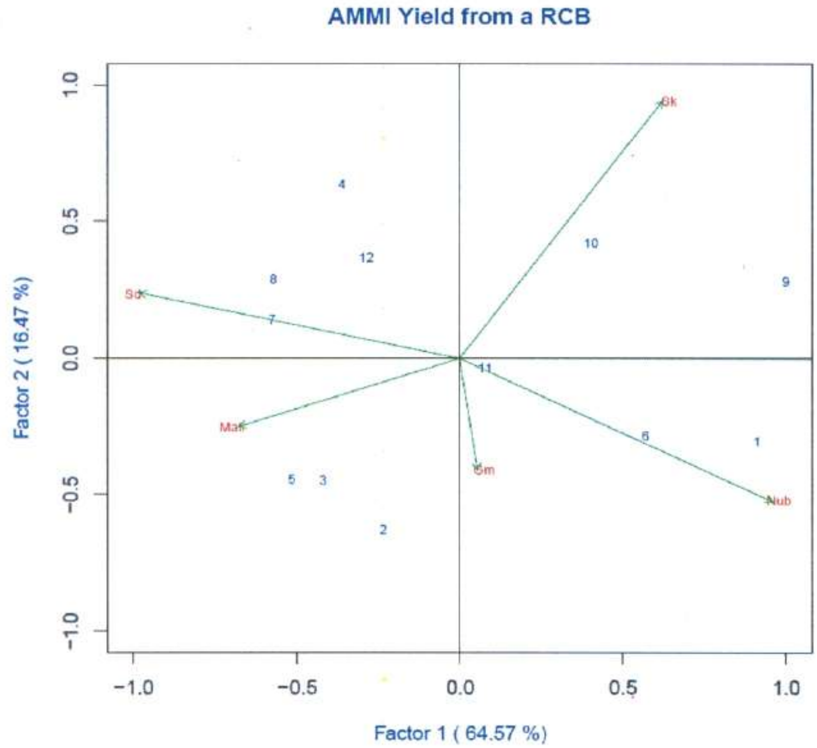

Fig. 2. The AMMI biplot of hybrids × locations interaction for the first IPCA scores, IPCA1 (Factor 1) *vs.* IPCA2 (Factor 2) for grain yield.

GGE biplot analysis of 12 hybrids evaluated in five locations for grain yield is presented in Figure 3. It showed the which-won where, meaning which hybrids performed well at which location. The line that starts from the origin of the biplot and passes perpendicular to the side of the polygon was divided into seven sectors. Hybrids that formed the vertex of the polygon were the highest yielding in the corresponding environments within each sector. Meanwhile the hybrids located faraway from all test locations were considered as poor yielding at each testing location. Also, the genotype within the polygon was less responsive to location than the corner genotypes. So, vertex hybrids no.1 (SC-Sk176) and no.8 (SC-Sk183) were promising yielding or wining in locations (Nub, Gm and Sk) and (Sd and Mall) respectively. Meanwhile the hybrids no.2 (SC-Sk177), no.9 (SC-Sk184) and no.11 (SC128) were low yielding across all or some testing locations. Yan *et al* (2010), Badu-Apraku *et al* (2015), Bishwas *et al* (2021), Ruswandi *et al* (2021), Araujo *et al* (2022) and Zaid *et al* (2022) stated that genotypes positioned at the vertices of a polygon without nearby environmental indicator perform poorly while those at vertices with environmental indicators have the best performance in those specific environments. Also, the less responsive genotypes to any testing environment are located within the polygon.

The analysis of mean *vs.* stability was conducted by the GGE biplot with an average environmental coordinate (AEC). The genotype is more stable when the vertical segment between the genotypes and the (AEC) axis is the shorter. The genotypes were ranged along the average environment axis with the arrow pointing to a higher value based on mean performance across all testing environments. Hence from Figure 4, the results showed that the highest hybrids for grain yield (ard/fed) > grand mean were (no. 4, 8, 1, 10, 3 and 5) or SC-Sk179, SC-Sk183, SC-Sk176, SC-Sk85, SC-Sk178 and SC-Sk180, respectively while the lowest hybrids for grain yield were no. 2 (SC-Sk177) and no. 11 (SC128). Also, hybrids no. 4, 8, 10, 3 and 5 or SC-Sk179, SC-Sk183, SC-Sk185, SC-Sk178, and SC-Sk180, respectively had higher grain yield above grand mean (24.23 ard/fed) and short vertical distances from the AEC.

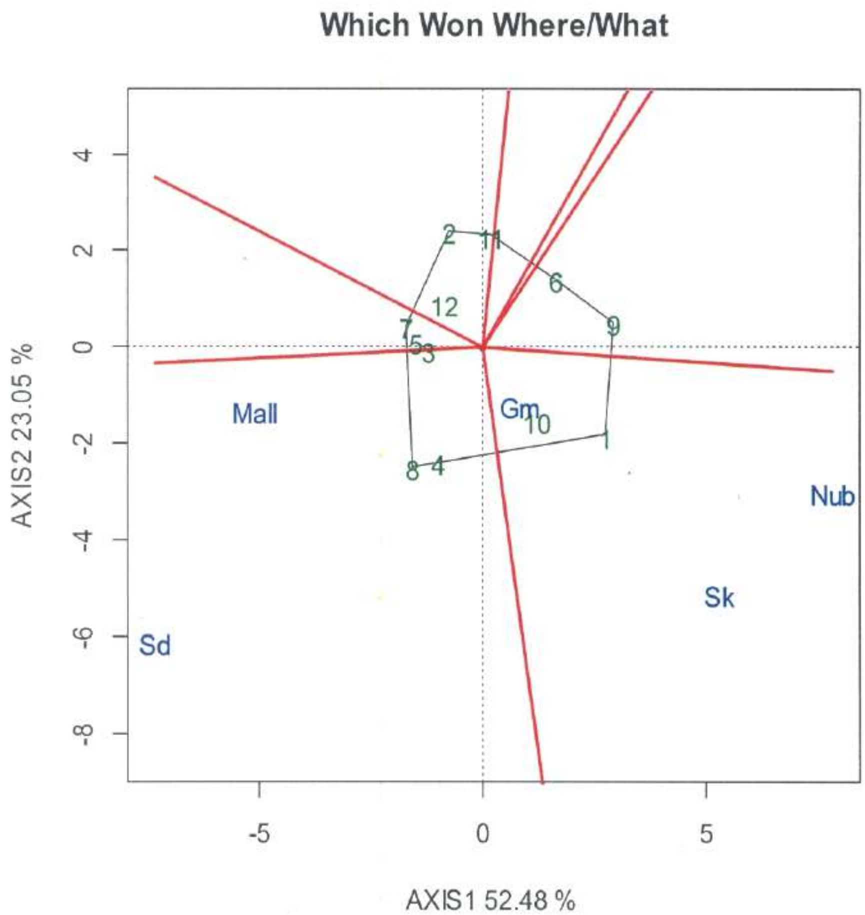

Fig. 3. Which-won-where view of the GGE biplot of 12 hybrids evaluated in five locations for grain yield.

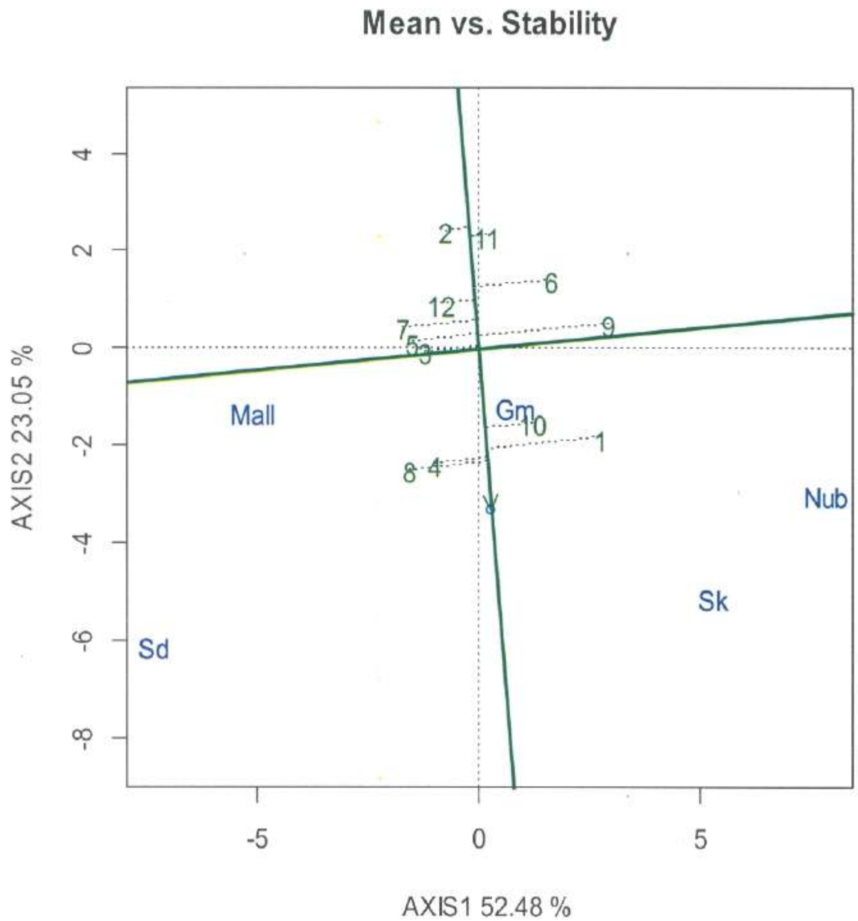

Fig. 4. Mean *vs.* stability view of the GGE biplot based on grain yield of 12 hybrids evaluated in five locations (The arrow is the best point that the software determines the best hybrid).

Hence, these hybrids were considered as stable (less influence from GEI effects) however, hybrids no, 2 and 11 or SC-Sk177 and SC128 were displayed below-average yield but demonstrated higher stability (had the least deviation from the AEC). Meanwhile, hybrid no. 1 (SC-Sk176) had high grain yield but not stable. Hance, it is could be used in the specific environments. Engida *et al* (2024) and Thapa and Rawal (2024) reported that GEE biplot is effective to identify the stable and high yield genotypes across the environments.

Discriminativeness *vs.* representativeness view of The GGE biplot based on grain yield (ard/fed) of 12 hybrids evaluation in five locations is shown in Figure 5. The location with a longer vector length and a small angle to the (ACE) can be considered as an ideal environment for hybrid selection (Discrimination and representativeness environment), while the location with lower vector length and small angle to the (AEC) is more representative than the other environments, also the location with a longer vector length and large angle with (ACE) is the most discriminating. In this study the locations; Sids (Sd) and Nubaria (Nub) were the most discriminating, indicating that they were the most informative locations for genetic differentiation of the hybrids. While the location Gemmeiza (Gm) was the most representative or offered limited information about the hybrids. Meanwhile, the location Sakha (Sk) was more discriminating and representative. Hence, this location Sakha can be used to select the top yielding hybrids that will perform consistently across environments. Yan and Tinker (2006) stated that the environments have small angles with the AEC are more representatives whereas long vectors from the biplot origin is considered as more discriminative environments. Mebratu *et al* (2019) stated that the environments that have both long vectors and small angles with the AEC abscissa are more discriminating and representative environments and considered ideal testing sites and are important to identify desirable hybrids.

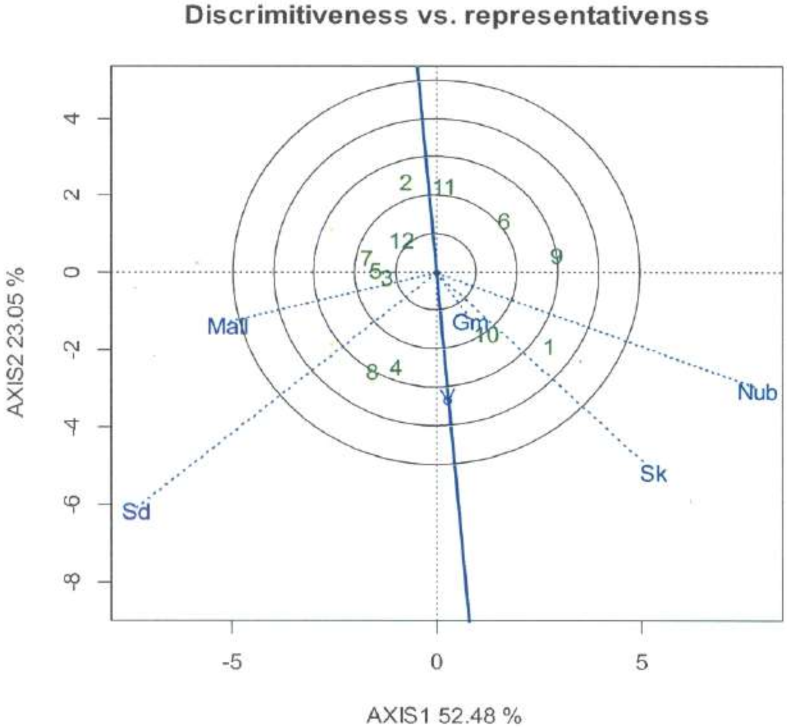

Fig. 5. Discriminativeness *vs.* representativeness view of the GGE biplot based on grain yield of 12 hybrids evaluated in five locations.

GEE biplot view showing ranking of 12 hybrids evaluated across five locations for grain yield is illustrated in Figure 6. An ideal hybrid, located at the center of concentric circle an arrow pointing, has both high mean grain yield and stability. Hence the hybrids; no.4 (SC-Sk179) followed no.8 (SC-Sk183) and no.10 (SC-Sk185) were the most ideal hybrids. Although hybrid no.1 (SC-Sk176) was the highest yielding hybrid but it was not far from the center of concentric circle, suggesting that it is adapted to most of the test locations.

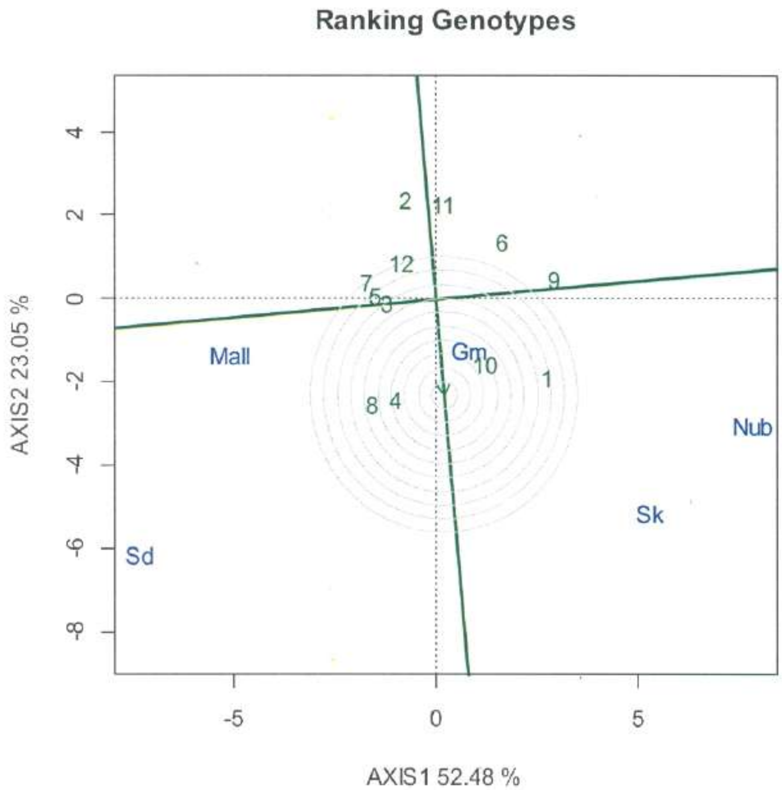

Fig. 6. GGE biplot view showing ranking of hybrid based on grain yield of 12 hybrids evaluated across five locations.

The GGE biplot graphic analysis showed that rankings based on the discriminating ability and representativeness of the test environments revealed that (Sk) location was the closest to the ideal test environment because it was near to the center of concentric circle (Figure 7). The methodology employed for ranking genotypes and environments conforms to the frame work outlined by Yan and Tinker (2006). An ideal evaluation environment must be more representative of all environments and discriminate among genotypes (Kang 1988 and Yan and Kang 2002). Genotypes near the center of concentric circle have a good yield and those far from the circle's center have lower yield (Kendal *et al* 2019). Ideal genotypes should have high yield and stability in multi-environment and the ideal environment should be both strongly discriminating and representative (Yan and Kang 2002 and Li *et al* 2023).

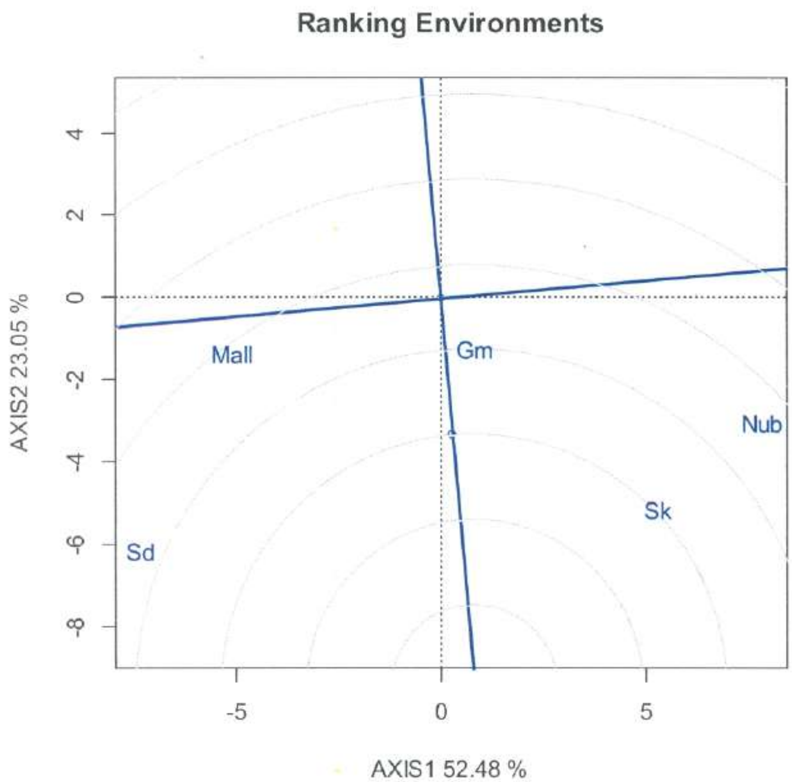

Fig. 7. GGE biplo tview showing ranking of locations based on grain yield of five locations across 12 hybrids.

From this study, the combination of the two analyses provided a comprehensive and reliable approach for evaluating the yield and stability of maize hybrids and the selected hybrids and environments were conductive to guiding the production in Egypt and bringing economic and social benefits.

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تقدير الأداء والثبات المحصولى لهجن الذرة الشامية عبر البيئات بإستخدام تحليل AMMI وتحليل GGE biplot

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يختلف محصول الهجن بإختلاف المواقع ولذلك إنتخاب الهجن المناسبة للمواقع المختلفة يكون أمراً ضرورياً. تهدف هذه الدراسة إلى تقدير إنتاجية هجن جديدة من الذرة الشامية فى مواقع مختلفة للتعرف على أفضل الهجن فى التأقلم والثبات المحصولى وكذلك معرفة أفضل المواقع لتقييم هجن الذرة الشامية. اشتملت الدراسة على ١٠ هجن ذرة شامية بيضاء مبشرة واثنين من الهجن التجارية حيث تم تقييمها فى خمس مواقع بمصر فى تصميم القطاعات الكاملة العشوائية فى ثلاث مكررات. أظهر التباين بين المواقع والهجن والتفاعل بينهما معنوية عالية لمحصول الحبوب. كانت أعلى الهجن فى نسبة التفوق عن هجن المقارنة لمحصول الحبوب هو الهجين (SC-Sk176) يليه الهجين (SC-Sk183) ثم الهجين (SC-Sk179). أظهر أول محورين من محاور المكونات الرئيسية للتفاعل وهما (IPCA1) و (IPCA2) الجزء الأكبر من مكونات التفاعل بين الهجن والمواقع بنسبة ٨١,٠٤%. أظهرت الهجن (SC-Sk178) و (SC-Sk179) و (SC-Sk180) و (SC-Sk183) و (SC-Sk185) قيم عالية فى المحصول وقيم منخفضة فى (IPCA1) ويشير هذا أن هذه الهجن لها قدرة محصولية عالية وثبات تحت مختلف البيئات. بينما كان الهجين (SC-Sk176) يمتلك أعلى محصول وقيمة عالية فى (IPCA1) ويدل ذلك على أن هذا الهجين ذو أداء محصولى عالى وأقلمة خاصة. أظهر موقع سدس يليه موقع النوبارية ثم سخا قيم عالية فى (IPCA1) والتى تشير إلى قدرة هذه المواقع على التمييز لسهولة الإنتخاب بين الهجن. بينما كان موقع الجميزة الأقل فى القدرة على التمييز بين الهجن. أظهر تحليل GGE biplot أن الهجين (SC-Sk176) كان متميزاً فى المحصول بمواقع سخا والجميزة والنوبارية ، بينما الهجين (SC-Sk183) كان متميزاً فى مواقع ملوى وسدس. أظهر الترتيب للهجن من تحليل GGE biplot أن الهجين (SC-Sk179) هو الهجين المثالى فى المحصول والثبات يليه الهجين (SC-Sk183) ثم الهجين (SC-Sk185) ، وكان موقع سخا هو الموقع المثالى فى القدرة التمييزية بين الهجن والقدرة التمثيلية عن البيئات وبالتالى يعتبر أفضل المواقع للتعرف على الهجن المرغوبة. ومن هذه النتائج يمكن إستخدام تحليل AMMI وتحليل GGE biplot بشكل متكامل لإجراء تقييم شامل لإنتاجية هجن الذرة ، وكذلك يمكن الإستفادة من الهجن المنتخبة ذات الإنتاجية العالية والثبات المحصولى فى برنامج تربية هجن الذرة الشامية.

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