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Agronomic performance and stability of Padjadjaran hybrid maize in different agroecosystems

Abstract: The development of high-yielding hybrid maize is a strategic step to address global food demand amidst climate change. This study evaluates the agronomic performance of 14 maize genotypes—10 newly developed F1 hybrids and 4 commercial checks—under two planting densities (95,000 and 55,000 plants/ha) across three agroecosystems (lowland, midland, and highland). The objectives were to identify superior and adaptive genotypes and analyze genotype × environment interactions using AMMI and GGE biplot methods. Genotype G12 exhibited the highest yield (338.4 g/plant) at high density, especially in the highland, but showed poor stability. In contrast, G5 demonstrated consistent performance and stability across environments. This study highlights G5's potential for broad adaptation and provides insights for breeding programs targeting maize productivity in diverse agroecosystems.

Keywords: AMMI · GGE · Planting density · Environment · Stability · Regression

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Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops for global food security, providing a significant portion of caloric intake worldwide (Desoky et al., 2021; Luo et al., 2022; Ma et al., 2024). In Indonesia, however, maize production is challenged by a 39.18% decline in harvested area and a 13.4% drop in output due to land-use change, urbanization, and climate variability (Directorate General of Food Crops, 2024). To maintain national food security, it is critical to develop high-yielding and environmentally adaptable hybrids.

Modern hybrids are designed for resource efficiency and better performance under dense planting, but this approach introduces inter-plant competition for light, water, and nutrients (Omar et al., 2022; Ruswandi et al., 2021; Kamara et al., 2021). Therefore, determining the optimal density and assessing phenotypic stability under multiple environments is essential (Jaikumar et al., 2021; Rizzo et al., 2022; Fadhillah et al., 2021).

In plant breeding, yield stability is an important parameter determining the success of genotype adaptation to environmental variations (Pramitha et al., 2022; Ruswandi et al., 2023). This yield stability is often influenced by the genotype-environment interaction (G × E) (Mansour et al., 2018). According to Ruswandi et al. (2022), differences in the growing conditions result in varying responses for each genotype tested. Analysis methods such as Additive Main Effects and Multiplicative Interaction (AMMI) and Genotype plus Genotype-by-Environment Interaction (GGE) biplot have proven effective in evaluating G × E interactions and identifying genotypes with high stability (Wicaksana et al., 2022). This method clearly visualizes the relationship between genotypes and environments and helps select suitable genotypes for various agroecosystem conditions (Vaezi et al., 2019). AMMI analysis is widely used to evaluate the yield of hybrid maize in multi-environment field trials (Mohammed, 2020).

This study aims to (i) evaluate the agronomic performance of new Padjadjaran hybrid maize across agroecosystems and densities, (ii) analyze genotype, environment, and G × E effects on yield, and (iii) identify genotypes with high yield and stability using AMMI and GGE biplot analysis. This research offers practical implications for breeding climate-resilient maize suited to Indonesia's varied topography.

Materials and Methods

This research was conducted in three locations with different agroecosystem characteristics, namely Bojongsoang (lowland), Arjasari (midland), and Ciwidey (highland). The experiment used 14 genotypes comprising 10 new F1 hybrids and four superior commercial hybrids as comparisons. A split-plot design was used, with the main plot being planting density (95,000 plants/ha and 55,000 plants/ha) and the subplot treatment being genotype. Each treatment was repeated three times.

Observations included plant height, stomatal conductance, leaf chlorophyll, leaf area index, and weight per plant. Data were analyzed using combined ANOVA to identify the effects of genotype, environment, and G × E interaction using the PBSTAT statistical software (Maulana et al., 2023). Phenotypic stability parameters, such as regression standard deviation (S^2di) and regression coefficient (bi), were analyzed based on the approach developed by Eberhart & Russell (1966). Significant differences between the value of bi and one were tested using the t-test, while the deviation S^2di was tested using the F-test.

The AMMI (Additive Main Effects and Multiplicative Interaction) model is applied according to the method described by Gauch (2006). The AMMI Stability Value (ASV) is calculated using the formula developed by Purchase et al. (2000). Additionally, the AMMI and SREG (Site Regression) models are used to generate GE and GGE biplots, which illustrate the genotype and environment interactions. The first two principal components (PCA) visualize the relationship between the evaluated genotype and environment (Kempton, 1984).

Results

ANOVA. Combined analysis of variance shows that the main effects of planting environment, planting density, and genotype factor significantly influence all observed characters (Table 1). Variation in rice yield is influenced by genotype by 35.0% of the total sum of squares, while the growing environment and planting density contribute 29.6% and 12.1%, respectively. Furthermore, most of the agronomic traits analyzed were significantly influenced by the two-way and three-way interactions between the growing environment, planting density, and genotype. These results are also consistent with Luo et al. (2015) and Shojaei et al. (2022), where the genotype, location, and interactions were statistically significant.

Agronomic Performance. The agronomic performance of ten developed hybrid maize and four commercial hybrids was tested at two planting density levels in three environments, as shown in Figure 1. All observed traits showed significant variation among hybrids in different environments and planting densities. The Ciwidey environment provided the best performance for plant height, stomatal conductance, and seed yield parameters, with respective values of 42%, 12%, and 22.4%. Meanwhile, for the leaf chlorophyll and leaf area index parameters, the best performance was observed in the Arjasari environment with values of 20% and 138%, respectively.

High planting density also increases plant height, leaf area index, and yield by 19.5%, 94%, and 25.9%, respectively. Plant height ranged from 40.4 to 235.9 cm, with hybrids G14, G9, G12, G4, and G3 showing the best performance in Ciwidey, while G11, G4, G7, G13, and G2 excelled in Arjasari (Figure 1a). The leaf area index ranges from 1.21 to 11.7, with hybrids G3, G4, and G1 excelling in Arjasari and G6, G2, and G14 in Ciwidey (Figure 1d); as for the parameters that perform better at low density, such as stomatal conductance and leaf chlorophyll, where the values are 28% and 1% respectively. Stomatal conductance with hybrids G14, G7, and G3 was best in Arjasari and hybrids G2 and G10 in Bojongsoang (Figure 1b). Meanwhile, the chlorophyll values with the G14 and G12 hybrids had the best values in Arjasari and Bojongsoang.

Genotype G12 recorded the highest yield (338.40 g) at high planting density in all locations, although its stability was low. On the other hand, genotype G5 showed the highest stability with a moderate yield (251.12 g) (Figure 1e).

Stability Parameters. The phenotypic stability of the 14 tested hybrid corn has been calculated using the Eberhart and Russell method (Eberhart & Russell, 1966). The results of the combined regression analysis show that the G × L (linear) component has a highly significant influence. In contrast, L + G × L and the agro-environment (linear) do not show a significant influence (Table 2). This emphasizes the importance of linear (bi) and non-linear (s^2di) sensitivity to the expression of agronomic traits (Omar et al., 2022). As shown in Table 3, the regression coefficients (bi) among hybrids range from -0.45 (G6) to 2.91 (G7), indicating the presence of genetic diversity in the regression response. The deviation from regression (s^2di) ranges from -366.43 (G5) to 5306.66 (G12).

Table 1. Combined analysis of variance of 14 hybrid corns at two planting density levels and three planting environments on yield and its characteristics

Source of Variation	df	Plant height	Stomatal conductance	Leaf chlorophyll	Leaf area index	Seed weight
Replication (U)	2	297.97 ns	15236.7 ns	123.54 ns	0.0045 ns	1763.37 ns
Genotype (G)	13	3217.01**	31739.4 ns	445.20**	4.0456**	41643.97**
Error a	26	127.85	975432.5	67.20	0.5437	717.40
Populations (P)	1	47498.11**	500537.1**	76.43 ns	467.90**	48563.90**
Environment (L)	2	110291.89**	503418.1**	1488.52**	231.46**	54790.38**
G × P	13	1175.26**	44187.4**	56.67ns	1.98**	10850.65**
G × L	26	1350.89**	55518.6**	167.46**	2.55**	10982.97**
P × L	2	4802.07**	204498.0**	1012.92**	67.85**	6991.44**
G × P × L	26	695.79**	49900.18**	157.72**	1.73**	5405.97**
Error b	140	136.22	19428.68	64.04	0.45	1462.73
Total	251					

Notes: df was degree of freedom; ** was significant at $p < 0.05$; ns was not significant

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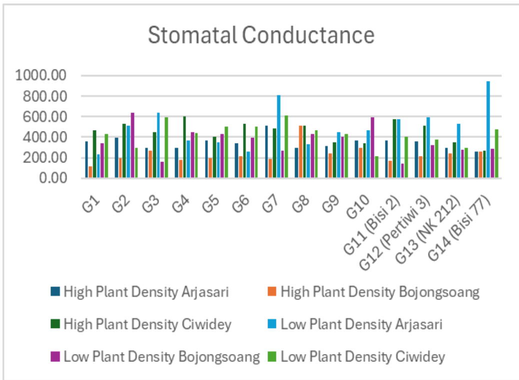
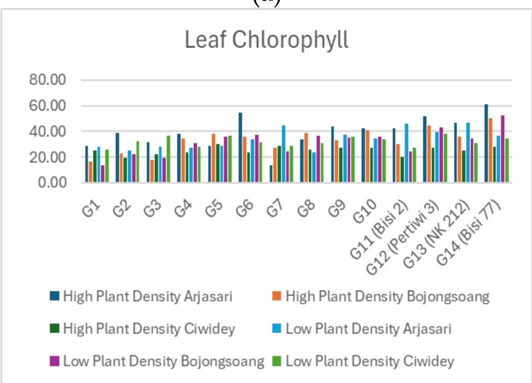
Hybrids with a bi value greater than one (bi > 1) and a non-significant s²di, such as G5 and G11, adapt well to supportive agronomic environments, including planting density, planting environment, and other inputs. On the other hand, hybrids with a bi value less than one (bi < 1) and a non-significant s²di, such as G4, show better suitability in less optimal environmental conditions. Hybrids with a bi value close to one and a non-significant s²di, such as G4, show consistent performance stability across various agronomic environments (Table 3). Based on Breese (1969), genotypes with a regression coefficient more significant than one adapt better to favorable environmental conditions, while genotypes with a regression coefficient less than one tend to be more suited for less favorable environmental conditions.

Based on the analysis of the regression coefficient values (bi) and the deviation from the regression (s²di), the most superior and highly stable hybrid is G5. This hybrid has excellent potential to support maize breeding programs in increasing grain yield under high planting density conditions in the three tested growing environments.

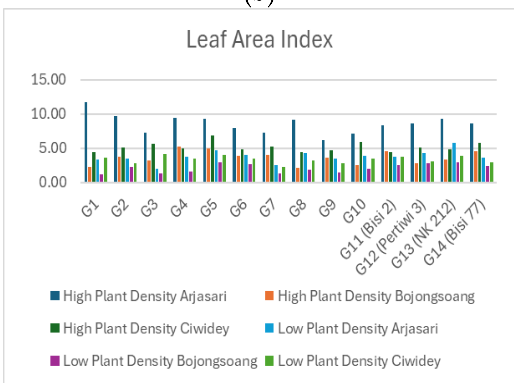
(a)



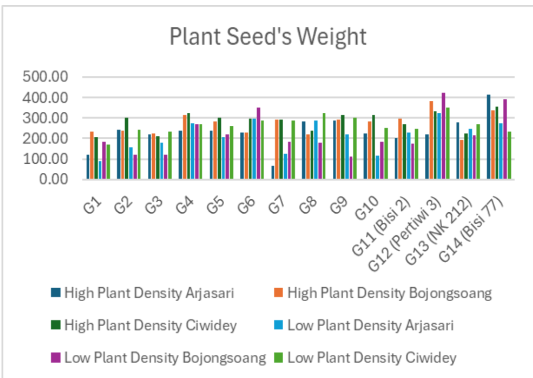
(b)



(c)



(d)



(e)

Figure 1. Agronomic performance of 14 hybrid maize genotypes under two planting densities across three agroecosystems: (a) Plant Height (cm), (b) Stomatal Conductance (mmol m⁻² s⁻¹), (c) Leaf Chlorophyll (SPAD), (d) Leaf Area Index (unitless), (e) Seed Weight per Plant (g)

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AMMI Analysis. The results of the AMMI analysis revealed that the genotype factor (G), agroecological environment (L), and the interaction between the two (G × E) have a significant influence on the yield (Table 4). The contribution of the sum of squares for each is 46.66% for genotype, 14.75% for environment, and 37.39% for GEI. Visualization through the AMMI1 biplot shows that the G14 hybrid recorded the highest average yield, followed by G12, G5, G13, and G9. Among the groups, G14, G13, G6, and G8 have the lowest first principal component (PC1) values (Figure 2a). G7 showed the highest PC1 value of all the hybrids tested, while G14 had the lowest PC1 value (Figure 2, Table 4). Some hybrids showed specific adaptation to the agroecological conditions of Env5 (low planting density in Ciwidey) and Env1 (low density in Arjasari), compared to other environmental conditions. The Env5 environment produced the highest yield with a PC1 value close to zero, indicating minimal interaction. On the other hand, the highest PCA value was recorded in Env4 (high planting density in Bojongsoang).

The Env3 environment (low planting density in Bojongsoang) and Env4 (high planting density in Bojongsoang) are unstable and more responsive due to their distance from the original location, whereas Env6 and Env2 are less responsive. Similarly, in AMMI2, hybrids G1, G10, G11, G4, and G3 are more stable because they are located near the original site (Figure 2b). On the other hand, hybrids G14, G12, G7, G9, and G2 are far from the original site. Moreover, the environments Env5, Env2, and Env6 are unstable and more responsive due to their distance from the origin.

AMMI shows that genotypes G1, G4, and G10 are the most stable under various environmental conditions.

Table 2. Combined variance regression analysis for the yield of 14 hybrids in six planting environments

Model	83	426860	5143
Genotype (G)	13	173.56	13882 **
L + G × L	70	246391	3520
Environment (linear)	1	57369	57369
G × L (linear)	13	61487	4730 *
Pooled Deviation	56	127534	2277
Pooled Error	156	64954	416

Notes: ns was not significant; ** was significant at $p < 0.01$; * was significant at $p < 0.05$; df was degree of freedom

Table 3. The stability parameters of 14 hybrid corn were evaluated for Plant Seed's weight at two planting densities and three planting environments

Genotype	Mean (g_i)	b_i	S^2_{di}	ASV	Rank
G1	166.12	1.45	1060.01**	4.62	5
G2	216.48	1.95**	1119.95**	6.18	6
G3	197.71	0.93	857.46*	4.49	4
G4	280.59	0.78	211.67	2.38	2
G5	251.12	1.25	-366.43	0.80	1
G6	281.64	-0.45**	1926.35**	7.94	9
G7	207.91	2.91**	2824.63**	10.48	13
G8	254.67	0.03**	3036.29**	6.67	11
G9	253.86	1.95**	3246.36**	9.34	10
G10	228.68	2.39**	313.66	207.06	7
G11 (Bisi 2)	236.91	1.25	451.48	71.45	3
G12 (Pertiwi 3)	338.40	0.30*	5306.66**	262.73	12
G13 (NK 212)	238.54	-0.30**	798.22*	215.64	8
G14 (Bisi 77)	332.95	-0.43**	5267.98**	357.41	14

Notes: * was Significant at $p < 0.05$; ** was Significant at $p < 0.01$; g_i was the mean of genotype; b_i was the regression coefficient; S^2_{di} was the ean square deviation from linear regression; ASV was AMMI stability value.

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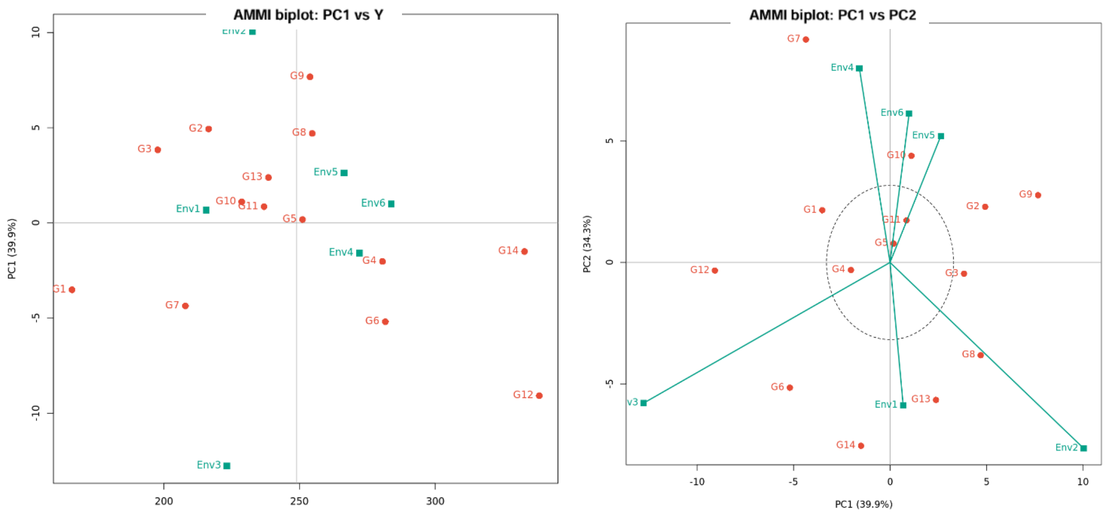
Table 4. AMMI analysis of yield variability (ton ha^{-1}) from 14 hybrid corn in six planting environments

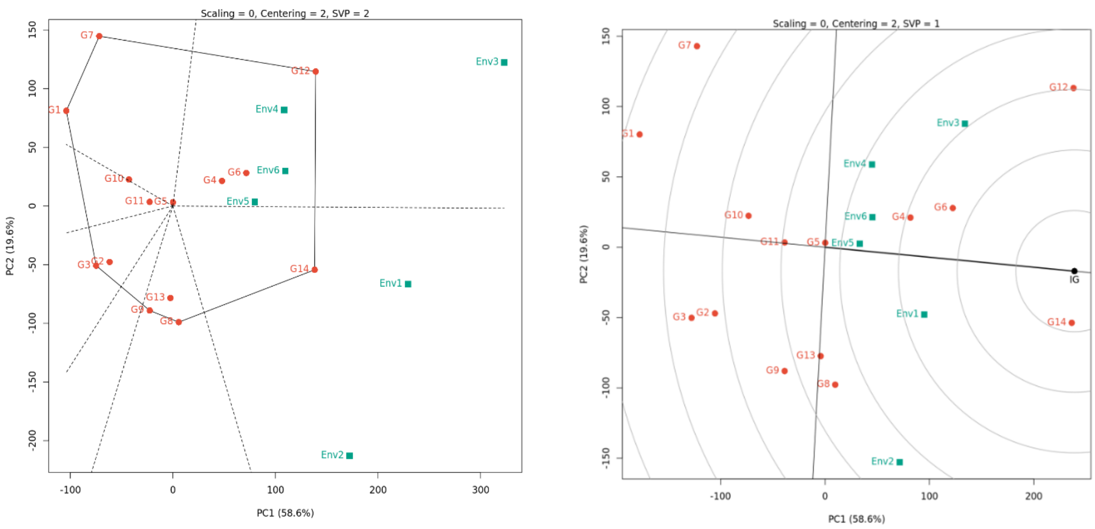
Source of Variation	df	Sum of Squares	Mean Square	Percentage
Environment (L)	5	164.57	32.91**	14.75
Replication (U)	12	13.52	1.12 *	1.21
Genotype (G)	13	520.68	40.05 **	46.66
G × L	65	417.21	6.24 **	37.39
PC1	17	200.31	11.78 **	17.95
PC2	15	112.80	7.50 **	10.11
PC3	13	79.15	6.08 **	7.09
PC4	11	16.38	1.48 **	1.47
PC5	9	8.56	0.95 ns	0.77
Residuals	156	77.46	0.49	
Total	95	1115.98		

Notes: ^{ns} was not significant; ** was significant at p < 0.01; * was significant at p < 0.05; df was the degree of freedom.



a b

Figure 2. AMMI1 (a) and AMMI2 (b) biplots of 10 developed hybrid corn and four commercial checks (G1–G14) evaluated in six agro-environments (Env1-Env6)



A B

Figure 3. Distribution plot (a) and comparison graph (b) of the GGE biplot for the yield of 14 hybrid corn (G1-G14) in six environments (Env1-Env6). The horizontal black line directs the tested hybrids towards higher yields, and the other vertical black line crossing the origin of the biplot indicates stability

GGE Biplot. The angle between the environmental vectors indicates the association of genotypes in an environment. The relative length of the vectors in the biplot reflects the proportion of variability associated with each variable. When the angle between two vector properties is less than 90 degrees, it indicates a positive correlation between the two variables. On the other hand, if the angle is more than 90 degrees, it indicates a negative correlation. In addition, a 90-degree angle between two vectors indicates no significant correlation between the two variables (Al-Naggar et al., 2020). The GGE biplot identifies the Env5 environment (Ciwidey with low planting density) as the most representative environment for evaluating hybrid corn, with a high PC1 value and a low PC2 value. Additionally, Env6 (Ciwidey with high planting density) is a favorable environment, but Env1 (Arjasari with low planting density) and Env2 (Arjasari with high planting density) are unfavorable environments with environmental stress.

The GGE biplot graph for the SREG model is illustrated in Figure 3b. The G5 corn hybrid is stable with a GE close to zero. This indicates high yields with the best performance in all agro-environments. In addition, the G12 hybrid is also desirable and closer to the ideal hybrid.

Discussion

This study evaluates 10 new corn hybrids and four superior commercial hybrids at two different plant density levels in three locations (Arjasari, Bojongsoang, and Ciwidey). Analysis of variance was applied to assess the impact of genotype, environmental factors, and their interaction on the agronomic characteristics and quality of hybrid corn (Katsenios et al., 2021). The results of this study confirm that maize genotypes have varying responses to planting density and environmental conditions, consistent with previous research by Sun et al. (2023). Plant density is a factor that influences the survival chances of plants and the efficiency of other input usage. With optimal density, each plant has a better chance to thrive and compete for the necessary resources (Huang et al., 2021).

The values of stomatal conductance, leaf chlorophyll, and leaf area index are also influenced by density treatments, and each genotype produces different responses. Of course, the values of these parameters show specific and stable results across different planting densities. The higher the value of these parameters, the better the plants perform metabolism, especially photosynthesis (Soleh et al., 2020). El Shamey et al. (2022) and Sandhu & Dhillon (2021) reported that the latest hybrid corn is designed for better tolerance to high planting density, which increases yield per unit area. However, the increase in density also heightens competition among plants, which can reduce resource use efficiency. This is evident in the G12 genotype, which, despite recording the highest yield, shows a high dependence on specific environmental conditions, as determining the optimal planting environment becomes a crucial aspect in supporting maize production efficiency, especially in the face of current climate change dynamics (Han et al., 2022).

On the other hand, the G5 genotype shows high yield stability across various environments. This stability can be attributed to better phenotypic adaptation to environmental variations, as Breese (1969) explained. Genotypes with regression coefficient values close to one tend to have better stability, as they can maintain consistent yields despite environmental changes, as in the study by Ma et al. (2020), which explains that the latest hybrids have parameter values that adjust when planting density increases. The phenotypic variability of hybrids developed in various agro-environmental conditions can enable maize breeders to study the genetic potential of hybrids to enhance maize productivity (Omar et al., 2022).

AMMI and GGE biplot analysis provides information about genotype and environment interaction. AMMI is considered significant in evaluating the stability of crop yields under various environmental conditions and in determining the optimal environment for all analyzed genotypes (Agahi et al., 2020). AMMI results show that genotypes G5, G4, and G11 are the most stable, while the GGE biplot identifies the Ciwidey environment as the most representative location. These results are consistent with the research by Gauch (2013), which states that the AMMI and GGE biplot methods are very effective in evaluating the stability and adaptation of genotypes in various environments.

However, this study has limitations, including the lack of evaluation of the impact of pests, diseases, and other agronomic input factors, such as fertilizers and irrigation. Further research needs to include these factors to provide a more comprehensive picture of the performance of maize genotypes in the field.

Conclusion

Analysis shows a highly significant genetic difference among the 14 corn hybrids studied. The evaluated yield characteristics were greatly influenced by the location and plant density. The increase in plant density improved the seed yield of all evaluated hybrids at the Bojongsoang and Ciwidey locations, except for Arjasari. Hybrid corn showed varying responses to the tested agro-environmental conditions. Overall, the G12 and G14 hybrids showed the highest seed yields and attributes in various agro-environments compared to other hybrids. Combined regression analysis, AMMI, and GGE can be used to identify stable maize hybrids across various environments. Stability analysis shows that hybrids G5, G4, and G11 are stable and desirable hybrids. Therefore, these hybrids are recommended for further inclusion in the corn breeding program to increase corn production.

Acknowledgments

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