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ASSESSMENT OF PROMISING MAIZE HYBRIDS WITH FAVORABLE ENVIRONMENTS USING GENOTYPE-BY-ENVIRONMENT INTERACTIONS

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SUMMARY

Maize is the second staple food after rice that supports livestock feed and the rural economies of smallholder farmers. However, the broad agroecological variability causes variations in maize (*Zea mays* L.) productivity due to genotype-environment interaction (GEI) in Indonesia. Thus, the following study aimed to evaluate the promising maize hybrids with favorable environments using the GGE (genotype + genotype × environment) biplot through GEIs. Seventeen single-cross maize hybrids and two check cultivars (NASA-29 and P-36) underwent evaluation in 2021 through a randomized complete block design (RCBD) with three replications at nine locations in Indonesia. Results revealed significant differences among genotypes, environments, and their interactions ($p < 0.01$), indicating strong GEI effects. Based on the biplot analysis, West Lombok emerged as the most favorable environment, while Manado was the most unfavorable environment for maize hybrid productivity. Based on the GGE biplot analysis, hybrid ST-201328 demonstrated the highest grain yield and stability, becoming the most recommendable as a promising maize hybrid in Indonesia. These findings underscore the usefulness of the GGE biplot analysis in guiding hybrid selection and targeting suitable test sites for future hybrid maize breeding and development programs.

Keywords: Maize (*Z. mays* L.), promising hybrids, favorable location, GGE biplot, genotype-by-environment interactions, grain yield

Key findings: According to this study, West Lombok is distinctly the most favorable environment for maize (*Z. mays* L.) production, while Manado is the most unfavorable. Hybrid ST-201328 demonstrated the highest grain yield and stability and came as the most recommended promising maize hybrid in Indonesia.

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INTRODUCTION

Maize (*Zea mays* L.) is a strategic crop both globally and in Indonesia. Besides being a staple food in Sub-Saharan Africa and Latin America, maize is also vital for animal feed, industrial raw materials, and international trade (Erenstein *et al.*, 2022). Maize is the second most important staple food after rice in Indonesia, also serving as a key component of livestock feed and supporting the rural economies of smallholder farmers (Ardie *et al.*, 2021). In international trade, the value of maize trade is USD 64.7 trillion, which is twice that of rice (Praseto *et al*., 2024). Indonesia's corn trade balance position in 2023 has a deficit of 1,173,930 tons, equivalent to USD 353,668 million (Komalasari, 2024). Widihastanto *et al*. (2024) reported uses for Indonesian maize are 41% for animal feed, 28% for human consumption, and 31% for other purposes (industry, seeds, and so on). Addressing such a deficit requires agricultural research to develop new hybrid varieties with high productivity.

Indonesia has broad agroecological variability, which leads to remarkable variations in maize (*Zea mays* L.) grain yield across various locations (Wicaksana *et al.*, 2022). The yield differences are ascribable to genotype-environment interaction effects. Several studies authenticated the genotype-environment interaction effects that caused disparities in maize genotypes at different locations (Shojaei *et al.*, 2021; Ye *et al.*, 2021). Therefore, further research is earnestly essential at these diverse locations to better explain the genotype-environment interaction effects.

The genotype + genotype × environment (GGE) biplot is a graphical tool widely used in plant breeding to study different genotypes' performance and genotype-by-environment interaction (GEI) effects. It has been successful to evaluate the adaptability and stability of maize genotypes, including silage cultivars over two seasons (Yue *et al.*, 2022), hybrids over three years (Bojtor *et al.*, 2021), and maize hybrids across four locations (Shojaei *et al.*, 2022). As a proper GEI analysis, the GGE biplot is well-suited for addressing genotypes' functions, genotype-by-environment association, environment grouping by mega-environment, stability analysis, and identifying ideal genotypes through graphical visualization (Badu-Apraku *et al.*, 2020).

The GGE biplot can also display the best genotypes with the highest grain yield in each mega-environment, as well as ideal genotypes and environments (Mehareb *et al.*, 2022). The presented study aimed to analyze the genotype-by-environment interaction effects on maize hybrids and the check cultivars, focusing on identifying promising hybrids with favorable environments through the GGE-biplot approach. This valuable information will help plant breeders to decide the desirable location and selection of promising maize hybrids with better productivity.

MATERIALS AND METHODS

The promising research on maize (*Z. mays* L.) hybrids and check cultivars ran from January to July 2021 at nine locations, i.e., Malang, Kediri, Maros, Gowa, Probolinggo, Manado, West Lombok, Sigi, and Soppeng. The selected locations have varying soil types, latitudes, altitudes, and climate types (Table 1). The genetic material used in this research comprised 17 single cross-maize hybrids and two extensively cultivated and high-yielding commercial hybrids (NASA-29 and P-36) as check cultivars (Table 2). The hybrid materials' development used 17 distinct female lines and 11 males. In selecting these parents, researchers looked into their contrasting genetic backgrounds and superior agronomic traits (high-yield potential, downy mildew resistance, stay green, and drought tolerance).

The experiment layout was in a randomized complete block design (RCBD) with three replications. The experimental subplot size was 3 m × 5 m (15 m^2), with a planting space of 75 cm × 20 cm, and one plant per hole, making 25 plants per row. Soil preparation included plowing and harrowing to a fine tilth, ensuring proper seedbed conditions across all locations.

Table 1. Altitude, type of soil, altitude level, and climate type of research sites used in the study.

Code	Locations	Altitude	Soil type	Altitude (masl)	Climate type*
E1	Malang	-8.175, 112.560	Alfisol	335	C3
E2	Kediri	-7.771, 112.234	Inceptisol	50	C
E3	Maros	-4.980, 119.574	Latosol	5	C3
E4	Gowa	-5.310, 119.507	Ultisol	49	C3
E5	Probolinggo	-7.801, 113.160	Andosol	10	E1
E6	Manado	1.577, 124.881	Inceptisol	50	C
E7	West Lombok	-8.694, 116.067	Alluvial	100	D3
E8	Sigi	-1.096, 119.880	Latosol	10	C
E9	Soppeng	-4.210, 119.884	Alluvial	200	C3

*: Oldeman classification of climate types (1982).

Table 2. Name and the origin of maize hybrids and check cultivars used in the study.

Genotype Code	Name	Origin
Hybrids		
G1	ST-201315	XT 728/XT 118
G2	ST-201328	XT 308/XT 118
G3	ST-201342	XT 831/XT 118
G4	ST-201364	XT 138/XT 118
G5	ST-201320	XT 605/GTX 704
G6	ST-201359	P 417/BB 12
G7	ST-201312	P 913/TN 124
G8	ST-201309	9197 K/K1914
G9	ST-201311	43601 C/C 1114
G10	ST-201322	1195 K/K 1915
G11	ST-201316	3195 K/K 2041
G12	ST-201355	19116 C/C 1411
G13	ST-201357	6192 K/K 1914
G14	ST-201340	1711 C/C 1114
G15	ST-201381	25-37-84-2/SGI 1
G16	ST-201325	SM1-5-6/SGI 3
G17	ST-201376	18-2-1-1/SGI 4
Check cultivars		
G18	NASA-29	-
G19	Pioneer 36	-

In the research, the maize seeds received pre-treatment with a fungicide containing dimethomorph, which is used to prevent early infections of downy mildew (*Peronosclerospora maydis*). The treatments involved dissolving 3 g of dimethomorph 50 WP per kilogram of seed.

The first fertilizer application proceeded 10 days after planting (DAP), with a dose of 135 kg N + 45 kg P_2O_5 + 45 kg K_2O ha^{-1}. The second fertilizer application ensued 35 DAPs, with a 90 kg N ha^{-1} dose. Plant management, including weeding, irrigation, and hoeing, took place optimally.

The observed variable was grain yield, with a correction to 15% moisture and conversion to units per hectare, using the following formula:

$$\text{Yield (t/ha)} = \frac{10.000}{HA} \times \frac{100-GM}{85} \times EHW \times SP \div 1.000$$

Where HA = the harvested area (m^2), GM = grain moisture (%), EHW = the ear harvested weight (kg), and SP = shelling percentage (%).

Analysis of variance continued as a pooled analysis of variance based on a linear model:

$$Yi = \mu + R(kj) + \alpha i + \beta j + (\beta\alpha)ij + \varepsilon ij$$

Where Yi: observation, μ: general mean, R(kj): effect of nested k repeats on j location, αi: location effect to i, βj: hybrid effect to j, (βα)ij: interaction of genotype to i x location to j, and εij: residual value.

Genotype stability analysis proceeded when the interaction between genotype and environment was significant. The GGE biplot method followed a mathematical model:

$$Y_{ij}-Y_{j} = \lambda_{i1}\xi_{i1}\eta_{i1} + \lambda_{i2}\xi_{i2}\eta_{i2} + \varepsilon ij$$

$$Y_{ij}-Y_{j} = \lambda_{l}\xi_{il}\eta_{il} + \lambda_{2}\xi_{i2}\eta_{i2} + \varepsilon_{ij}$$

Where Yij is the mean of the i genotype at the j location, Y_j is the mean value of all genotypes in the j neighborhood, λ_{i1} λ_{i2} is the value of the singular principal component axis (PCA), $\xi_{i1}\xi_{i2}$ is the PCA1 and PCA2 value for the i genotype, $\eta_{i1}\eta_{i2}$ is the PCA1 and PCA2 value for the j environment, and εij is the residual value.

The creation of the GGE biplot used the metan package in R Studio (Olivoto and Lúcio, 2020). The biplot generation utilized a singular value partitioning (SVP = 2), with no transformation (transform = 0), environment-centered data (centering = 2), and standardized by standard deviation (scaling = 0).

RESULTS

The pooled analysis of variance revealed that locations, maize (*Zea mays* L.) hybrids, and hybrid × location interactions had significant effects on grain yield (Table 3). The contributions of each factor to the grain yield were as follows: hybrids (27.04%), error (25.93%), hybrid-by-environment interactions (18.87%), locations (17.86%), and replication within the location (10.29%). Among all these factors, the maize hybrids had the most significant and considerable effects.

Table 4none of the hybrids gave the highest yield across all test locations (Table 4). The hybrid ST-201328 had the maximum total average grain yield, with an average grain yield of 11.64 t ha^{-1}. However, hybrid ST-201328 unveiled the topmost grain yield only at the locations of Malang (12.55 t ha^{-1}) and Gowa (13.6 t ha^{-1}). The hybrid ST-201312 demonstrated the highest grain yield at the locations of Kediri and Soppeng (13.46 and 11.24 t ha^{-1}, respectively). At the Maros location, hybrid ST-201325 possessed the ultimate grain yield (12.73 t ha^{-1}). Hybrid ST-201340, with a grain yield of 11.81 t ha^{-1}, was Probolinggo's highest for yield. The maize check cultivar Pioneer-36 appeared with the superior grain yield at Manado (13.15 t ha^{-1}), while hybrid ST-201381 was leading with the highest grain yield at West Lombok (11.49 t ha^{-1}). Finally, maize hybrid ST-201357 exhibited the premier grain yield at the Sigi location (11.92 t ha^{-1}).

The projection of the test locations on PC1 and PC2 scores onto a biplot illustrated the position of the environment (Figure 1). The environment vector is a line representation from the biplot's origin to the environment marker. Each environmental indicator has a different length and angle relative to the PC2 axis, based on the PC1 and PC2 scores. West Lombok was the location with the longest vector (5.63), and Soppeng was the location with the shortest vector (1.56). The biggest

Table 3. Pooled analysis of variance of the maize genotypes for grain yield at nine locations.

Source of variation	d.f.	SS	MS	F. value	F probability	Contribution to variation (%)
Locations (E)	8	142.05	17.76**	3.9	0.01	17.86
R/L	18	81.86	4.55**	4.37	0.00	10.29
Genotypes (G)	11	215.09	19.55**	11.46	0.00	27.04
G x E interaction	88	150.09	1.71**	1.64	0.00	18.87
Error	198	206.26	1.04			25.93
Total	323	795.35	2.46			

** : Significant at $P \leq 0.05$.

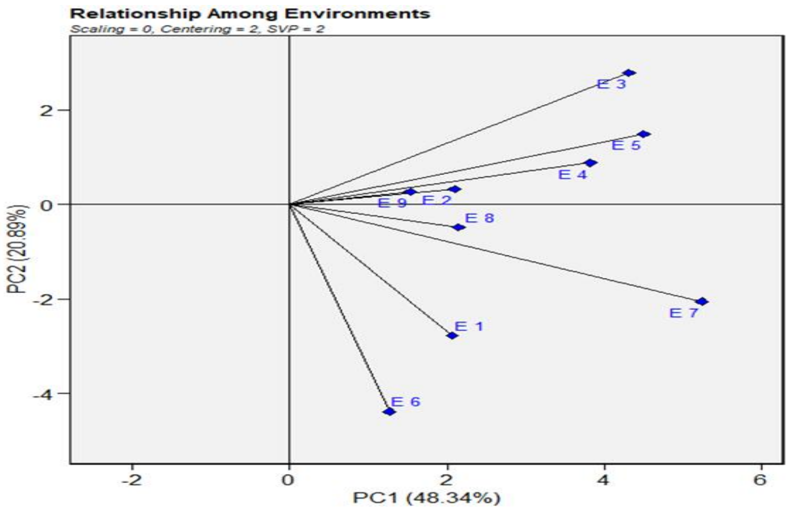

Figure 1. The environment-vector view of the GGE biplot showing the relationship among the test locations.

Table 4. Mean grain yield of the maize hybrids and check cultivars at nine locations.

Hybrids	Grain yield (t ha^{-1})									
	E1	E2	E3	E4	E5	E6	E7	E8	E9	Means
ST-201315	9.78	9.24	8.48	9.28	7.76	8.90	7.16	8.36	9.13	8.68
ST-201328	12.55	12.27	11.49	13.60	11.53	10.42	11.44	11.33	10.12	11.64
ST-201342	9.99	10.85	7.93	8.86	9.03	10.72	7.16	9.97	9.76	9.36
ST-201364	10.13	10.92	9.73	10.29	9.08	10.51	9.40	10.63	9.11	9.98
ST-201320	11.04	10.01	9.48	10.51	9.48	11.77	10.68	10.32	10.04	10.37
ST-201359	11.67	12.08	10.30	10.99	10.23	11.54	11.41	10.96	9.46	10.96
ST-201312	11.39	13.46	9.99	11.87	10.37	10.86	10.28	11.57	11.24	11.23
ST-201309	11.03	12.17	9.74	10.53	10.21	11.26	9.35	10.90	10.00	10.58
ST-201311	10.39	11.60	9.49	11.19	9.52	10.05	7.67	9.97	9.67	9.95
ST-201322	10.31	12.39	8.91	10.68	7.40	11.99	8.43	10.85	8.90	9.99
ST-201316	9.67	11.54	12.43	10.69	11.05	12.26	9.65	11.17	10.88	11.04
ST-201355	11.83	11.28	11.14	12.43	11.42	10.38	11.19	10.01	10.28	11.10
ST-201357	9.20	12.75	11.62	9.92	10.42	9.88	10.31	11.92	9.96	10.66
ST-201340	9.41	12.24	12.03	12.07	11.81	9.42	8.92	9.76	10.61	10.70
ST-201381	10.28	11.62	11.25	11.20	11.63	11.10	11.49	11.02	9.69	11.03
ST-201325	9.21	10.03	12.73	11.45	10.36	9.40	8.96	11.23	9.71	10.34
ST-201376	9.79	12.03	11.05	12.38	10.28	8.10	9.03	10.41	9.86	10.33
NASA-29	9.85	10.26	10.21	10.56	9.61	10.70	9.13	10.53	9.53	10.04
Pioneer 36	11.97	10.15	11.04	11.92	10.60	13.15	11.25	10.85	10.30	11.25
Means	10.50	11.41	10.48	11.07	10.09	10.65	9.63	10.62	9.91	10.48

Notes: E1 = Malang, E2 = Kediri, E3 = Maros, E4 = Gowa, E5 = Probolinggo, E6 = Manado, E7 = West Lombok, E8 = Sigi, and E9 = Soppeng.

environmental angle to the PC2 axis was at Manado, with an angle of 73.87°, and the smallest environmental angle was at Kediri, with an angle of 8.67°.

The combination of the vector's length and angle formed three distinct classes. The test locations with low PC1 and PC2 scores, such as Kediri, Sigi, and Soppeng, showed short vectors with small angles. The length vector of the three locations is 2.12, 1.56, and 2.20, with angles of 8.67°, 9.95°, and 12.83°, successively. The locations of Gowa, Probolinggo, and West Lombok were evident to have high PC1 and small PC2 scores, resulting in long vectors with small angles. The lengths and angles for Gowa were 3.92 and 12.95°, for Probolinggo were 4.73 and 18.27°, and for West Lombok were 5.63 and 21.45°, respectively. The Manado location exhibited long vectors (4.57) with a large angle (73.87°) due to its small PC1 and high PC2 scores. Additionally,

Figure 1 demonstrates the angles formed between the two environment vectors. The vectors for the locations, Kediri and Soppeng, occurred almost aligned (1.28°), emphasizing the similarity of these locations, while those for Manado and Probolinggo form an angle of 92.15° (approximately a right angle). In contrast, the vectors for the locations of Maros and Manado develop an obtuse angle (106.79°).

The coordinates of environment markers and the average environment axis (AEA) appear in Figure 2. The AEA is a biplot line passing through the origin and the average coordinates of all the environmental markers. The arrow in the center of the circle means the longest positive position projected onto the AEA, and the center represents the ideal environment. The concentric circles on the arrow help estimate the environment marker's distance from the ideal environment.

Figure 2 displayed the spread of test locations across six concentric circles. However, no test location falls to the center of concentric circles. The West Lombok location was in the second circle. In the third circle, the test locations were Gowa and Probolinggo, followed by the Sigi location (in the fourth circle). In the fifth circle, the locations were Kediri, Maros, and Soppeng. Moreover, the location of Manado sat outside the circle (sixth circle).

Based on PC1 and PC2 scores, the maize hybrid positions were spread randomly in the biplot (Figure 3). The hybrid at the farthest point from the biplot center represents the highest and lowest grain yield. The hybrids' order based on their grain yields was ST-201328>Pioneer-36>ST-201340>ST-201376> ST-201322>ST-201342>ST-201315. These maize hybrids formed the vertices of an irregular polygon, with perpendicular dividing the plot into seven sections. However, not all the sections contain hybrids and test locations. Three sections contain both genotypes and environments, while four sections contain only the maize genotypes without associated environments. The first section comprised six environments and four hybrids. Five hybrids and two locations belonged to the second section. The third section included one test location and four maize hybrids. The remaining sections just contained the hybrids without the test location.

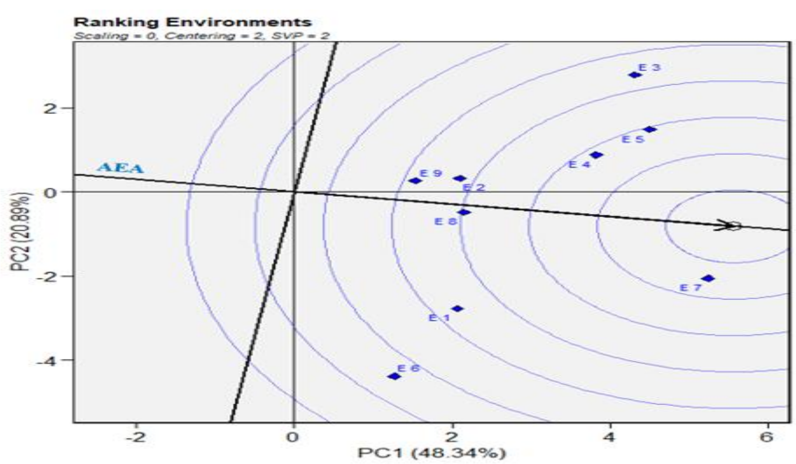

Figure 2. The GGE biplot showing ranking of the test locations.

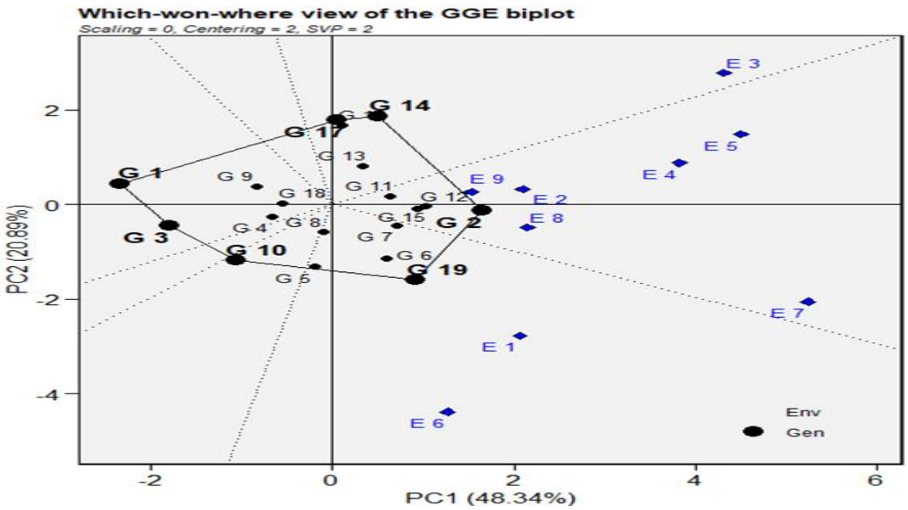

Figure 3. The which-won-where view of the GGE biplot of maize hybrids and check cultivars at nine locations.

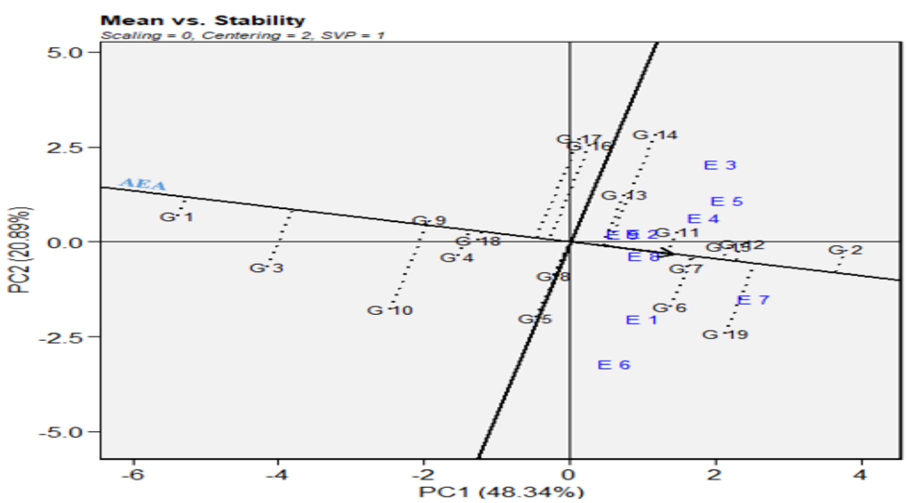

Figure 4. The average-environment coordination (AEC) view showing the mean performance and stability of the maize genotypes.

Figure **4** is analogous to Figure 2, and this figure showed the distribution of maize hybrid markers projected onto a biplot. A perpendicular line originating from the biplot origin separated the hybrids into two sides. Hybrid ST-201328 stood at the farthest right side, while ST-201315 maintained a position at the farthest left. Hybrids ST-201320 and ST-201309 indicated locations near the line. Nine hybrids fell on the right side and eight hybrids on the left. In determining the distance of each hybrid marker from the AEA, drawing a perpendicular line helps connect the hybrid marker to the AEA line. Among the maize hybrids on the right side, hybrid ST-201381 has the closest distance to the AEA line. For hybrids on the left side, hybrid ST-201311 was the nearest, and hybrid ST-201376 was the farthest.

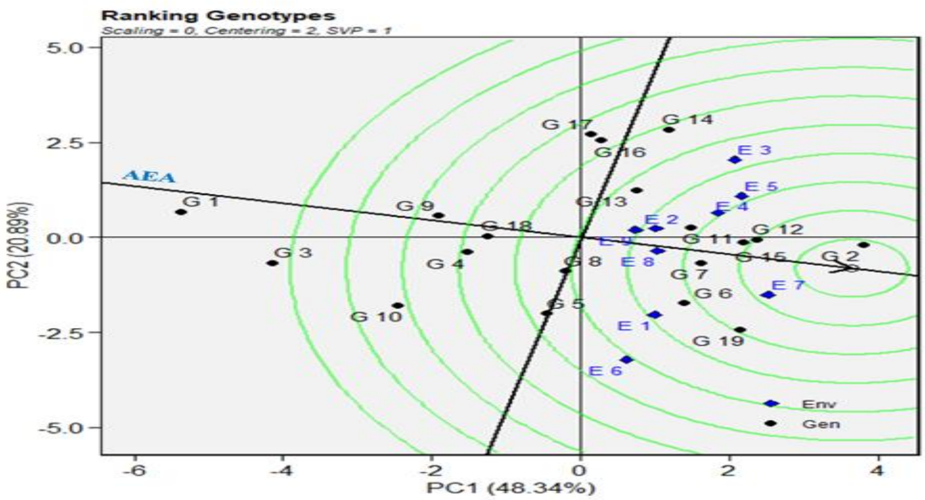

Figure 5. The average-environment coordination (AEC) view showing maize genotypes ranking relative to an ideal genotype.

The arrow on the AEA refers to the ideal maize genotype becoming the circle's center (Figure 5). Identical to Figure 2, the concentric circles on the arrow help estimate the hybrid marker's distance from the ideal genotype. The position of hybrid ST-201328 was at the first circle. Two hybrids (ST-201315 and ST-201342) exhibited a spot outside the concentric circles.

DISCUSSION

In this research, all the factors individually and in interaction have shown a significant impact on the maize grain yield. Table 1 research locations comprised six soil types and four climate types. All the research locations have diverse soil and climate types, with distinct characteristics. These differences in location characteristics lead to varying capacities, which subsequently affect the grain yield (Sebetha, 2018). The hybrids' significant effects revealed that the hybrids used in this research have diverse genetic backgrounds. The test hybrids' development came from 17 female and 13 male parental genotypes. Constantly, the hybrids with a broad genetic background perform differently for yield-related traits (Uriarte-Aceves *et al.*, 2019). The GEI effects reflected the unique responses of hybrids in each location. The GEI effects in maize genotypes have also had previous reports (Azrai *et al.*, 2022; Ruswandi *et al.*, 2022; Tabu *et al.*, 2023). The GEI caused a hybrid to not maintain the grain yield sustainably. A hybrid may have the highest grain yield at one location but a low yield at other locations. Therefore, proper statistical analysis can help in selecting the desirable and promising hybrids with better productivity potential. As one of the proper tests, the GGE biplot serves as an effective method for identifying and selecting superior genotypes by visualizing their performance through the biplot.

The GGE biplot explains the location capacity and its relationship through Figure **1**. The length and angle of the environment vector explain the test location discrimination and representativeness (Dia *et al.*, 2016). The vector length describes the location discriminating capability, which is the location capacity to expand variability among genotypes, making it easier to identify which lines perform better or worse. The location with the longest vector (West Lombok) means it is the most discriminating location, while Soppeng, with the shortest vector, is the least discriminating. The vector angle represents the location test representativeness, which shows how well a test environment reflects the average performance of all genotypes across environments. The location with the smallest vector angle (Kediri) indicates it as the most representative, whereas Manado, with the biggest angle, is the least representative.

The combination of vector environment length and angle gives each location different characteristics. The test locations (Kediri, Sigi, and Soppeng) that construct the short vector with a small angle were representative but not discriminating. These locations exhibited limited utility as test environments because in these locations the maize genotypes showed relatively similar performance and exhibited little variation (Gerrish *et al.*, 2019). The test locations, Gowa, Probolinggo, and West Lombok, with the high PC1 and low PC2 scores, have long vectors with small angles, making them representative and discriminative. These locations were also ideal for selecting the promising genotypes because the genotypes revealed an optimal performance with enormous variations (Enyew *et al.*, 2021). The test location of Manado, with long vectors and large angles due to low PC1 and high PC2, was discriminative but less representative. Locations with long vectors and large angles, like Manado, are only suitable to the genotypes with the highest performance only at its location. The location was appropriate for selecting the promising maize genotypes with specific adaptability (Adham *et al.*, 2022).

Environmental vectors form an angle with each other, describing the relationship between the environments. The relationship between two environments appeared from the angle cosine values (Matongera *et al.*, 2023). The cosine of test locations Kediri and Soppeng is 0.99, indicating a strong correlation that maize genotypes in these environments will show similar performance. The vectors of the locations, Manado and Probolinggo, have a cosine value of 0.04, indicating no association, meaning that genotypes perform independently in these environments. In contrast, the vectors of the locations, Maros and Manado, create an obtuse angle (cosine value = -0.29), implying a negative correlation. This means a moderate interaction existed between the maize genotypes and the environment, which leads to varied performance for grain yield. Identifying redundant test locations using correlation coefficients will improve efficiency (Esan *et al.*, 2023). Research at significantly correlated locations (Kediri and Soppeng) can be a representation of one location, which will reduce the costs and resources used without compromising data validity.

The GGE biplot can also be applicable to identify the ideal environment. The ideal environment's description is the most representative and discriminating (Vaezi *et al.*, 2017). The selection of desirable hybrids in this location was easier because hybrids demonstrated performance variation by expressing their genetic potential optimally (Fonseca *et al.*, 2022). No test location falls to the center of concentric circles, indicating no ideal environment. However, the detection of favorable test locations can be through their proximity to the ideal marker in the biplot (Rahmati *et al.*, 2024). The test location that has the nearest distance to the arrow marker was successful in identifying as the most favorable test location (Aboye and Edo, 2024). The closest test location to the ideal environment was West Lombok, which was in the second circle and considered the most favorable environment. In the third circle, the test locations, Gowa and Probolinggo, were still favorable, followed by the Sigi location (in the fourth circle), which was also desirable. However, the location of Manado (sixth circle) emerged as the most unfavorable. This test location had three other locations following it (Kediri, Maros, and Soppeng) in the fifth circle, becoming the most unfavorable test locations.

The GGE biplot is a powerful tool used for visualizing the genotype-by-environment interaction effects and helps the plant breeders in selecting the most suitable genotypes for specific environments. In this study, the test locations entailed dividing into three mega-environments based on the distribution of environments within the biplot sections. The hybrid at the respective vertex of a section was the winning hybrid at each mega-environment (Mushayi *et al.*, 2020). The first mega-environment comprised six environments (Kediri, Gowa, Probolinggo, West Lombok, Sigi, and Soppeng) and four maize hybrids (ST-201328, ST-201316, ST-201355, and ST-201381), while the hybrid ST-201328 was the winning hybrid. The check cultivar Pioneer-36 has the highest grain yield at the locations Malang and Manado compared with four other hybrids, ST-201320, ST-201359, ST-201312, and ST-201309, which belonged to the second mega environment. The third mega-environment only contains one test location (Maros) and four hybrids (ST-201357, ST-201340, ST-201325, and ST-201376). Hybrid ST-201340 was notably the winning hybrid in this mega-environment. The remaining maize genotypes, positioned in sections without environments, revealed low yields across all test locations. This delineation of mega-environments enhances one's understanding of genotype performance and facilitates the selection of promising hybrids for specific environments (Wang *et al.*, 2020).

The ranking biplot and a variant of the GGE biplot employ the average environment coordination (AEC) method to assess the genotypes' stability. The AEA line indicates hybrid yield across the environments, with a perpendicular line arising from the biplot origin separating hybrids into below-mean and above-mean grain yields (Dos-Santos Silva *et al.*, 2022). The hybrids fall on the right side of the perpendicular line, indicating above-mean yields, while hybrids on the left revealed below-mean yields (Göçmen, 2025). Hybrid ST-201328 was the highest-yielding and leading genotype among all the evaluated hybrids, whereas ST-201315 was the lowest in yield. Two hybrids near the perpendicular lines (ST-201320 and ST-201309) reflected grain yields close to the overall hybrid mean. The hybrid marker distance to the AEA line points to yield stability of the hybrids, regardless of direction (Kebede *et al.*, 2023). The shorter vector reflects the higher yield stability and vice versa. Among the maize hybrids with above-mean yield, hybrid ST-201381 was the most stable, while hybrid ST-201340 was the most unstable. For hybrids below-mean grain yield, hybrid ST-201311 was the most stable, and ST-201376 was the most unstable.

The GGE biplot analysis effectively identified the ideal maize genotypes demonstrating the highest and most stable grain yield across test locations. In the biplot, the ideal genotype has a representation of a point on the AEA with a positive position and a vector length equal to the longest genotype vector (Ghaffari *et al.*, 2021). Like the ideal environment, the perfect genotype does not exist. The ideal genotype can be a reference in selecting the best genotype by comparing the genotyped marker's distance to the circle's center (Ansarifard *et al.*, 2020). Hybrid ST-201328 seemed the best genotype due to its location in the first concentric circle. The said maize hybrid was the most stable and high-yielding genotype. The hybrids in the next concentric circle (ST-201316, ST-201355, and ST-201381) tended to be as desired genotypes. Meanwhile, the hybrids ST-201315 and ST-201342 were in the outermost circle, considerably becoming the worst hybrids, followed by ST-201322 in the previous circle.

In addition to being the closest genotype to the center of the biplot, the hybrid ST-201328 also showed the highest grain yield in the first mega-environment. Based on these criteria, the hybrid ST-201328 can be a high recommendation for the high-yielding maize cultivar based on its stability and grain yield.

CONCLUSIONS

Based on the GGE-biplot analysis, maize (*Z. mays* L.) hybrid ST-201328 demonstrated the highest grain yield and stability, resulting in a high recommendation for the promising maize hybrid in Indonesia. The location of West Lombok was the most favorable, while Manado was the most unfavorable location for maize production.

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