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RESEARCH ARTICLE

A comprehensive evaluation of the adaptability and stability of promising maize hybrids in Indonesia using different stability approaches

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ABSTRACT

The Indonesian wide range of biogeophysical conditions lead to Genotype×Environment interaction (G×E). Multiple stability analysis methods can provide more comprehensive and reliable information about the G×E. The objective of this research was to determine the yield stability of seven promising maize (*Zea mays* L.) hybrids (SJI 1, SJI 2, SJI 3, SJI 4, SJI 5, SJI 6, SJI 7) and three control cultivars (Pioneer 36, Bisi 18 and Pertiwi 6) using Francis and Kannenberg, Finlay and Wilkinson, Eberhart and Russel, Shukla and GGE biplot analyses. The hybrids and cultivars were arranged in a randomized complete block design (RCBD) with three replicates in 10 locations in the dry season 2022. The results indicated that hybrid SJI 001 had the highest yield (12.57 t ha^{-1}) and was stable according to the five stability analyses. On the other hand, hybrid SJI 002 (8.36 t ha^{-1}) performed well in unfavourable environments, while hybrid SJI 006 (12.02 t ha^{-1}) and 'Pertiwi 6' (11.48 t ha^{-1}) performed well in favourable ones. In addition, GGE biplot analysis revealed that SJI 006 was well adapted to Prambon and 'Pertiwi 6' to Bajeng.

Key words: Genotype × Environment interaction, maize, stability analysis, *Zea mays*.

INTRODUCTION

The maize (*Zea mays* L.) yield in Indonesia is influenced by various factors, including the interaction between genotype and environment (G×E). Indonesia has a wide range of biogeophysical conditions that can affect the maize hybrids differently (Ruswandi et al., 2022). The G×E can be classified into three types: No interaction, no interaction between environments, and interactions between environments (González-Barrios et al., 2019). This interaction can lead to difficulty in selecting a genotype that performs well across different environments. When G×E is high, it can produce different plant responses to specific environments (Adie and Krisnawati, 2015; Wanga et al., 2022). Therefore, understanding G×E is crucial for selecting the best maize hybrids for different environments in Indonesia.

The selection of maize varieties with broad or specific adaptations depends on G×E and the breeding objectives. Broad adaptation refers to static stability, which means that a genotype has a small variance among environments and can perform consistently regardless of environmental changes. A genotype with broad adaptation shows the same productivity in a variety of growing environments. Specific adaptation is related to dynamic stability, which means that a genotype responds to environments that parallel the mean response of all genotypes in the trial. A genotype with specific adaptation can adapt to better environment and management conditions and shows how much its yield follows the environmental index (Aryana and

Wangiyana, 2016; Sjoberg et al., 2020). Thus, static and dynamic stability are important for selecting maize varieties that perform well under different environmental conditions.

Francis and Kannenberg's and Finlay and Wilkinson's analysis are methods for estimating static stability. They need a regression coefficient value (bi) of 0. Plaisted, Wricke, Shukla, Finlay and Wilkinson's analysis estimates dynamic stability with a regression coefficient value (bi). Alternatively, Perkins and Jinks, Eberhart and Russell's analysis can estimate dynamic stability. However, achieving both static and dynamic stability is difficult because they usually affect the genotype performance in different ways. Genotype and Genotype by Environment (GGE) biplot can show static and dynamic stability. For instance, it can identify the ideal genotype and environment and the best genotype with the highest yield per mega-environment (Noerwijati et al., 2014; Mohammadi et al., 2015).

Genotype stability across environments can be evaluated by using multiple stability analysis methods. For instance, Vaezi et al. (2019) used additive main-effects and multiplicative interaction (AMMI) model, GGE biplot, and regression analysis to assess the stability of 20 barley genotypes in Iran. Belete et al. (2020) use several univariate and AMMI models to identify high yielding and stable varieties of finger millet. Similarly, Wijaya et al. (2022) applied AMMI, GGE biplot, and Eberhart and Russell methods to evaluate the stability of 12 black soybean genotypes in Indonesia. On the other hand, Maulana et al. (2022) used AMMI, GGE biplot, and Finlay and Wilkinson methods to determine the stability of 15 sweet potato genotypes in West Java. These studies demonstrate that combining stability analysis methods can provide more comprehensive and reliable information about G×E. Therefore, this research objective was aimed to determine the yield stability of Indonesian promising maize hybrids using five stability analyses. The information obtained can be used as consideration in releasing cultivars in Indonesia.

MATERIALS AND METHODS

The experiment was conducted in 10 locations in the dry season of 2022. The location's climate, soil type, and altitude are shown in Table 1. Seven promising maize (*Zea mays* L.) hybrids (SJI 1, SJI 2, SJI 3, SJI 4, SJI 5, SJI 6, SJI 7) and three control cultivars (Pioneer 36, Bisi 18 and Pertiwi 6) were arranged in a randomized complete block design (RCBD) with three replicates.

The dimensions of the experimental plot were 3 m × 5 m, with a spacing of 75 cm × 20 cm, so there are 25 plants per row. The first fertilization was carried out 7 d after planting (dap) at 135 kg N + 45 kg P_2O_5 + 45 kg K_2O ha^{-1}. Second fertilization at 35 dap with a rate of 90 kg N ha^{-1}. Plant maintenance includes weeding, irrigation, and control pest management. Harvesting was done in the middle two rows of the experimental plot in order to eliminate the marginal effects.

Table 1. Location's soil types, altitudes and climate types. [1]Oldeman classification of climate types (Oldeman and Frere, 1982).

Code	Location	Soil type	Altitude (m a.s.l.)	Climate type[1]
E1	Kepung	Alluvial	203	C2
E2	Gondanglegi	Inceptisol	400	C2
E3	Pagelaran	Inseptisol	347	C2
E4	Nglegok	Entisol	280	D3
E5	Kepanjenkidul	Entisol	238	B1
E6	Badas	Alluvial	131	C2
E7	Ngoro	Alluvial	161	E2
E8	Ngronggot	Alluvial	87	C3
E9	Prambon	Alluvial	79	E3
E10	Bajeng	Alluvial	89	D1

The observed character is yield (Y) which was corrected to 15% moisture that converted to units per hectare according to the formula (Carangal et al., 1971):

$$\text{Yield}\left(\frac{t}{ha}\right) = \frac{FW \times (100-HMP) \times SP \times 10}{(100-DMP) \times NPA}$$

where FW is fresh weight of ear in kg per plot at harvest (kg), HMP is grain moisture percentage at harvest (%), SP is shelling percentage (%), DMP is desired moisture percentage, i.e., 15%, NPA is net harvest plot area (m^2).

The stability and adaptability analysis used were as follows:

$$\text{Francis and Kannenberg (1978) } CV_i = \left(\frac{\sqrt{S_i^2}}{\overline{Y}_{i.}}\right) x\, 100\%,\ S_i^2 = \frac{\sum_i(\overline{Y}_{ij}-\overline{Y}_{i.})}{j-1}$$

$$\text{Finlay and Wilkinson (1963) } b_i = \frac{\sum_j(\overline{Y}_{ij}-\overline{Y}_{i.})-(\overline{Y}_{.j}-\overline{\overline{Y}})}{\sum_j(\overline{Y}_{.j}-\overline{\overline{Y}})^2}$$

$$\text{Eberhart and Russel (1966) } b_i = \frac{\sum_j Y_{ij} I_j}{\sum_j I_j^2},\ S_{di}^2 = \left(\frac{\sum_j \hat{\delta}_{ij}^2}{j-2} - \frac{s_e^2}{r}\right)$$

$$\text{Shukla (1972) } \sigma_i{}^2 = \frac{i}{(i-2)(j-2)}\left(\frac{\sigma_i - \sum_i \sigma_i}{i(i-1)}\right)$$

$$\text{GGE Biplot (Yan, 2001) } Y_{ij} = \lambda_1 \xi_{i1} \eta_{i1} + \lambda_2 \xi_{i2} \eta_{i2} + \varepsilon_{ij} + \overline{Y}_l$$

where CV_i is coefficient of variation, S_i^2 is environmental variance, $\overline{Y}_{ij}$ is mean yield of i[th] genotype and j[th] environment, $\overline{Y}_{.j}$ is mean yield of the j[th] environment overall genotype, $\overline{Y}_{i.}$ is mean yield of i[th] genotype overall environment, $\overline{Y}_{.}$ is mean yield of all genotype, i is number of genotype, j is number of environment, bi is regression coefficient, $\overline{\overline{Y}}$ is mean of environment index, Ij is mean index, i.e., a mean yield of j[th] environment minus by the mean yield of all genotype, S_{di}^2 is deviation from regression, $\sigma_i{}^2$ is deviation of stability variance, σ_i is stability variance, $\sum_j \hat{\delta}_{ij}^2$ is pooled variance, $\sum_j \hat{\delta}_{ij}^2$ is pooled ANOVA error, $\lambda_{i1}, \lambda_{i2}$ is singular value of Principal Component Axis (PCA) 1 and PCA 2, ξ_{i1}, ξ_{i2} is PCA1 and PCA 2 value of i[th] genotype, η_{i1}, η_{i2} is PCA1 dan PCA 2 value of j[th] environment and ε_{ij} is error.

Stability analysis used GEA-R (Genotype × Environment Analysis with R for Windows) Version 4.0 and Plant Breeding Tools (PBTools) Version 1.3 software.

RESULTS AND DISCUSSION

The yield was influenced by the locations, hybrid, and Hybrid × Location interaction significantly, as shown in Table 2. The yield variation was mainly due to the hybrid (56.45%), followed by the location (18.62%) and the Hybrid × Location interaction (15.51%). The CV is a measure of the research accuracy (Wang et al. 2017), CV value of this research was 6.6%, which indicated a low level of variation and a high level of reliability. The lower the CV values, the higher precision the research, and vice versa.

Table 2. Combined ANOVA for yield in 10 locations 2022. **Significantly different at the level of 1%.

Source of variance	df	Sum square	Mean square	F-Value	Prob-F	Contribution to variation (%)
Location (L)	9	202.104	22.456	43.71**	0.00	18.62
Replication in location	20	10.275	0.514	1.01	0.46	0.95
Hybrid (H)	9	612.873	68.097	32.75**	0.00	56.45
H×L	81	168.404	2.080	4.07**	0.00	15.51
Error	180	91.949	0.511			8.47
Total	299	1085.600	3.631			

The high hybrid contribution shows that the hybrids in this study have a broad genetic background. Ruswandi et al. (2022) said the new quiet material could cause a high hybrid difference contribution. Moreover, the various parents that constitute hybrid also cause high hybrid contributions (Priyanto et al., 2023). All the hybrids in this study were constituted from a distinct parent combination (Table 3). The hybrid yields range from 9.31 to 12.59 t ha^{-1}. Only two test hybrids yielded significantly higher than three control cultivars, namely SJI 001 (12.57 t ha^{-1}) and SJI 004 (12.59 t ha^{-1}). The mean yield of hybrid SJI 005 (11.86 t ha^{-1}) and SJI 006 (12.02 t ha^{-1}) is significantly higher than control 'Pioneer 36' and 'Bisi 18'. Meanwhile, the yield of SJI 002, SJI 003, and SJI 007 was not significantly higher than the three control cultivars. The yield of control 'Pioneer 36', 'Bisi 18', and 'Pertiwi 6' are 10.53, 10.73, and 11.48 t ha^{-1}, respectively (Table 4).

Table 3. Hybrids of maize used in this study and their origins.

Hybrids	Origin
SJI 001	TA197 × TA227
SJI 002	AB967 × BP977
SJI 003	VT947 × TW947
SJI 004	TA457 × TA997
SJI 005	B0170 × TW907
SJI 006	AP177 × TW917
SJI 007	SN971 × NA997
Pioneer 36	YEP × 14TJ
Bisi 18	FS46 × FS17
Pertiwi 6	PWI-5 × PWM-1

Table 4. Maize's mean yield at each location. E1: Kepung; E2: Gondang legi; E3: Pagelaran; E4: Nglegok; E5: Kepanjen kidul; E6: Badas; E7: Ngoro; E8: Ngronggot; E9: Prambon; E10: Bajeng; EI: environmental index. [a]Higher than 'Pioneer 36' based on LSD 5%; [b]higher than 'Bisin 18' based on LSD 5%; [c]higher than 'Pertiwi 6' based on LSD 5%.

Hybrid	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	Mean
SJI 001	13.08^{abc}	12.43^{ab}	13.04^{ab}	13.18^{ab}	12.67^{ab}	13.18^{abc}	12.64^{ac}	12.53	12.77^{abc}	10.15	12.57^{abc}
SJI 002	7.38	8.14	8.24	8.44	8.23	8.65	8.95	8.72	9.07	7.75	8.36
SJI 003	8.17	8.08	9.04	8.26	10.00	9.09	8.88	11.30	10.00	8.43	9.12
SJI 004	12.73^{abc}	12.90^{ab}	13.25^{ab}	13.35^{ab}	13.42^{ab}	12.64^{abc}	13.18^{abc}	12.57	13.07^{abc}	8.78	12.59^{abc}
SJI 005	12.36^{abc}	11.73^{ab}	12.54^{a}	12.17^{a}	12.01	12.07^{ac}	12.79^{abc}	12.91	12.06^{abc}	7.95	11.86^{ab}
SJI 006	11.81^{ac}	12.93^{ab}	12.76^{a}	12.39^{a}	12.03	12.70^{abc}	12.61^{ac}	12.73	12.82^{abc}	7.38	12.02^{ab}
SJI 007	8.36	8.94	8.86	8.75	10.46	9.80	8.88	11.60	9.69	7.78	9.31
Pioneer 36 (a)	9.99	9.39	10.96	10.49	11.53	10.39	10.38	12.22	10.36	9.55	10.53
Bisi 18 (b)	10.67	9.33	12.06	11.03	10.98	11.08	11.75	12.23	9.16	9.04	10.73
Pertiwi 6 (c)	9.65	11.87	13.11	12.17	13.14	10.37	11.67	12.15	10.34	10.30	11.48
Mean	10.42	10.57	11.39	11.02	11.45	11.00	11.17	11.89	10.93	8.71	10.86
SE	0.40	0.51	0.26	0.53	0.37	0.34	0.31	0.36	0.51	0.46	0.26
LSD 5%	1.19	1.51	0.77	1.57	1.09	1.00	0.92	1.07	1.51	1.35	0.74
CV, %	6.60	8.30	3.90	8.30	5.50	5.30	4.80	5.20	8.10	9.00	6.60
EI	-0.44	-0.28	0.53	0.17	0.59	0.14	0.32	1.04	0.08	-2.15	

Table 4 shows that the location effect was significant, meaning the site selection was effective for this experiment. Similar results were reported by Bharathiveeramani et al. (2016) and Abid (2018), who observed that the location influenced the yield in their multi-environment trials. The variability in the effect of location suggests that the chosen study sites exhibited diverse capacities for maize performance, as elucidated by Karuniawan et al. (2021).

Table 4 provides an overview of the average yields across the study sites, ranging from 8.71 to 11.89 t ha^{-1}. The overall mean yield of the locations was 10.86 t ha^{-1}. An environmental index was calculated to estimate the environmental impact, which reflects the environment's capability to support yield production. This index is calculated as the difference between the mean yield of all hybrids in a specific environment and the mean yield across all locations. Locations with a mean yield lower than this overall mean were categorized as having a negative environmental index, signifying less favourable environmental conditions. As explained by Islam et al. (2021) a negative environmental index implies unfavourable environmental conditions, while a positive index implies favourable conditions.

In this study, three locations exhibited a negative environmental index, namely Kepung (-0.44), Gondanglegi (-0.28), and Maros (-2.15), suggesting less favourable environmental conditions. Conversely, seven locations displayed a positive environmental index, including Pagelaran (0.53), Nglegok (0.17), Kepanjen kidul (0.59), Badas (0.14), Ngoro (0.32), Ngrongot (1.04), and Prambon (0.08), indicating more favourable environmental conditions for maize yield (Table 4).

Hybrid × Location interaction led in genotype performance variation across different locations. These variations are due to different hybrid's responses to various locations. This phenomenon is not unique to maize (Faria et al., 2017), but has also been observed in other crops such as cassava (N'zué et al., 2017), soybean (Silveira et al., 2016) and potato (Wang et al., 2017), demonstrating the universality of Hybrid × Location interactions. As depicted in Table 4, significant differences in yield between the test hybrid and the control were observed in all study locations except Ngronggot and Bajeng. The test hybrid yield shows different yields at different locations. Hybrid SJI 001's yield is significantly higher than the three control cultivars at Kepung, Badas, and Prambon; meanwhile, hybrid SJI 004 at Kepung, Badas, Ngoro, and Prambon. The yield of SJI 001 and SJI 004 is significantly higher than the two control cultivars or is not significantly higher than all three control cultivars at the other locations. This phenomenon is challenging for plant breeders (van Eeuwijk et al., 2016). Hybrid × Location interaction makes it difficult for plant breeders to select the desired hybrid. On the flip side, Hybrid × Location interaction also provides an opportunity for selecting hybrids with broad adaptability across various locations or hybrids for specific environmental conditions.

This study's hybrid CV values ranged from 6.28% to 13.88% (Table 4). Francis and Kannenberg (1978) used the coefficient of variation to select varieties with both high yield and low variance (small variance between locations). Furthermore, based on the mean yield and CV values, hybrids can be categorized into four groups (Di Matteo et al., 2016; Long and Ketterings, 2016). The first group comprised hybrids with a yield above the mean and CV below the mean. Only one hybrid consisted of the first group, i.e., SJI 001. Hybrids SJI 004, SJI 005, SJI 006, 'Bisi 18', and 'Pertiwi 6' belong to the second group. The second group consisted of hybrids with yield and CV above the mean. The third group consisted of hybrids with yield and CV below the mean, namely SJI 002, 'Pioneer 36'. The last group was hybrid, with a yield below the mean and CV above the mean. Hybrids involved in this group are SJI 003 and SJI 007. Adhikari et al. (2023) state that the hybrid in the first and third groups is stable, while the second and fourth groups are unstable.

The stability analysis stated by Finlay and Wilkinson (1963) determines stable hybrids by considering the slope of the regression line or regression coefficient (bi) and the hybrids' mean yield at the overall location. Akbar et al. (2021) state that bi-value differences indicate hybrid responses to environmental changes. A stable hybrid is shown by a hybrid with bi-values not significantly different from 1, a hybrid with above-average stability (suitable for sub-optimal environments conditions) has bi-values less than 1, and a hybrid with below-average stability (suitable for optimal environments conditions) has bi-values more than 1 (Kartina et al., 2019; Shojaei et al., 2022).

Hybrid SJI 001 and 'Pertiwi 6' had bi-values not significantly different from 1 (0.82 and 0.85) and the yield above the mean (12.57 and 11.48 t ha^{-1}). These hybrids are considered stable hybrids with high yields. SJI 007 and 'Bisi 18' are stable hybrids with a low yield. Hybrid SJI 007 and 'Bisi 18' had bi-values 0.96 and 100, respectively (not significantly different from 1), and the yield was 9.31 and 10.73 t ha^{-1} (below the mean). SJI 002, SJI 003, and 'Pioneer 36' had bi-values less than (0.34, 0.71, and 0.76) and the yield below the mean (8.36, 9.12, and 10.53 t ha^{-1}) belong to the hybrid that suitable for sub-optimal environments conditions. Hybrids with bi-values of more than 1 and yield above the mean are SJI 004, SJI 005, and SJI 006. The bi-values of SJI 004, SJI 005, and SJI 006 are 1.37, 1.51, 1.68, respectively; furthermore, the yield is 12.59, 11.86, and 12.02 t ha^{-1}, respectively. These hybrids are considered a hybrid suitable for optimal environmental conditions (Table 5).

Table 5. Stability estimation for yield of maize at 10 locations. CV: Coefficient of variation; bi: regression coefficient; S^2d_i: deviation from regression; ri^2: contribution of each hybrid to the G×E variance. ^{ns}: Non significant; $^*P \leq 0.05$; $^{**}P \leq 0.01$; $^{***}P \leq 0.001$.

Hybrid	Yield	CV	b_i		S^2d_i		ri^2
	t ha^{-1}	%					
SJI 001	12.57	7.09	0.82	ns	0.16	ns	0.31
SJI 002	8.36	6.28	0.34	***	0.04	ns	0.55
SJI 003	9.12	11.29	0.71	**	0.60	***	0.85
SJI 004	12.59	10.89	1.37	***	0.37	**	0.64
SJI 005	11.86	11.99	1.51	***	0.20	*	0.56
SJI 006	12.02	13.88	1.68	***	0.58	***	1.18
SJI 007	9.31	11.90	0.96	ns	0.43	***	0.58
Pioneer 36	10.53	8.17	0.76	*	0.17	*	0.35
Bisi 18	10.73	11.03	1.00	ns	0.56	***	0.73
Pertiwi 6	11.48	10.81	0.85	ns	0.96	***	1.19
Means	10.86						

Regression coefficient (bi) and regression deviation S^2d_i are used in the Eberhart and Russel (1966) method to determine genotype stability. Table 5 displays that the hybrids can be classified as four clusters based on bi values and S^2d_i significance. The first cluster only consisted of SJI 001 and was a hybrid with bi-values that were not significantly different from 1, and S^2di was not significantly different from 0. Hybrid SJI 002, the second with bi-values is significantly different from 1, and S^2d_i is not significantly different from 0 included in the second group. The third group consisted of hybrids with bi-values that are not significantly different from 1, and S^2d_i is significantly different from 0, namely SJI 007, 'Bisi 18', and 'Pertiwi 6'. Furthermore, SJI 003, SJI 004, SJI 005, SJI 006, and 'Pioneer 36' belong to the fourth group. This group comprised hybrids with bi-values significantly different from 1, and S^2d_i is significantly different from 0. Munda et al. (2020) state that bi is a hybrid response due to environmental changes, and S^2d_i is a stability parameter. When S^2di is significantly different from 0, hybrid is considered unstable. When S^2d_i is not significantly different from 0, there are three possibilities. If the bi-value is not significantly different from 1, the hybrid has wide stability; if less than 1, it is suitable for sub-optimal environments, and if more than 1, it is suitable for optimal environments. In compliance with bi-values and S^2d_i, SJI 001 is considered a hybrid with wide stability, SJI 002 is a hybrid that is suitable for sub-optimal environments, and the rest of the hybrids are unstable.

Shukla's stability hybrid method also used to evaluate the stability of maize hybrids, which measures the ri^2 value of each hybrid. The ri^2 value represents the contribution of each hybrid to the G×E variance. The lower the ri^2 value, the more stable the hybrid is. The ri^2 values ranged from 0.31 to 1.19, with SJI 001 being the most stable hybrid and 'Pertiwi 6' being the least stable hybrid (Table 5). The hybrids are classified into two groups based on their ri^2 values: Stable hybrids (ri^2 values less than the mean) and unstable hybrids (ri^2 values more than the mean). Six hybrids (SJI 001, SJI 002, SJI 004, SJI 005, SJI 007, and 'Pioneer 36') belonged to the stable group, while four hybrids (SJI 003, SJI 006, 'Bisi 18', and 'Pertiwi 6') belonged to the unstable group. Among the stable hybrids, SJI 001, SJI 004, and SJI 005 also had high yields, making them suitable for various environments.

Figure 1 illustrates the hybrid yield mean and hybrid stability. The average environment axis (AEA) was used to compare the mean yield of different genotypes and their adaptability to different environments. This line arises from the biplot origin and passes through the environment mean (de Oliveira et al., 2019). The y-axis is a perpendicular line to AEA that passes through the biplot origin (Ogunniyan et al., 2018). The Y-axis also shows hybrid stability and the overall hybrid mean yield. The hybrids on the right side of the Y-axis have a yield above the mean, while on the left, they are below the mean. In the above mean yield hybrid group, SJI 001 was the most stable, and 'Pertiwi 6' was the most unstable. SJI 007 was the most stable, and 'Pioneer 36' was the most unstable in the below mean yield hybrid group. The ideal hybrid is shown by a circle on the positive side of AEA as long as the most extended hybrid vector from the biplot origin (Silva et al., 2022). The best hybrid was the hybrid with the closest distance from the ideal hybrid (Singamsetti et al., 2021). It means the best hybrid has a similar yield and stability to the ideal hybrid. Based on this criterion, hybrid SJI 004 and SJI 001 were the best hybrids due to their distance from the ideal hybrid.

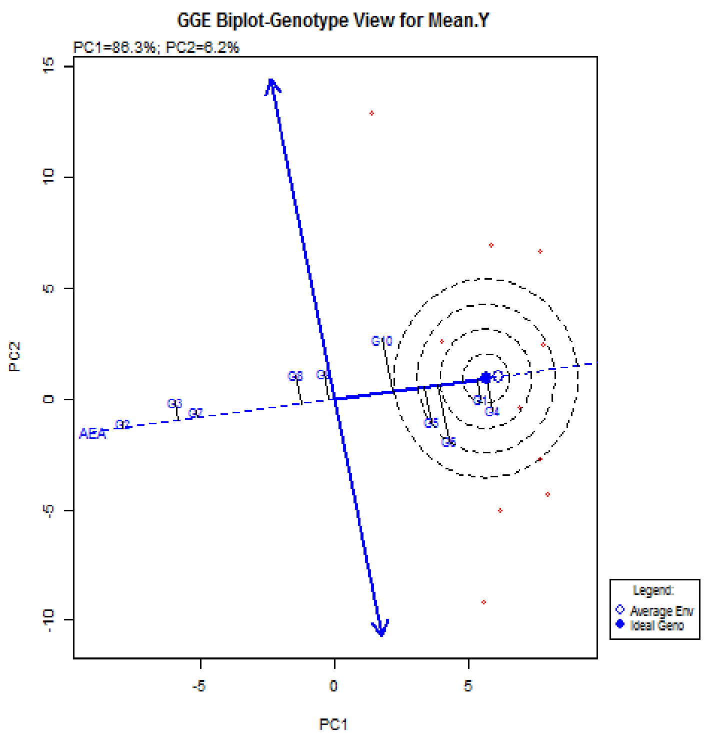

Figure 1. Biplot performance correlation between the test locations for the hybrid maize genotype in 2021. AEA: Average environment axis; G1: SJI 001; G2: SJI 002; G3: SJI 003; G4: SJI 004; G5: SJI 005; G6: SJI 006; G7: SJI 007; G8: 'Pioneer 36'; G9: 'Bisi 18'; G10: 'Pertiwi 6'.

The GGE biplot analysis unveils the interaction patterns between different genotypes and environments (Figure 2). This valuable insight aids plant breeders in selecting the most suitable genotypes for specific environmental conditions (Sousa et al., 2018; Silva et al., 2022). The specific genotypes exhibit the most significant vector lengths within their respective orientations and are connected by a straight line to form a polygon. This hybrid exhibits the highest or lowest yield across one or more environments. The hybrids are ranked based on yield as follows: G4 > G1 > G6 > G10 > G3 > G2. Conversely, the remaining genotypes, like G5, G7, G8 and G9, are enclosed within the polygon due to their shorter vectors, suggesting a lower degree of responsiveness to the environmental factors encompassed by that region.

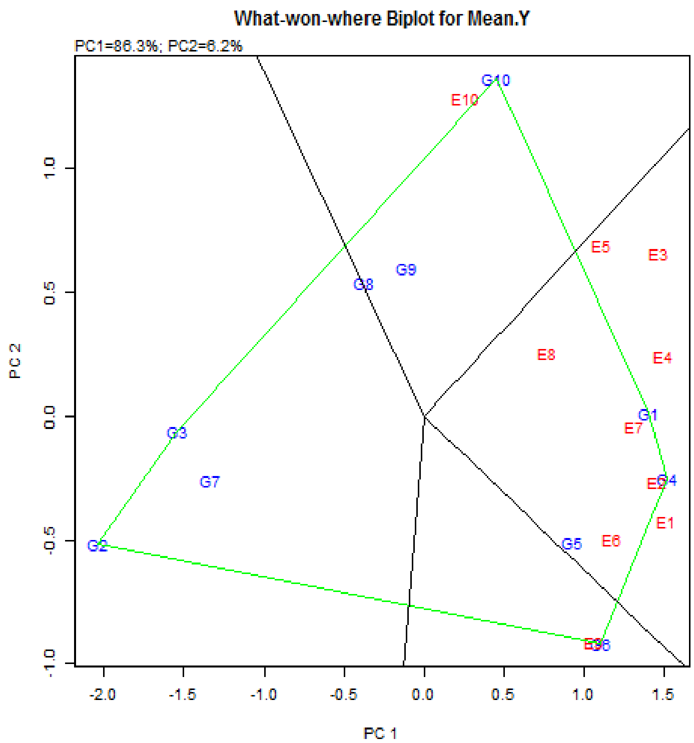

Figure 2. GGE Biplot showing which-won-where. G1: SJI 001; G2: SJI 002; G3: SJI 003; G4: SJI 004; G5: SJI 005; G6: SJI 006; G7: SJI 007; G8: 'Pioneer 36'; G9: 'Bisi 18'; G10: 'Pertiwi 6'; E1: Kepung; E2: Gondang legi; E3: Pagelaran; E4: Nglegok; E5: Kepanjen kidul; E6: Badas; E7: Ngoro; E8: Ngronggot; E9: Prambon; E10: Bajeng.

A line perpendicularly from the biplot origin divides the polygon into four segments. The initial segment comprises G1, G4, E1, E2, E3, E4, E5, E6, E7, E8. The second segment includes G9, G10 and E10, while the third encompasses G6 and E9. The last segment comprises G2, G3, G7, and G8. A segment encompassing one or more environments can be termed a "mega environment" (Zhang et al., 2016). This study identifies three mega-environments. Consequently, this research identifies the presence of three mega-environments. Among the hybrids, SJI 002 displays broad adaptability by yielding exceptionally well in Kepung, Gondang legi, Pagelaran, Nglegok, Kepanjen kidul, Badas, Ngoro, and Ngronggot. In contrast, hybrid SJI 006 and 'Pertiwi 6' exhibit specific adaptability. SJI 06 is most suited for Prambon, and 'Pertiwi 6' for Bajeng. Conversely, hybrids SJI 002, SJI 003, SJI 007 and 'Pioneer 36' show consistently low yields across all locations. Such hybris are deemed undesirable for the ecosystems in which they were assessed, and breeders will not suggest their use (de Souza et al., 2023).

According to the stability analysis used, Table 6 summarizes the stability of the hybrids. Among the five analyses, hybrid SJI 001 is consistently a stable hybrid across all stability analyses. This hybrid also had the highest yield potential among all hybrids. Hybrid SJI 002 had specific adaptability; it was more suitable for unfavourable environments. Conversely, hybrid SJI 006 and 'Pertiwi 6' performed well in favourable environments. Notably, GGE biplot analysis highlights specific adaptability patterns. The GGE biplot analysis revealed that SJI 006 had specific adaptability to Prambon, while 'Pertiwi 6' had specific adaptability to Bajeng (Table 6).

Table 6. The stability resume of 10 hybrids in 10 locations based on the five-stability analysis.

	Stability analysis				
Hybrid	Francis and Kannenberg (1978)	Finlay and Wilkinson (1963)	Eberhart and Russel (1966)	Shukla (1972)	GGE Biplot (Yan, 2001)
SJI 001	Stable, high yield	Stable, high yield	Stable	Stable, high yield	Stable, high yield
SJI 002	Stable, low yield	Specific for suboptimal	Specific for suboptimal	Stable, low yield	Not suggested
SJI 003	Unstable, low yield	Specific for suboptimal	Unstable	Unstable, low yield	Not suggested
SJI 004	Unstable, high yield	Specific for optimal	Unstable	Stable, high yield	Stable, high yield
SJI 005	Unstable, high yield	Specific for optimal	Unstable	Stable, low yield	Not suggested
SJI 006	Unstable, high yield	Specific for optimal	Unstable	Unstable, high yield	Specific location for Prambon
SJI 007	Unstable, low yield	Stable, low yield	Unstable	Stable, low yield	Not suggested
P 36	Stable, low yield	Specific for suboptimal	Unstable	Stable, low yield	Not suggested
Bisi 18	Unstable, low yield	Stable, low yield	Unstable	Unstable, low yield	Not suggested
Pertiwi 6	Unstable, high yield	Stable, high yield	Unstable	Unstable, high yield	Specific location for Bajeng

CONCLUSIONS

Based on the five stability analyses, hybrid SJI 001 was stable and had the highest yield. Hybrid SJI 002 suited unfavourable environments, while hybrid SJI 006 and 'Pertiwi 6' suited favourable ones. GGE biplot analysis showed that SJI 006 adapted well to Prambon and 'Pertiwi 6' to Bajeng.

Author contribution

Conceptualization: A.T.M., R.N.I. Methodology: A.T.M., O.J. Software: S.B.P. Validation: O.J., R.N.I. Formal analysis: S.B.P. Investigation: A.T.M., S.B.P. Resources: A.T.M., R.N.I. Data curation: O.J., R.N.I. Writing-original draft: S.B.P., R.N.I. Writing-review & editing: A.T.M., O.J. Visualization: R.N.I. Supervision: O.J. Project administration: A.T.M. Funding acquisition: A.T.M. All co-authors reviewed the final version and approved the manuscript before submission.

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