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Genotype by Environment Interaction on Early-Maturing and High-Yield Maize Hybrids

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Abstract

Assembling hybrid maize varieties with early-maturing and high-yield traits is one of the methods to increase maize productivity in drylands in Indonesia. Trials of hybrid maize candidates in several locations and different seasons are highly needed to determine the stability of hybrid maize candidates prior to commercial release. The objectives of the research were: (1) to evaluate the performance of maize hybrids in several locations and different seasons; (2) to assess the stability of early-maturing and grain yield characteristics of genotypes evaluated in several locations and seasons; and (3) to determine hybrid maize candidates that can be released as new superior/elite varieties. The research was conducted at 14 research populations (7 different locations, 2 seasons). Each population was planted according to the randomized block design with 10 genotypes as treatments and 4 replicates, so 40 experiment units were obtained. Ten genotypes were tested: six hybrid maize candidates derived from a diallel cross with high yield potential and early-maturing traits (G1, G2, G3, G4, G5, G6) and 4 elite varieties as checks (G7 = SK, G8 = ANM, G9 = Pertiwi-x, and G10 = BISI-x). The combined analysis of variance (ANOVA) conducted on 10 genotypes and 14 research populations revealed that genotypes, environments (season, location, season x location), and interactions (genotype x season, genotype x location, genotype x season x location) significantly affect harvest age and grain yield per hectare ($p < 0.01$). G4 had an early harvest age (91.93 days) and grain yield per hectare above the average of all genotypes in all environments (8.71 ton ha^{-1}), and was also declared stable based on three stability analyses: Finlay-Wilkinson, Eberhart-Russel, and AMMI. Thus, G4 is recommended as an elite hybrid maize variety with early-maturing, high-yield, stable, and broad adaptability traits.

Keywords: Grain Yield; Harvest Age; Maize Hybrid; Stability.

1. Introduction

Indonesia is one of the biggest maize-producing countries in Southeast Asia, with 20.01 million tons of maize production in 2021 [1]. Maize planting areas in Indonesia commonly reside in drylands, which are suboptimal for rice cultivation and horticulture [2]. As many as 24,530,076 ha of drylands in Indonesia are maize planting areas. Drylands in Indonesia are characterized by a scarcity of water due to low Rainfall (less than 2,000 mm/year) and a short rain season (3-5 months); thus, water availability is a limiting factor for maize production in Indonesia [3–5]. These soil conditions caused maize production in Indonesia (5.72 ton ha^{-1}) to be lower than the average maize production worldwide (5.87 ton ha^{-1}) [1].

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Plant tolerance to drought stress can be obtained from the mechanism of escape from drought stress. Planting early-maturing varieties can avoid drought stress and increase the intensity of planting maize [6]. Therefore, assembling hybrid maize varieties with early-maturing and high-yield traits is one of the methods to increase maize productivity in drylands in Indonesia [7, 8]. Assembling hybrid maize varieties with early-maturing and high-yield traits can be done by hybridizing two or more pure, superior strains [9, 10]. Hybridization is an attempt to add genetic variability and make new genotypes superior. The hybridization method in assembling varieties will produce superior hybrid varieties by utilizing the heterosis effect [11, 12]. Heterosis of two or more pure strains with early-maturing and high-yield traits will result in early-maturing and high-yield maize hybrids [13].

One of the methods usually used by plant breeders to produce maize hybrids with early-maturing and high-yield traits is the diallel cross. Diallel crosses are crosses carried out between all pairs of parents (pure lines) so that the yield potential of a hybrid combination, heterosis value, general combining ability (GCA), special combining ability (SCA), and genetic variety values can be known which can be used as a guideline for plant breeders to obtain superior maize varieties [14, 15]. Diallel crosses help maize breeders select parents to produce the best combinations with a heterosis effect. Nasser et al. (2020) [16] resulted in two crosses combination with early-maturing, high-yield, and resistance to drought stress traits from 15 pure lines on diallel crosses. Badu-Apraku & Obisesan (2021) [17] resulted in two crosses combination with early-maturing, high-yield, and stability at 13 drought-stress locations and low N soil conditions on diallel crosses.

Trials of hybrid maize candidates in several locations and different seasons are highly required to assess the stability of the maize hybrids before they are commercially released. This act must be done since the performance of plants is influenced by genotype, environment, and genotype-by-environment interactions (GEI) [18–20]. Moreover, testing hybrid maize candidates in several locations and seasons must be done in several locations and seasons to determine a variety that is stable in all environments and specifically stable in specific environments [21, 22]. Genotype-by-environment interactions in multilocation research studies are caused by unpredictable macro- and micro-environment effects such as temperature, Rainfall, and humidity [23]; thus, the tested genotypes will respond differently in each growth environment [24, 25].

Stability analysis of the hybrid maize candidates can be performed using Finlay-Wilkinson's method [26], Eberhert-Russell [27], and AMMI (Additive Main Effect and Multiplicative Interaction) [28]. Finlay-Wilkinson's method applies regression coefficient as its stability parameter, while Eberhart-Russell applies regression coefficient (bi) and regression deviation (S^2_{di}) as its parameters in determining the stability of a genotype. AMMI is a multivariate method to assess the effect of an environment on genotypes tested in a multilocation trial [29–31]. Therefore, the objectives of the research were: (1) to evaluate the performance of maize hybrids in several locations and different seasons; (2) to assess the stability of early-maturing and grain yield characteristics of genotypes tested in several locations and seasons; and (3) to determine hybrid maize candidates that can be released as new superior/elite varieties.

2. Materials and Methods

2.1. Plant Materials

Plant materials used in the research were six hybrid maize candidates derived from a diallel cross with high yield potential and early-maturing traits, and four other varieties as checks (SK, ANM, Pertiwi-x, and BISI-x) (as listed in Table 1). SK and ANM were composite varieties, while Pertiwi-x and BISI-x were single-cross hybrids [32]. These four maize varieties have been widely planted by farmers in Indonesia.

Table 1. 10 genotypes tested in the research

Genotypes	Code	Parental Lines		Pedigree
		Female	Male	
G1	MHC1	UTM31	UTM07	The female is a high-yield strain; the male is a drought-tolerant and early-maturing strain
G2	MHC2	UTM31	UTM22	The female is a high-yield strain; the male is a drought-tolerant and early-maturing strain
G3	MHC3	UTM31	UTM18	The female is a high-yield strain; the male is a drought-tolerant and early-maturing strain
G4	MHC4	UTM31	UTM15	The female is a high-yield strain; the male is a drought-tolerant and early-maturing strain
G5	MHC5	UTM31	UTM02	The female is a high-yield strain; the male is a drought-tolerant and early-maturing strain
G6	MHC6	UTM31	UTM14	The female is a high-yield strain; the male is a drought-tolerant and early-maturing strain
G7	SK	-	-	Composite variety: ICERI
G8	ANM	-	-	Composite variety: ICERI
G9	Pertiwi-x	-	-	Commercial hybrid: Pertiwi
G10	BISI-x	-	-	Commercial hybrid: BISI

2.2. Research Implementation and Data Collection

The flow of research implementation from diallel crossing to multilocation testing is presented in Figure 1. The multilocation test was conducted in March-October 2020 at seven locations during rainy and dry seasons (Table 2 and Figure 2). The research was designed in a randomized block design with ten genotypes as treatments and four replicates, so 40 experiment units were obtained in each research location. In each research location, each genotype was planted in a 2×5 m sized crop with a plant spacing of 70×20 cm. Each trial crop consisted of 100 maize plantations. Maize seeds were planted at 3 – 5 cm depth with one seed in each hole. Fertilization was done in three stages: (1) the first fertilization was given at seven days after planting with 100 kg of urea, 200 kg/ha SP-36, and 50 kg/ha KCl, (2) the second fertilization was given at 25 days after planting with 100 kg Urea and 50 kg KCl, and (3) the third fertilization was given at 40 days after planting with 100 kg Urea.

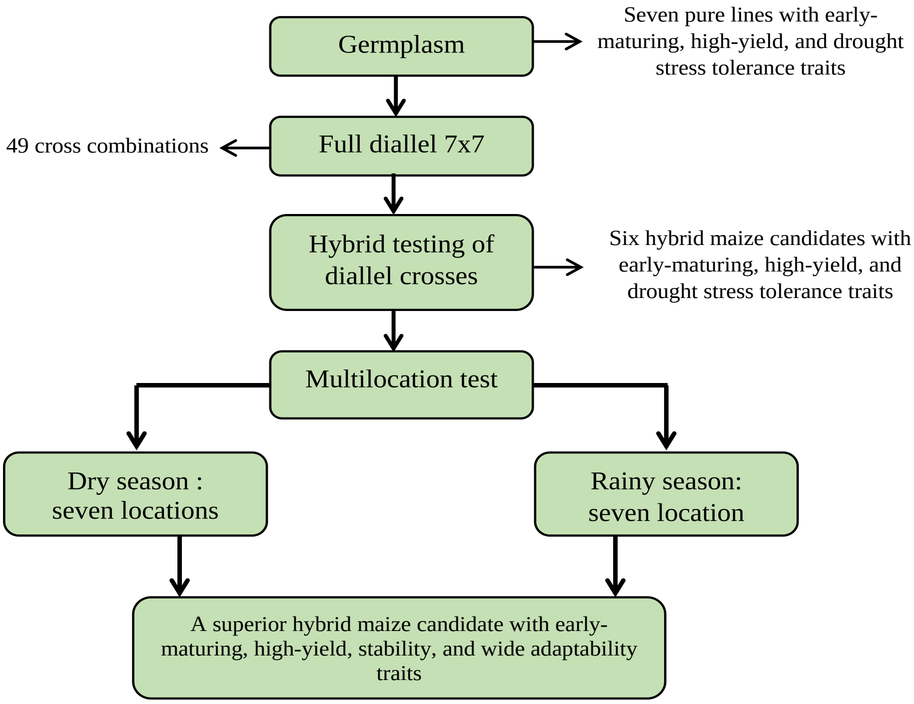


Figure 1. Research workflow

Table 2. Description of 14 research locations

Location Code	Location	Cropping Season	Altitude (m asl)	Mean annual Rainfall (mm)	Temperature (°C)		Soil type
					min	max	
E1	Kamal, Bangkalan, East Java	Dry	5 m	1741	24	34	Grumusol
E2	Jrengik, Sampang, East Java	Dry	25 m	848	28	32	Grumusol
E3	Pademawu, Pamekasan, East Java	Dry	7 m	2161	25	33	Aluvial
E4	Lenteng, Sumenep, East Java	Dry	50 m	1798	20	35	Litosol
E5	Leces, Probolinggo, East Java	Dry	54 m	1120	26	33	Aluvial
E6	Mojoroto, Kediri, East Java	Dry	76 m	1741	24	34	Grumusol
E7	Godean, Sleman, Yogyakarta	Dry	117	3059	21	34	Regosol
E8	Kamal, Bangkalan, East Java	Rainy	5 m	1741	24	34	Grumusol
E9	Jrengik, Sampang, East Java	Rainy	25 m	848	28	32	Grumusol
E10	Pademawu, Pamekasan, East Java	Rainy	7 m	2161	25	33	Aluvial
E11	Lenteng, Sumenep, East Java	Rainy	50 m	1798	20	35	Litosol
E12	Leces, Probolinggo, East Java	Rainy	54 m	1120	26	33	Aluvial
E13	Pojok, Kediri, East Java	Rainy	76 m	1741	24	34	Grumusol
E14	Godean, Sleman, Yogyakarta	Rainy	117	3059	21	34	Regosol

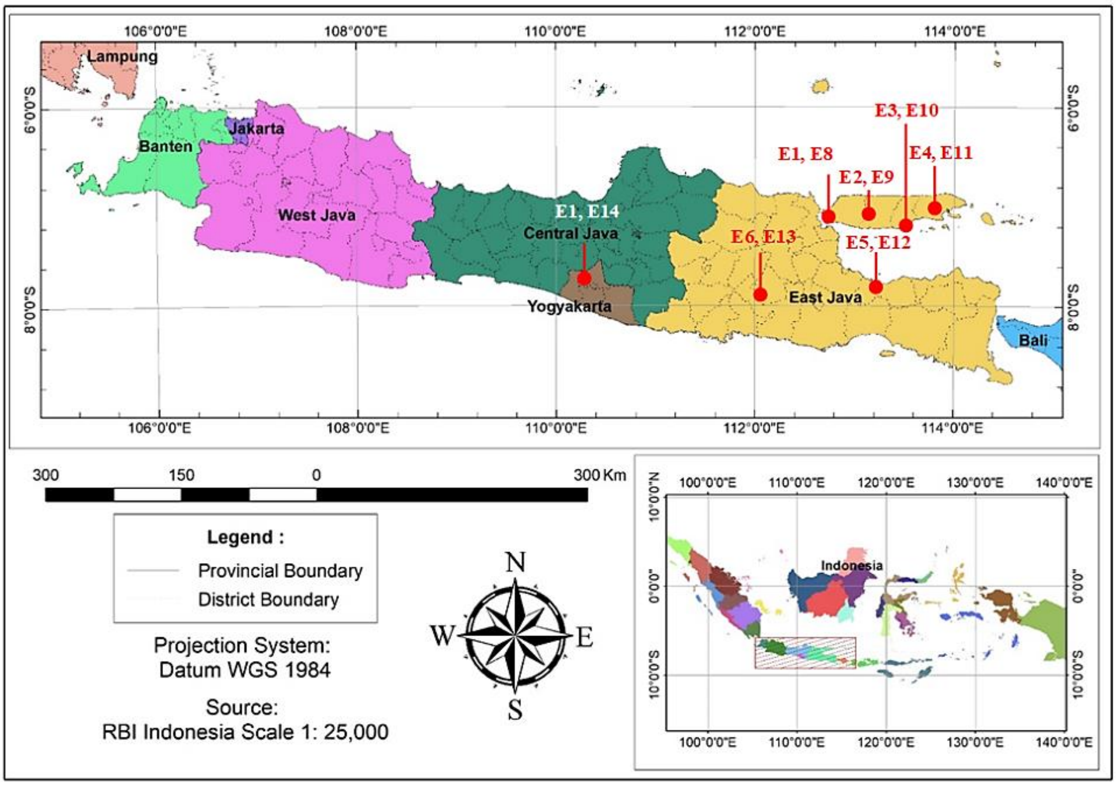


Figure 2. Map of research locations on Java Island, Indonesia

Observations of harvest age and grain yield per hectare were conducted on 50 plant samples in each trial crop of all research locations. The harvest age was calculated when the ear of the maize ripened physiologically, characterized by the dried or brownish husk, hardened seed, and black layer formed at least 50% in each seed line. At that time, the water content of the seed usually had reached less than 30%. Grain yield observation was conducted on all plant samples in each trial crop, and the results were then converted into grain yield per hectare at 15% water content using the following formula:

$$Y = \frac{10.000}{HA} \times \frac{100-MC}{100-15} \times GW \quad (1)$$

where Y is grain yield (kg ha^{-1}), HA is harvested area per plot (m^2), MC is moisture content at harvest time (%), and GW is harvested grain weight per plot (kg).

2.3. Data Analysis

Data results of the harvest age and grain yield per hectare were analyzed using the F-test and the combined analysis of variance. If the results were significantly different, data results were analyzed further with the HSD (Honestly Significant Difference) test to assess the difference among tested treatments. The stability test was conducted when the genotype-by-environment interactions (GEI) occurred. The combined analysis of variance and stability analysis were calculated using the PBTools and STAR. The stability was analyzed using Finlay-Wilkinson's regression coefficient and Erberhart-Russell. AMMI method was used to describe the genotype-by-environment interactions (GEI) by showing the relative positions of genotypes toward the environment so that the environmental suitability of a genotype can be mapped clearly [33, 34].

The Formula used to calculate the stability based on the three methods were as follows:

1. Finlay-Wilkinson [26]:

$$b_i = \frac{\sum_{j=1}^{q}\left(x_{ij} - \overline{X}_{i.}\right)\left(\overline{X}_{j.} - \overline{X}_{..}\right)}{\sum_{j=1}^{q}\left(\overline{X}_{j.} - \overline{X}_{..}\right)^2} \quad (2)$$

where bi is the i^{th} genotype regression coefficient; x_{ij} is the mean value of the i^{th} genotype in the j^{th} environment; X_i. is the mean value of the ith genotype; X_j. is the mean value of the j^{th} environment; $X_{..}$ is the mean value of all environmental indices, and q is the number of environments.

2. Eberhart-Russell [27]:

$$S_{di}^2 = \frac{1}{q-2}\left[\left(\sum_{j=1}^{q} X_{ij}^2\right) - \left(\frac{\left(\sum_{j=1}^{q} x_{ij} I_j\right)^2}{\sum_{j=1}^{q} I_j^2}\right)\right] \tag{3}$$

where S_{di}^2 is the square of deviations from regression; x_{ij} is the mean value of the i^{th} genotype in the j^{th} environment; I_j is the jth environment index; and q is the number of environments.

3. Multivariate analysis (Additive Mean Effect Multiplicative Interaction = AMMI) [35]:

$$Y_{ij} = \mu + G_i + E_j + \sum_{k=1}^{n} \lambda_k \gamma_{ik} \alpha_{jk} + \rho_{ij} + \varepsilon_{ij} \tag{4}$$

where Y_{ij} is the average response of genotype *i* in environment j; μ is the grand mean score; G_i is the genotype effect; E_j is the environment effect; λ_k is the singular value for the PCA axis k; γ_{ik} and α_{jk} is the genotype and environment PCA score for the PCA axis k, respectively; ρ_{ij} is the residual not explained by principal components used; and $\mathcal{E}_{ij}$ is the associated error.

3. Result and Discussions

3.1. Effects of Genotype × Environment Interactions on Harvest Age and Grain Yield

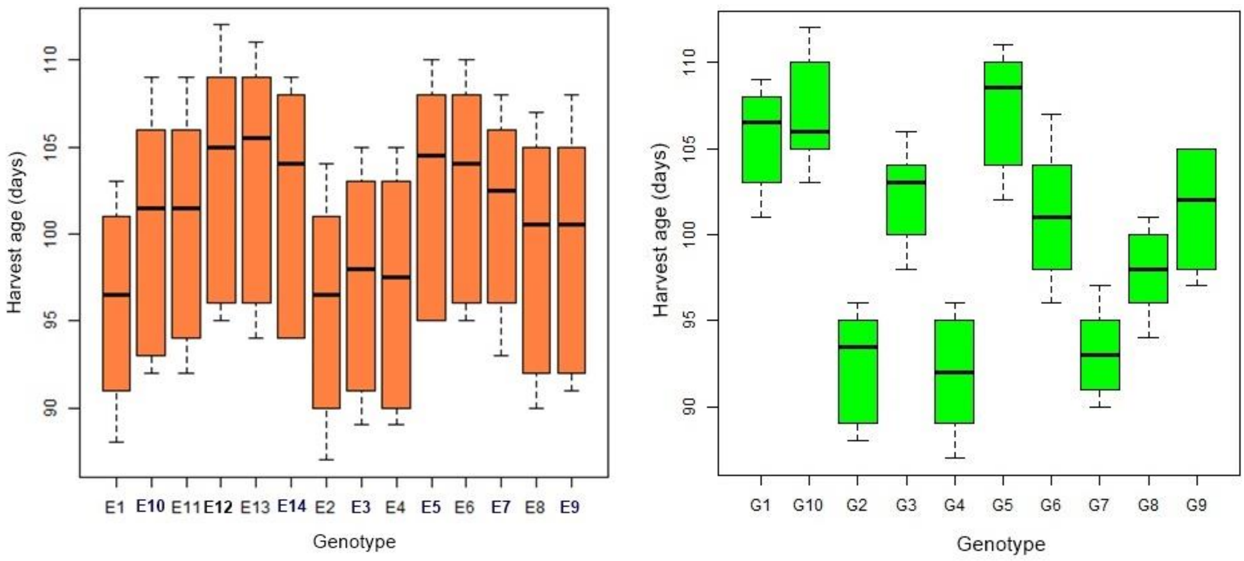
The combined analysis of variance (ANOVA) for harvest age and grain yield per hectare on ten genotypes in 14 research locations (seven locations, two seasons) revealed that genotypes, environments (season, location, season × location), and interactions (genotype × season, genotype × location, genotype × season × location) significantly affect harvest age and grain yield per hectare ($p < 0.01$) (as shown in Table 3). As a factor, genotypes resulted in a significant influence since the tested materials had different genetic backgrounds [36, 37]. The combined ANOVA results revealed that genetics, environment, and interactions were the main determinants of harvest age and grain yield per hectare.

Table 3. Combined ANOVA for yield in seven locations for two cropping seasons

Source of variance	d_f	SS		MS		F Value	
		HA	GY	HA	GY	HA	GY
Block	2	0.17	4.12	0.09	2.06	1.20^{ns}	54.34**
Season (S)	1	512.61	10.74	512.61	10.74	7186.07**	283.36**
Genotype (G)	9	13512.05	153.59	1501.34	17.07	21049.03**	450.15**
Location (E)	6	2285.29	59.38	380.88	9.90	5340.03**	261.05**
G × S	9	74.06	6.82	8.23	0.76	115.37**	19.98**
E × S	6	173.42	0.17	28.90	0.03	405.24**	0.74**
G × E	54	78.85	11.50	1.46	0.21	20.47**	5.62**
G × E × S	54	67.58	7.75	1.25	0.14	17.54**	3.78**
Error	278	19.83	10.54	0.07	0.04		
Total	419	16723.86	264.60				

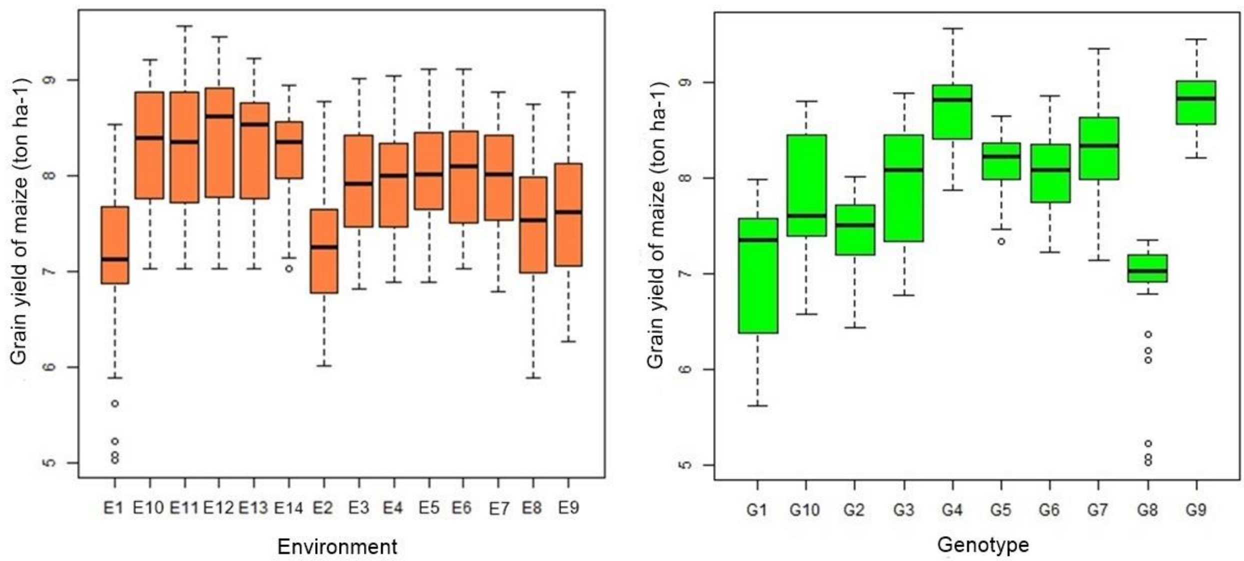
Note: ** = significant at the α level of < 0.01; ns = nonsignificant; df = degree of freedom; SS = sum of squares; MS = mean squares; HA = harvest age; GY = grain yield

The variance level of the research locations and genotypes of tested maize highly influenced the maize grain yield (Figures 3 and 4, Tables 4 and 5). The variance of harvest age based on research locations showed a short harvest period in Bangkalan (dry season), while a long harvest period was shown in Sleman (rainy season) (Figure 3-a). Based on tested genotypes, the variance of harvest age showed a short harvest period by G7, while a long harvest period was shown by G9 (Figure 3-b). The variance of grain yield based on research locations showed less variance of maize grain yield in Sleman (dry season), while a wide variance of grain yield was shown in Sumenep (dry season) (Figure 4-a). The variance of grain yield based on tested genotypes revealed less variance in grain yield by G8, while a wide variance was shown by G1 (Figure 4-b). The variance level of harvest age and maize grain yield based on tested genotypes is higher than that of harvest age and maize grain yield based on research locations since genotype is the biggest contributor (harvest age = 80.79%, grain yield = 59.48%) (See Tables 7 and 8). The difference among variances (harvest age and maize grain yield) in 14 research locations is highly affected by the adaptability of tested genotypes to their growth environments [38]. Plant adaptability to environmental changes is due to the combinations of plant traits capable of overcoming environmental changes affecting plant yield [39, 40].



(a) (b)

Figure 3. (a) Data distribution of harvest age (days) based on research locations, (b) Data distribution of harvest age (days) based on genotypes



(a) (b)

Figure 4. (a) Data distribution of maize grain yield (ton ha^{-1}) based on research locations, (b) Data distribution of maize grain yield (ton ha^{-1}) based on genotypes

Table 4. Harvest age (days) of 10 maize genotypes at 14 locations

Genotypes	Harvest age (days)							Mean
	E1	E2	E3	E4	E5	E6	E7	
Dry Season								
G1	105.00 b	105.00 b	107.00 b	107.00 b	109.00 b	109.00 b	108.00 b	107.14 a
G2	92.00 e	92.00 g	93.00 h	94.00 h	96.00 e	96.00 f	94.00 f	93.86 d
G3	101.00 c	102.00 c	103.00 d	103.00 d	106.00 c	106.00 cd	104.00 d	103.57 b
G4	91.00 ef	91.00 h	92.00 i	92.00 i	95.00 e	96.00 f	94.00 f	93.00 d
G5	107.00 a	108.00 a	109.00 a	109.00 a	111.00 a	110.00 ab	109.00 a	109.00 a
G6	100.00 c	100.00 e	101.00 f	101.00 f	105.00 c	107.00 c	105.00 c	102.71 b
G7	90.67 f	92.33 g	92.33 hi	92.67 i	95.33 e	95.00 f	94.33 f	93.24 d
G8	98.00 d	96.67 f	97.67 g	98.33 g	99.67 d	100.67 e	99.67 e	98.67 c
G9	101.00 c	101.00 d	102.00 e	102.00 e	105.00 c	105.00 d	104.00 d	102.86 b
G10	105.00 b	105.00 b	106.00 c	106.00 c	112.00 a	111.00 a	109.00 a	107.71 a
Mean	99.07	99.30	100.30	100.50	103.40	103.57	102.10	101.18
CV (%)	5.38	5.25	5.25	5.25	5.38	5.35	5.25	6.89

Rainy Season								
Genotypes	**E8**	**E9**	**E10**	**E11**	**E12**	**E13**	**E14**	**Mean**
G1	101.00 b	101.00 c	103.00 c	103.00 c	108.00 b	108.00 b	106.00 b	104.29 a
G2	88.00 h	88.00 i	89.00 h	89.00 i	95.00 f	95.00 g	94.00 h	91.14 d
G3	98.00 c	98.00 d	99.00 d	100.00 d	105.00 c	104.00 d	103.00 d	101.00 b
G4	88.00 h	87.00 j	89.00 h	89.00 i	95.00 f	95.00 g	93.00 i	90.86 d
G5	103.00 a	102.00 b	104.00 b	104.00 b	110.00 a	110.00 a	108.00 a	105.86 a
G6	96.00 e	96.00 f	98.00 e	97.00 f	104.00 d	104.00 d	102.00 e	99.57 bc
G7	90.67 g	90.33 h	90.67 g	90.33 h	95.33 f	96.33 f	96.00 g	92.81 d
G8	94.00 f	94.00 g	96.00 f	96.00 g	100.00 e	101.00 e	99.00 f	97.14 c
G9	97.00 d	97.00 e	98.00 e	98.00 e	105.00 c	105.00 c	104.00 c	100.57 b
G10	103.00 a	104.00 a	105.00 a	105.00 a	110.00 a	110.00 a	108.00 a	106.43 a
Mean	95.87	95.73	97.17	97.13	102.73	102.83	101.30	98.97
CV (%)	5.19	5.19	5.19	5.18	5.18	5.18	5.31	8.13

Note: Numbers in one column followed by the same letter show no significant difference based on the HSD test at α = 0.05.

Table 5. Grain yield (ton ha−1) of 10 maize genotypes at 14 locations

Genotypes	**Grain Yield (ton ha^{-1})**							**Mean**
	E1	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	
Dry season								
G1	6.11 h	6.40 g	7.19 e	7.22 f	7.38 e	7.39 f	7.82 c	7.07 e
G2	6.60 g	7.01 f	7.69 d	7.70 e	7.81 d	7.80 e	7.90 c	7.50 d
G3	7.12 ef	7.21 f	8.31 c	8.42 cd	8.64 c	8.82 b	8.52 ab	8.15 c
G4	8.10 b	8.30 b	9.10 a	9.30 a	8.90 b	9.10 a	8.80 a	8.80 a
G5	7.91 b	8.02 c	8.30 c	8.41 cd	8.53 c	8.39 d	8.41 b	8.28 bc
G6	7.60 cd	7.71 de	8.50 bc	8.20 d	8.59 c	8.50 cd	8.31 b	8.20 bc
G7	7.89 bc	7.93 cd	8.92 a	8.80 b	9.20 a	8.69 bc	8.39 b	8.55 ab
G8	7.00 f	7.00 f	7.19 e	7.20 f	7.22 e	7.09 g	7.12 d	7.12 e
G9	8.61 a	8.71 a	9.10 a	9.11 a	9.32 a	8.71 bc	8.53 ab	8.87 a
G10	7.41de	7.51 e	8.52 b	8.50 c	8.68 c	8.61 bcd	8.52 ab	8.25 bc
Mean	7.44	7.58	8.29	8.29	8.43	8.31	8.23	8.08
CV (%)	6.36	6.05	5.99	5.99	5.84	6.13	6.23	9.46
Rainy season								
Genotypes	**E8**	**E9**	**E10**	**E11**	**E12**	**E13**	**E14**	**Mean**
G1	5.81 d	6.21 h	7.31 d	7.39 c	7.82 d	7.61 d	7.70 e	7.12 c
G2	7.02 c	7.11 ef	7.42 d	7.49 c	7.52 e	7.51 d	7.51 ef	7.37 c
G3	6.92 c	6.92 fg	7.91 c	8.01 b	8.23 c	8.29 bc	8.03 cd	7.76 b
G4	8.21 a	8.03 b	8.81 a	8.92 a	8.81 b	8.89 a	8.71 a	8.62 a
G5	7.61 b	7.61 c	8.11 bc	8.12 b	8.22 c	8.29 bc	8.22 bc	8.02 b
G6	7.43 b	7.31 de	8.04 c	8.21 b	8.22 c	8.10 c	8.01 d	7.90 b
G7	7.41 b	7.51 cd	8.32 b	8.19 b	8.23 c	8.43 b	8.29 b	8.05 b
G8	5.11 e	6.21 h	7.02 e	7.03 d	7.11 f	7.12 e	6.91 g	6.64 d
G9	8.41 a	8.53 a	8.92 a	8.89 a	8.99 a	8.88 a	8.70 a	8.76 a
G10	7.00 a	6.81 g	7.53 d	7.39 c	7.60 e	7.52 d	7.50 f	7.34 c
Mean	7.09	7.22	7.94	7.96	8.07	8.06	7.96	7.76
CV (%)	6.82	6.21	6.12	5.96	5.77	6.29	5.85	8.01

Note: Numbers in one column followed by the same letter show no significant difference based on the HSD test at α = 0.05.

The average harvest age in the research ranged between 90.86-109.00 days (Table 4). The average harvest age during the dry season (101.18 days) was higher than during the rainy season (98.97 days). The harvest age of maize was highly affected by air temperature [41, 42]. Low air temperatures would cause a longer harvest age [43, 44]. The air temperature of maize plants grown during the dry season was lower than those grown during the rainy season, causing maize grown during the dry season to have a longer maturity age [45]. Grown during the rainy season, maize candidates G2 and G4 showed the shortest average harvest age; they were found to have a shorter harvest age than the four checks (SK, ANM, Pertiwi-x, and Bisi-x) in two locations, namely Sampang (G2 = 92.00 days and G4 = 91.00 days) and Sleman (G2 and G4 = 94 days). Moreover, G2 and G4 that were grown during the dry season also showed the shortest average harvest age and were shorter than the four checks (SK, ANM, Pertiwi-x, and Bisi-x) in all research locations (Bangkalan, Sampang, Pamekasan, Sumenep, Probolinggo, Kediri, and Sleman). Maize candidate G4 had a shorter average harvest age than the four checks in seven research locations, whether they were grown during the rainy or dry seasons. Meanwhile, maize candidate G2 had a shorter harvest age than the four checks in seven research locations only when they were grown during the dry season. Based on observations of the harvest age, G2 and G4 were found to be the hybrid maize candidates to have early-maturing traits due to their < 95 days of harvest age [46, 47]; thus, they had high suitability to be developed in drylands in Indonesia.

According to the test results, the mean grain yield per hectare ranged between 7.07-8.85 ton ha^{-1} (Table 5). The mean grain yield per hectare of maize grown during the dry season (7.76 ton ha^{-1}) was higher than the average grain yield per hectare of maize grown during the rainy season (8.08 ton ha^{-1}). These findings follow study findings by Yasin et al. [48] and Wicaksana et al. [23], which stated that grain yield per hectare of maize grown during the dry season was higher than those grown during the rainy season. The grain yield of maize is highly influenced by air temperature [49, 50]. An increased grain yield per hectare of maize grown during the dry season compared to maize grown during the rainy season, is due to the optimal temperature for photosynthesis and dry material allocation [51]. Grown during the dry season, G4 showed the highest mean grain yield per hectare; it surpassed the four checks (SK, ANM, Pertiwi-x, and Bisi-x) in three locations: Sumenep (9.30 ton ha^{-1}), Kediri (9.10 ton ha^{-1}) and Sleman (8.80 ton ha^{-1}). Similarly, G4 grown during the rainy season also showed the highest mean grain yield per hectare and surpassed the four checks in three locations: Sumenep (8.92 ton ha^{-1}), Kediri (8.89 ton ha^{-1}) and Sleman (8.71 ton ha^{-1}). G4 exhibited a higher grain yield per hectare than three checks (SK, ANM, and Bisi-x) in seven locations during the rainy and dry seasons.

3.2. Stability Analysis based on Finlay-Wilkinson and Eberhart-Russell Methods

The Finlay-Wilkinson method uses the regression coefficient (bi) as a parameter to assess the stability of genotypes toward the environment. A regression coefficient value of 1 indicates the average stability of a genotype in an environment. A regression coefficient value greater than 1 indicates the sensitivity of a genotype against environmental changes, while a value of less than 1 indicates an increased sensitivity of a genotype against environmental changes. A large difference in bi values of some tested genotypes will ease plant breeders' selection of a stable genotype in an environment [52, 53]. Test results of 10 genotypes in 14 environments for harvest age traits showed that G1, G2, G3, G4, G5, G7, G8, G9, and G10 had bi values with insignificant differences to 1, so these candidates are considered stable genotypes (Table 6). G6 had bi>1 and was significantly different; thus, it can be categorized as a stable genotype in an optimal environment. Furthermore, test results of 10 genotypes in 14 environments for grain yield traits revealed that G2, G4, G6, G7, and G8 had bi values with insignificant differences to 1, so these candidates are considered stable genotypes. G1, G3, and G10 were stable genotypes in an optimal environment since their bi>1 and had significant differences. G5 and G9 had bi<1 and were significantly different, so they can be categorized as genotypes with good adaptability in marginal environments.

Table 6. Mean grain yields, harvest age (days), and yield stability estimates of stability for the yield of 10 maize genotypes at 14 locations

Genotypes	Character		*bi* (Finlay-Wilkinson)		S^2_{di} (Eberhart-Russel)	
	HA (days)	GY (ton ha^{-1})	HA (days)	GY (ton ha^{-1})	HA (days)	GY (ton ha^{-1})
G1	105.71 a	7.10 ef	0.99^{ns}	1.36*	0.06^{ns}	0.24*
G2	92.50 d	7.44 e	1.03^{ns}	0.78^{ns}	0.05^{ns}	0.12^{ns}
G3	102.29 b	7.95 cd	0.97^{ns}	1.49*	0.49*	0.10^{ns}
G4	91.93 d	8.71 a	1.04^{ns}	0.86^{ns}	0.03^{ns}	0.11^{ns}
G5	107.43 a	8.15 bc	1.02^{ns}	0.65*	0.08^{ns}	0.04^{ns}
G6	101.14 b	8.05 bcd	1.26*	0.92^{ns}	0.07^{ns}	0.07^{ns}
G7	93.02 d	8.30 b	0.76^{ns}	1.14^{ns}	0.10^{ns}	0.11^{ns}
G8	97.90 c	6.88 f	0.81^{ns}	1.05^{ns}	0.06^{ns}	0.24*
G9	101.71 b	8.82 a	1.12^{ns}	0.45*	0.04^{ns}	0.12^{ns}
G10	107.07 a	7.79 d	0.98^{ns}	1.30*	0.10^{ns}	0.22*
Environment mean	100.07	7.92				

Note: Numbers in one column followed by the same letter show no significant difference based on the HSD test at α = 0.05; ns = nonsignificant; HA = Harvest age; GY = Grain yield.

The Eberhert-Russell method uses both coefficient regression (bi) and regression deviation (S^2_{di}) to determine the stability of a genotype. A genotype is considered stable when having bi insignificantly differ to 1 and regression deviation (S^2_{di}) close to 0. In terms of harvest age traits, G1, G2, G4, G5, G7, G8, G9, and G10 had regression coefficient (bi) values insignificantly differ to 1 and regression deviation (Sd^2_{di}) values close to 0; thus, they were considered stable based on the Eberhart-Russell method. G6 had S^2_{di} value close to 0 but bi greater than 1, so it can be categorized as a stable genotype in an optimal environment. G3 had bi value insignificantly different from 1 but S^2_{di} value significantly different from 0; thus, it was categorized as an unstable genotype based on the Eberhart-Russell method. In terms of grain yield traits, G2, G4, G6, and G7 were categorized as stable genotypes based on the Eberhart-Russell method due to their regression coefficient (bi) values being insignificantly different from 1 and their regression deviation (S^2_{di}) values being close to 0. G3, G5, and G9 had S^2_{di} values close to 0 but bi values greater than 1; thus, they can be categorized as genotypes with stable grain yield traits in an optimal environment.

3.3. AMMI Analysis

The analysis of variance using AMMI on harvest age and grain yield per hectare of six hybrid variety candidates and four checks (SK, ANM, Pertiwi-x, and Bisi-x) revealed that genotype (G), location (E), and genotype x environment interactions (GEI) had a significant effect (p < 0.01) (Tables 7 and 8). Therefore, the three source components of diversity highly affect harvest age and grain yield per hectare. Contributions of genotype (G), location (E), and genotype-by-environment interactions (GEI) on harvest age traits were 80.79%, 17.76%, and 1.36%, respectively. Meanwhile, the contributions of genotype (G), location (E), and genotype-by-environment interactions (GEI) on grain yield per hectare as a trait were 59.48%, 27.22%, and 10.09%, respectively. Genotype and location were the biggest contributors to diversity in harvest age and grain yield traits; thus, these traits were highly influenced by the genotype type and the conditions of maize plantation locations. The high percentage of genotype and environment influences on harvest age and grain yield traits indicates that the variations of genotype and trial location in the research were highly wide [54]. The variation of genotype and environmental conditions for maize plantations can cause different plant expressions, so that the same genotype will respond differently to harvest age and grain yield traits when grown in different environments [55].

Table 7. AMMI analysis of Variance (ANOVA) for harvest age

Source of Variance	df	SS	MS	F-Value	% Variance explained	Accumulation
Block	2	0.17	0.09	1.20^{ns}	0.00	-
Genotype (G)	9	13512.05	1501.34	21049.03**	80.79	-
Location (E)	13	2971.32	228.56	3204.50**	17.76	-
GxE	117	220.49	1.88	26.42**	1,32	-
IPCA 1	21	30.23	1.49	21.28**	41.10	41.10
IPCA 2	19	21.70	1.14	16.28**	29.50	70.60
IPCA 3	17	8.87	0.52	7.42*	12.10	82.70
IPCA 4	15	6.80	0.45	6.43*	9.30	92.00
IPCA 5	13	2.26	0.17	2.48^{ns}	3.10	95.10
IPCA 6	11	1.46	0.13	1.86^{ns}	2.00	97.10
IPCA 7	9	1.19	0.13	1.86^{ns}	1.00	98.70
IPCA 8	7	0.73	0.10	1.42^{ns}	0.30	99.70
IPCA 9	5	0.25	0.05	0.71^{ns}	0.00	100.00
Error	278	19.83	0.07			
Total	419	16723.86				

Note: E = Environment (location); IPCA = Interaction Principal Component Analysis; ** = significant at the α level of < 0.01; ns = nonsignificant; df = degrees of freedom; SS = Sum of squares; MS = mean squares

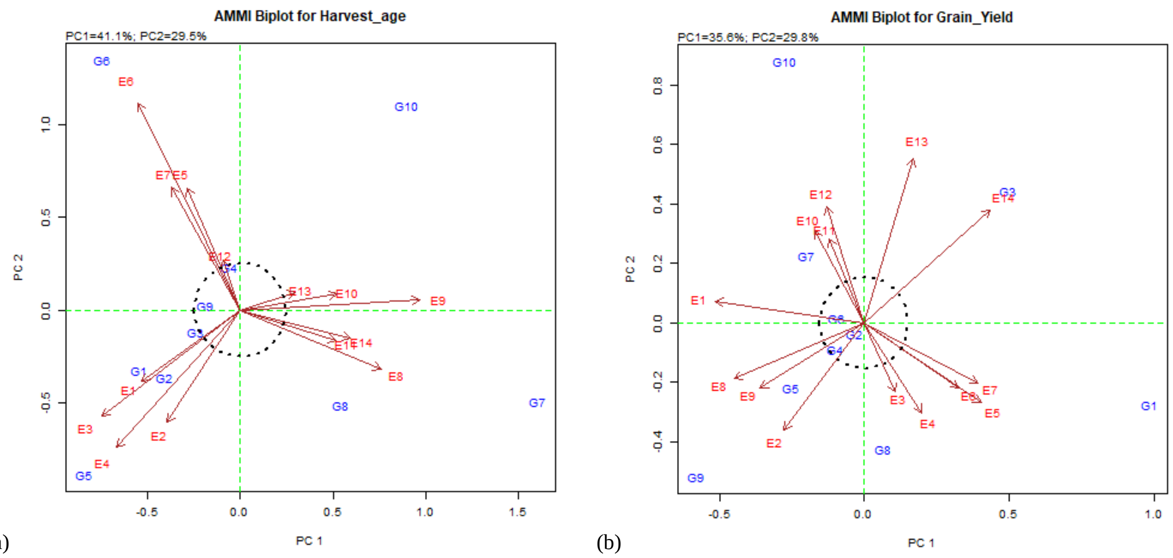
The genotype-by-environment interactions (GEI) and the stability of genotypes tested in different locations can be assessed using the AMMI analysis method [56–58]. The AMMI analysis is done when there is a significant genotype-by-environment interaction (GEI) [59]. Variance analysis by AMMI on harvest age revealed that interactions between IPCA1 and IPCA2 were highly significant (p<0.01), while IPCA3 and IPCA4 showed significant interactions (p<0.05) (Table 7). Moreover, variance analysis based on the AMMI method also revealed that the effect of GEI could be described as follows: the contributions of interaction effects for each component, from IPCA1 to IPCA4, were 41.10%, 29.50%, 12.10%, and 9.30%, respectively. According to the contribution percentages, IPCA1 and IPCA2 as components had dominant roles in describing the effect of interactions, which was 70.60%. Furthermore, the results of variance analysis based on the AMMI method for grain yield traits revealed that interactions between IPCA1, IPCA2, and IPCA3 were highly significant (p<0.01), while IPCA 4 and IPCA5 showed significant interactions (p<0.05) (Table 8). The contributions of GEI effects for each component, from IPCA1 to IPCA5, were 35.60%, 29.80%, 22.70%, 4.90%, and 3.00%, respectively. Components IPCA1 and IPCA2 had dominant roles in describing the interaction effects, which were 65.40%.

Table 8. AMMI analysis of variance (ANOVA) for grain yield

Source of variance	df	SS	MS	F-Value	% Variance explained	Accumulation
Block	2	5.99	2.99	364.24**	2.32	-
Genotype (G)	9	153.59	17.07	2077.13**	59.48	-
Location (E)	13	70.29	5.41	658.10**	27.22	-
GxE	117	26.06	0.22	27.11**	10.09	-
IPCA 1	21	6.19	0.29	26.83**	35.60	35.60
IPCA 2	19	5.18	0.27	32.93**	29.80	65.40
IPCA 3	17	3.94	0.23	28.05**	22.70	88.10
IPCA 4	15	0.86	0.06	7.32*	4.90	93.00
IPCA 5	13	0.51	0.04	4.88*	3.00	96.00
IPCA 6	11	0.27	0.02	3.01^{ns}	1.60	97.60
IPCA 7	9	0.18	0.02	2.46^{ns}	1.10	98.70
IPCA 8	7	0.16	0.02	2.70^{ns}	0.90	99.60
IPCA 9	5	0.08	0.02	2.07^{ns}	0.40	100.00
Error	278	2.28	0.01			
Total	419	258.21				

Note: E = Environment (location); IPCA = Interaction Principal Component Analysis; ** = significant at the α level of < 0.01; ns = nonsignificant; df = degrees of freedom; SS = Sum of squares; MS = mean squares

AMMI analysis results can be illustrated with Biplot PC1 vs. PC2 (Figure 5). Biplot PC1 vs. PC2 describes genotypes that are stable when grown in all trial environments as well as specific environments. Genotypes that are close to the environment line showed that genotypes could grow well in those environments, while genotypes that are close to the central coordinate line (0,0) describe high stability or can grow well in all tested environments. In terms of harvest age, G3, G4, and G9 (Pertiwi-x) were close to the central point, so these genotypes were grouped as genotypes that are stable and have broad adaptations (general adaptation) (Figure 5-a). G1, G2, and G5 were close to the environmental line in these research locations: E1, E2, E3, and E4. G6 was close to the environmental line in these research locations: E5, E6, E7, and E12. G10 was close to the environmental line in these research locations: E9, E10, and E13. G7 and G8 were close to the environmental line in these research locations: E8, E11, and E14. The seven genotypes, G1, G2, G5, G6, G7 (SK), G8 (ANM), and G-10 (Bisi-x), were genotypes that grew well in specific locations and had narrow adaptations (special adaptations). Moreover, regarding grain yield traits, G2, G4, and G6 were close to the central line, so those genotypes were grouped as stable genotypes with broad adaptations (general adaptation). G1 and G8 were close to the environmental line in these research locations: E3, E4, E5, E7, and E8. G3 was close to the environmental line in these research locations: E13 and E14. G7 was close to the environmental line in these research locations: E1, E10, E11, and E12. G5 and G9 were close to the environment line in E2, E8, and E9. The seven genotypes, G1, G3, G5, G7 (SK), G8 (ANM), G9 (Pertiwi-x), and G-10 (Bisi-x), were genotypes that can grow well in specific locations and have narrow adaptations (special adaptations).



(a) (b)

Figure 5. (a) Biplot of PC1 and PC2 interactions for maize harvest age, (b) Biplot of PC1 and PC2 interactions for maize grain yield

The adaptation map illustrated the average harvest age and grain yield per hectare for the ten genotypes of maize grown in 14 research locations as score functions in the IPCA1 environment (Figure 6). The lines in Figure 5 are projections of the predicted results of each genotype versus the scores of the IPCA1 environment. The sequence of environments in the IPCA1 axis reflects a greater impact of genotype-by-environment interactions (GEI). The gradient of the line reflects the adaptation pattern of a genotype in all environments. Genotypes with sharp gradient lines indicate an unstable trait in some of their growth environments [60]. For harvest age traits, G3, G4, and G9 had low gradient lines, so it can be concluded that these three genotypes had stable harvest ages in all research locations (Figure 6-a). Moreover, observations on grain yield traits revealed that G2, G4, and G6 were stable genotypes due to their low gradient lines (Figure 6-b).

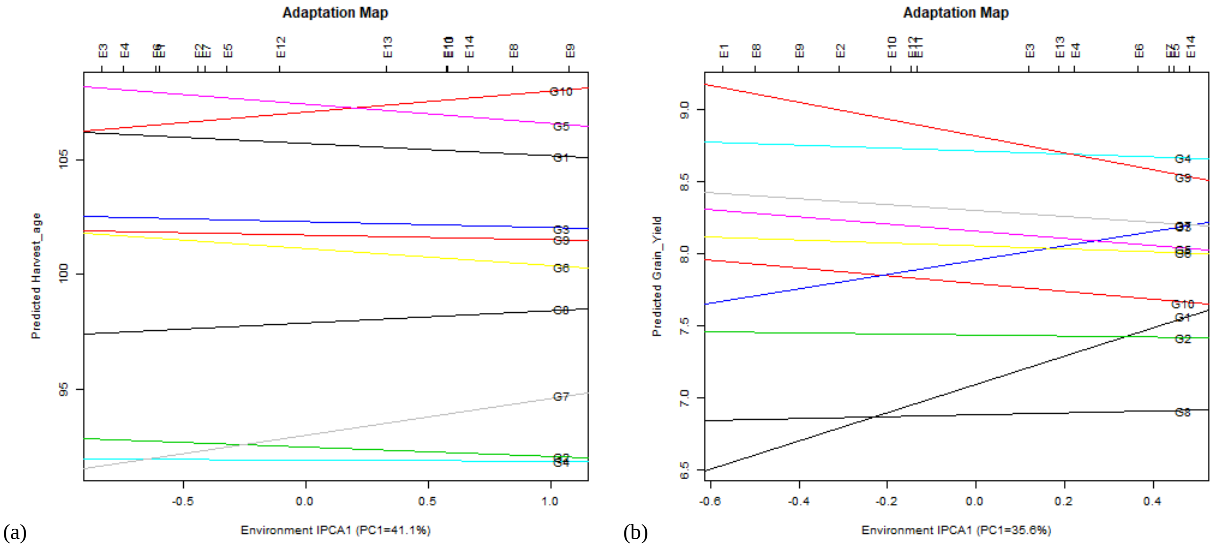


Figure 6. Adaptation maps for (a) harvest age, and (b) grain yield per hectare

3.4. Stability Criterion of Genotypes based on the Three Stability Analysis Methods

Stability analysis based on Finlay-Wilkinson and Eberhart-Russell methods effectively described the genotype's responses in various environments [61–63]. However, these two methods were unable to explain the overall impact of various locations and seasons on plant yields [53]. The two analysis methods can be used as early screening to select genotypes with desired traits. Then, genotypes with broad adaptability or specific locations can be identified using the AMMI analysis method [64–67].

G2, G4, and G6 were considered stable by the three stability analysis methods: Finlay-Wilkinson, Eberhart-Russell, and AMMI for harvest age and grain yield per hectare traits (Tables 9 and 10). The determination of the genotypes to be released into varieties in this study was based on the harvest age, production, and stability of the genotypes tested. This study aims to obtain genotypes that have early-maturing, high-yield, and stable traits at several test locations. Early-maturing maize can be divided into two categories: extra-early maturing (80–85 days) and early-maturing (90–95 days) [46]. G2 had a value of early-maturing (92.50 days) but had an average seed yield below the average yield of all genotypes at all test locations (7.44 tons ha^{-1}). G6 had an average seed yield that exceeded the average grain yield of all genotypes in all test environments (8.05 tons ha^{-1}) but had a harvest age of more than 95 days (101.14 days). G4 can be recommended as a superior hybrid maize variety with early-maturing (91.93 days), high-yield (8.71 tons ha^{-1}), stability, and wide adaptation traits at 14 test locations.

Table 9. Stability of harvest age of 10 maize genotypes in 14 locations

Genotypes	Harvest age (days)	Finlay-Wilkinson	Eberhart-Russell	AMMI
G1	105.71	Average stability	Stable	Specific
G2	92.50	Average stability	Stable	Specific
G3	102.29	Average stability	Unstable	Stable
G4	91.93	Average stability	Stable	Stable
G5	107.43	Average stability	Stable	Specific
G6	101.14	Above-average stability	Stable	Specific
G7	93.02	Average stability	Stable	Specific
G8	97.90	Average stability	Stable	Specific
G9	101.71	Average stability	Stable	Stable
G10	107.07	Average stability	Stable	Specific
Mean	100.07			

Table 10. Stability of grain yield of 10 maize genotypes at 14 locations

Genotypes	Grain Yield (ton ha^{-1}) = Y_i	Finlay-Wilkinson	Eberhart-Russel	AMMI
G1	7.10	Below-average stability	Unstable	Specific
G2	7.44	Average stability	Stable	Stable
G3	7.95	Below-average stability	Stable	Specific
G4	8.71	Average stability	Stable	Stable
G5	8.15	Above-average stability	Stable	Specific
G6	8.05	Average stability	Stable	Stable
G7	8.30	Average stability	Stable	Specific
G8	6.88	Average stability	Unstable	Specific
G9	8.82	Above-average stability	Stable	Specific
G10	7.79	Below-average stability	Unstable	Specific
Mean	7.92			

4. Conclusion

Testing six hybrid maize candidates at 14 testing locations is useful for determining the stability, specific adaptation, and broad adaptation of the genotype being tested. The results of the combined analysis of variance on harvest age and grain yield traits of 10 genotypes in 14 research environments (seven locations, two seasons) revealed genotype factor, environment (season, location, season x location), and interactions (genotype x season, genotype x location, genotype x season x location) had significant effects ($p < 0.01$). Genotype-by-environment interaction (GEI) is highly significant, which causes failure of the tested genotypes to show relatively the same diversity in different environments. G2, G4, and G6 were considered stable by the three stability analysis methods: Finlay-Wilkinson, Eberhart-Russell, and AMMI for harvest age and grain yield per hectare traits. The determination of genotypes to be released into varieties in this study was based on harvest age, production, and the stability of the genotypes tested. G2 had a value of early-maturing (92.50 days) but had an average seed yield below the average yield of all genotypes at all test locations (7.44 tons ha^{-1}). G6 had an average seed yield that exceeded the average grain yield of all genotypes in all test environments (8.05 tons ha^{-1}) but had a harvest age of more than 95 days (101.14 days). G4 had early-maturing traits (91.93 days), grain yield per hectare above the average of all genotypes in all research environments (8.71 ton ha^{-1}), and was considered stable by three stability analysis methods: Finlay-Wilkinson, Eberhart-Russel, and AMMI. G4 can be recommended as an elite hybrid maize variety with early-maturing, high-yield, stable, and highly broad adaptability traits.

5. Declarations

5.1. Author Contributions

Conceptualization, A.A. and S.; methodology, A.A.; software, A.M. and I.S.; validation, A.A.; formal analysis, A.A.; investigation, G.P. and S.; resources, A.A.; data curation, A.A.; writing—original draft preparation, A.A., S., and G.P; writing—review and editing, A.M. and I.S.; visualization, S.; supervision, A.A. and G.P.; project administration, S.; funding acquisition, A.A. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

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5.5. Declaration of Competing Interest

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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