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Influence of Genotype × Environment Interaction on Yield Stability of Maize Hybrids with AMMI Model and GGE Biplot

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Abstract: Maize yields perform differently in different environments, so the selection of suitable genotypes in diverse environments is essential for variety selection to enable better site-specific planting. Hence, the objective of the study was to estimate the productivity of 11 maize hybrids (G) in 10 different environments (E) and select high-yield and stable varieties for adaptive cultivation in 2022 and 2023. The combined analysis of variance showed that G (4%), E (50%), and their interaction (31%) had a significant effect ($p < 0.01$) on maize yield, with E factors contributing the most. In addition, the average yield ranged from 9398 kg/ha to 10,574 kg/ha, and ZF-2208 and DY-519 performed relatively well in both years. The AMMI model showed that the varieties DY-213, DY-605, and DY-519 had high and stable production in 2022, whereas it was ZF-2209 and LX-24 in 2023. The "W-W-W" biplot showed that DY-519 and JG-18 were the optimal varieties in 2022, and ZF-2208 and ZF-2210 were optimal in 2023. The "mean vs. stability" biplot indicated that JG-18, DY-605, and DY-213 (in 2022) and ZF-2208, LX-24, and ZF-2209 (in 2023) were the optimal varieties. Additionally, both the discrimination and representative biplot and the ranking biplot reflected that BinChuan and ShiDian (in 2022) and GengMa and YongSheng (in 2023) were the ideal test environments. In conclusion, DY-519, DY-605, ZF-2208, and LX-24 hybrids could be used for variety promotion. Moreover, BinChuan, ShiDian, GengMa, and YongSheng were the ideal test environments for selecting varieties. Therefore, the AMMI model and GGE biplot can be used to complement each other for a comprehensive evaluation of maize yield. In this way, excellent maize hybrids with high yield and stability can be selected, which could promote the selection and popularization of varieties and shorten the breeding process.

Keywords: maize hybrid; yield; AMMI; GGE biplot; G × E interaction

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1. Introduction

Maize (*Zea mays* L.) is the most crucial cereal globally, providing 42% of the world's human food calorie consumption. Stable production ensures global food security [1]. By 2050, global food production will increase by 60% or even double to meet people's food needs. Maize is a major food crop in China, using 21% of the world's maize area and producing 260 million tons, which is 23% of the world's supply. However, with temperatures increasing, most areas are experiencing significant yield losses [2]. Food security remains critical as the population grows, and fertilizer use in a changing climate will reduce yields by close to 20% by 2099 [3]. In order to increase production, Chang et al. and Huang et al. have predicted corn yield through a data-driven crop model and Bayesian model [4,5].

GEIs can reveal the contribution of new varieties to performance and influence breeding programs and resource allocation [6]. Crops are affected by genotype–environment interactions (GEIs), which are caused by variations in the environmental conditions [7]. In multi-site trials, often due to GEIs, variety selection is inefficient and the relative ranking of varieties varies according to the environment. So, it is necessary to analyze the interaction caused by GE effects on yield [8].

GEIs are often thought of as the differential ordering of genotypes in different environments. They can be used to predict the potential and effect of genotypes in different environments [9]. Genotypes exhibit different behaviors in different environments, and this interaction is critical for genotypes adapting to diverse environments [8]. Meanwhile, GEIs are a key issue affecting thousand kernel weight, yield, and breeding for quality traits in maize [10,11]. Currently, the AMMI model and the GGE biplot are statistical tools which are commonly used in the analysis of multi-environmental trials [8,12]. Compared to the AMMI model, the GGE biplot has a stronger regional genotype evaluation, but it is slightly lacking in breeding programmers, and it is an improved version of AMMI [13,14]. Additionally, it can combine the gene main effect with the GE interaction at the same time, so as to cluster the environments and divide the varietal eco-regions [8,15]. Moreover, this methodology combines the mean values of yield and stability and transforms them into a formula for graphical evaluation [16]. The GGE biplot can also be used for breeding-specific combining ability and general combining ability evaluation [17], disease evaluations [18], crop qualitative characteristics [19,20], and regional trial evaluations [21]. And the AMMI model GGE biplot has now been applied to cotton [21], oat [22], pigeonpea [23], cowpea [24], bambara groundnut [25], grain sorghum [26], as well as maize [27,28]. In previous studies, the yield of maize in one year was mostly analyzed by the AMMI model and GGE biplot or by a single method, and few were analyzed by combining the two methods for many years [11,29–32]. Combining the AMMI model with the GGE biplot can help us to better understand the effects of gene–environment interaction, optimal genotypes, and suitable environments on improving genotype yield [7,33].

Therefore, AMMI and the GGE biplot were used to analyze the yield of 11 maize hybrids in 10 environments across two seasons to comprehensively evaluate the productivity and stability of the participating varieties, as well as the discriminatory power and representativeness of the environment, which can guide the planting layout and the safe production of maize, and then increase social and economic benefits.

2. Materials and Methods

2.1. Environments and Hybrids

The 11 maize hybrids have been grown at 10 locations in 2 seasons (2022 and 2023). All of these 10 environments are located at mid-to-low altitudes in Yunnan, China, and the detailed information of these sites is given in Table 1.

Table 1. Basic information of the 10 test environments.

Locations	**Time**	**2022**								**2023**							
	Parameters	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Binchuan E1	TEMP (°C)	15.8	15.9	18.0	20.0	21.4	21.3	19.2	16.5	15.3	18.2	19.6	20.4	21.4	20.6	19.8	17.0
	Min (°C)	7.0	9.1	12.8	16.2	16.7	16.4	14.7	11.5	7.1	9.9	11.9	15.4	17.0	17.1	14.5	11.8
	Max (°C)	23.5	23.1	24.3	25.5	27.5	27.6	25.3	22.9	22.4	25.5	26.6	26.6	27.4	26.0	26.9	23.5
	PRCP (mm)	0.2	1.1	3.4	4.2	3.9	4.3	3.3	2.1	0.3	0.7	2.5	9.7	3.9	9.8	6.8	4.0
	RH (%)	47.7	63.8	72.5	76.3	73.7	74.9	78.0	77.3	42.8	43.8	52.8	72.4	73.3	82.0	74.6	73.0
Gejiu E2	TEMP (°C)	20.3	19.9	21.2	23.2	24.6	23.8	21.9	19.6	18.8	23.6	24.9	25.0	24.7	23.5	23.1	20.9
	Min (°C)	14.8	14.6	17.3	19.8	20.4	19.9	18.1	15.5	13.4	17.6	19.7	20.8	20.8	20.4	19.6	17.0
	Max (°C)	27.2	26.2	27.2	28.4	31.0	30.0	27.6	25.1	26.3	30.8	31.4	31.5	30.5	29.1	28.7	26.7
	PRCP (mm)	0.9	0.9	2.1	4.7	1.9	3.8	2.4	0.4	0.7	0.4	0.9	2.7	3.6	6.0	1.1	1.1
	RH (%)	61.8	62.2	70.3	73.1	69.6	73.5	74.7	70.1	62.4	51.4	57.7	66.6	70.5	79.7	72.1	73.4
Gengma E3	TEMP (°C)	20.8	20.5	22.5	22.9	24.8	24.1	23.3	21.4	19.6	23.1	24.6	24.7	24.3	23.8	24.0	21.3
	Min (°C)	11.9	14.3	18.1	20.1	20.2	20.3	19.2	16.8	11.9	15.3	17.6	20.7	20.7	21.1	19.7	17.1
	Max (°C)	30.0	29.5	29.0	28.4	32.3	31.2	30.7	28.2	28.3	32.1	32.2	32.2	30.6	29.6	31.4	28.4
	PRCP (mm)	1.0	1.8	3.4	8.1	3.0	6.9	5.6	3.0	1.0	0.6	3.7	5.4	5.4	7.5	5.0	1.6
	RH (%)	51.2	65.7	74.7	84.9	76.0	81.5	78.7	78.0	50.9	45.7	56.3	74.9	80.0	86.2	77.9	80.6
Guangnan E4	TEMP (°C)	19.1	18.6	19.2	23.9	24.9	23.8	21.4	18.3	17.1	22.2	24.2	23.8	25.3	23.5	22.3	19.3
	Min (°C)	12.5	12.3	15.6	19.9	20.6	19.7	17.5	14.2	11.5	15.7	18.6	19.7	20.8	20.1	18.5	14.7
	Max (°C)	27.3	25.9	25.2	29.1	31.7	30.4	27.1	23.3	24.2	30.4	31.5	30.4	31.3	29.1	28.0	25.5
	PRCP (mm)	1.1	2.0	13.4	1.8	1.6	4.5	3.6	2.0	0.6	0.2	1.2	3.5	5.4	8.8	2.3	1.5
	RH (%)	64.3	64.9	78.9	71.3	69.6	75.8	77.9	74.5	66.5	57.0	61.6	69.5	69.0	79.8	76.3	75.7
Jingdong E5	TEMP (°C)	21.2	21.9	23.6	23.6	25.3	24.6	23.9	22.2	20.0	23.9	24.6	24.9	24.9	24.1	24.4	22.9
	Min (°C)	13.3	15.2	19.6	20.9	21.1	21.2	19.8	17.9	12.2	15.2	18.3	21.2	21.4	21.5	20.4	19.1
	Max (°C)	30.7	30.3	30.2	28.7	31.8	31.1	30.3	28.4	29.3	33.3	32.4	31.2	30.9	29.3	30.9	29.1
	PRCP (mm)	1.1	2.1	7.3	10.4	5.0	6.0	7.7	3.3	0.1	0.1	4.2	9.6	7.7	9.4	3.1	3.4
	RH (%)	57.7	65.5	76.6	87.0	78.5	83.0	79.8	80.5	58.2	47.5	64.7	78.8	76.3	83.3	75.2	77.0
Jinghong E6	TEMP (°C)	24.7	24.5	25.5	26.2	27.6	26.4	26.1	24.5	23.9	27.6	27.4	27.4	27.6	26.5	27.0	25.7
	Min (°C)	17.5	18.1	21.7	22.9	23.3	22.7	22.0	20.1	16.5	19.8	21.4	23.7	23.6	23.4	22.8	21.7
	Max (°C)	33.8	33.1	32.7	32.1	34.8	33.4	32.5	31.0	33.2	38.0	36.2	34.3	34.4	32.2	33.8	31.9
	PRCP (mm)	1.5	2.2	5.7	6.0	1.8	12.8	4.4	3.1	1.0	0.8	2.2	2.8	2.5	4.3	2.5	3.1
	RH (%)	60.3	64.3	75.9	80.2	73.0	78.9	76.4	74.1	55.9	44.8	62.2	75.3	74.2	82.3	74.8	76.2
Mile E7	TEMP (°C)	17.1	16.5	17.7	21.0	22.0	21.9	19.6	16.6	16.0	20.4	22.2	21.8	22.5	21.6	20.4	17.4
	Min (°C)	9.4	9.3	13.8	17.4	17.3	17.9	15.7	12.4	8.9	12.3	15.6	17.7	18.1	18.0	15.4	12.9
	Max (°C)	25.3	24.2	23.7	26.2	28.8	28.2	25.4	22.1	24.2	29.6	29.8	29.0	28.2	27.2	26.5	23.6
	PRCP (mm)	1.6	1.7	7.3	4.5	5.0	3.4	10.0	0.6	0.4	0.1	0.3	7.6	1.8	6.5	0.9	3.0
	RH (%)	62.1	66.4	80.7	78.1	78.2	79.3	80.3	78.4	61.0	49.3	58.1	71.5	73.4	81.5	74.5	78.7

Table 1. *Cont.*

Locations	Time	2022								2023							
	Parameters	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Shidian E8	TEMP (°C)	16.2	17.0	19.2	21.0	22.1	22.4	21.0	18.8	15.2	18.5	20.0	21.7	22.0	21.8	21.5	18.6
	Min (°C)	7.1	10.5	14.7	18.4	17.9	18.1	16.8	13.8	6.6	10.0	12.7	17.6	18.4	18.8	16.4	13.4
	Max (°C)	25.0	24.3	25.5	25.7	28.5	28.8	27.3	25.4	23.6	26.9	27.4	27.7	27.1	27.1	28.3	25.4
	PRCP (mm)	0.6	2.7	3.1	2.5	5.8	3.7	2.3	2.5	0.8	0.6	2.3	7.6	4.2	9.5	5.4	4.9
	RH (%)	53.2	67.4	73.7	75.9	76.1	75.4	75.0	74.1	49.1	47.0	56.9	71.0	73.1	78.8	71.0	70.4
Yongsheng E9	TEMP (°C)	14.7	13.7	16.6	18.6	19.6	19.2	17.0	14.0	12.7	16.5	18.4	19.0	20.0	18.6	17.8	14.6
	Min (°C)	7.0	7.4	11.1	14.7	14.7	14.8	13.6	8.8	6.2	10.5	12.2	14.3	15.0	15.0	12.5	8.9
	Max (°C)	22.2	21.1	23.0	24.2	26.0	26.0	22.5	20.8	20.1	23.4	25.4	25.2	26.1	24.3	24.4	21.4
	PRCP (mm)	0.0	1.2	2.4	8.9	5.3	3.8	4.7	1.2	0.1	0.0	1.0	5.7	3.9	9.6	2.6	2.2
	RH (%)	33.3	56.0	67.4	73.5	72.9	77.2	82.4	77.1	39.1	36.9	43.3	67.4	71.2	84.0	77.1	71.0
Zhenyuan E10	TEMP (°C)	24.6	24.8	26.6	28.3	30.2	29.2	27.4	24.7	24.2	29.1	30.9	30.2	29.3	28.8	28.5	26.4
	Min (°C)	18.3	18.8	21.9	24.2	24.8	24.4	22.6	20.1	17.9	21.7	24.3	25.1	24.5	24.7	23.8	22.1
	Max (°C)	33.1	32.1	33.3	34.2	37.5	36.5	34.0	30.7	32.2	38.3	38.0	37.2	35.9	35.1	35.1	32.7
	PRCP (mm)	2.5	3.1	5.1	2.7	3.3	3.1	6.0	1.1	0.7	0.3	2.2	8.0	4.4	3.2	0.4	0.8
	RH (%)	59.6	60.2	65.2	69.5	61.8	66.8	68.1	65.8	52.6	42.6	48.2	62.9	69.8	75.4	65.8	66.6

Note: TEMP is temperature; Min is minimum temperature; Max is maximum temperature; PRCP is precipitation; RH is relative humidity.

The experimental materials were ZF-2208 (G1), ZF-2209 (G2), ZF-2210 (G3), DY-213 (G4), DY-605 (G5), JG-18 (G6), JG-812 (G7), DY-519 (G8), LX-24 (G9), and SS-2107 (G10), with ZD-808 (G11) as a control. G1, G2, and G3 have high ear height, resistance, and quality; G4 is neat and has a good yield; G5 is neat and has good resistance; G6 and G7 have high plant height, ear height, and resistance; and G8, G9, and G10 have high plant height, ear height, resistance, and yield. The detailed information of 11 hybrids is shown in Table 2.

Table 2. The detailed information of 11 maize hybrids.

Hybrids	Code	Parental	Source
ZF-2208	G1	DF-2 × ZF739	Yunnan Zu Feng Seed Industry Co., Ltd., Dali, China
ZF-2209	G2	ZF2749 × ZF895	Yunnan Zu Feng Seed Industry Co., Ltd., Dali, China
ZF-2210	G3	DF-2 × ZF824	Yunnan Zu Feng Seed Industry Co., Ltd., Dali, China
DY-213	G4	DY2071 × 3279	Yunnan Di Yu Seed Industry Co., Ltd., Qujing, China
DY-605	G5	DY1237 × 108B	Yunnan Di Yu Seed Industry Co., Ltd., Qujing, China
JG-18	G6	LX1849 × LX28	Mile Jin Gu Seed Industry Co., Ltd., Mile, China
JG-812	G7	LX890 × LX1847	Mile Jin Gu Seed Industry Co., Ltd., Mile, China
DY-519	G8	LX1849 × S5392	Yunnan Nong Zhi Ben Seed Industry Co., Ltd., Kunming, China
LX-24	G9	LFCD-9 × TA-1-3	Yunnan Lin Feng Seed Industry Co., Ltd., Shilin, China
SS-2107	G10	SFCB05 × SFCB03	Yunnan Shi Feng Seed Industry Co., Ltd., Shilin, China
ZD-808	G11	Y708M × F880	Xiangyang Zheng Da Seed Industry Co., Ltd., Xiangyang, China

2.2. Experimental Design

The experiment was conducted by a randomized block design with three replications. Five rows were planted in each plot, the row spacing was 0.8 m, and the area was 20 m^2; there were 60,000 plants per ha. Field management and fertilization were implemented according to the Maize Regional Trial Scheme. Maize was sown directly, and chlorfenapyr and imidacloprid were used to control spodoptera frugiperda and aphids, respectively. The base fertilizers were $(NH_4)_2SO_4$ and K_2SO_4 (450 kg/ha), and the topdressing fertilizer was CH_4N_2O, of which the first topdressing fertilizer was 300 kg/ha and the second was 225 kg/ha. Farming was entirely and extensively dependent on natural rainfall. After the maize matured, three rows of each plot were selected for grain yield measurement, and the yield was calculated by the following formula:

$$\text{Yield}(\text{kg}/\text{ha}) = \frac{\text{plot yield}}{\text{plot area}} \times 666.7 \times 15$$

where 1 mu = 666.7 square meters and 1 ha = 15 mu.

2.3. Data Analysis

Excel was used for basic data organization and calculation. The aov () function in the R package "agricolae" version 4.3.3 was used to perform the analysis of variance (ANOVA). For multiple comparisons, the LSD test was used, an AMMI analysis was conducted using the R package "agricolae", the "GGEBiplotGUI" package (R (4.3.3)) was used for the GGE biplot [34], the "pheatmap" package (R (4.3.3)) was used for clustering heatmaps, and the "psych" (R (4.3.3)) package was used for Pearson correlation analysis. The GGE biplot and AMMI methods based on giant environmental assessment were used to draw the model diagram to visually show the existence of G × E interactions.

3. Results

3.1. Analysis of Variance (ANOVA) for Yield

The multivariate analysis of variance of 11 varieties across 10 environments showed that all factors significantly influenced the maize yield in two growing seasons (2022 and 2023). Moreover, environmental factors contributed the most, up to 49.96% (Table 3). Therefore, the further analysis of genotypes and environments is necessary.

Table 3. Combined variance analysis of maize yield under GEIs in two years.

Source of Variation	Degrees of Freedom (DFs)	Sum of Squares (SS)	Mean Squares	F-Value	Proportion of SS (%)
year	1	65,040,000	65,041,806	157.37 **	2.85%
gen	10	88,230,000	8,822,693	21.35 **	3.87%
env	9	1,140,000,000	126,721,432	306.61 **	49.96%
Year: gen	10	38,100,000	3,810,337	9.22 **	1.67%
Year: env	9	579,900,000	64,438,849	155.91 **	25.41%
Gen: env	90	93,220,000	1,035,793	2.51 **	4.09%
Year: gen: env	90	95,530,000	1,061,453	2.57 **	4.19%
Residuals	440	181,900,000	413,301		7.97%

Note: ** highly significant at $p \leq 0.01$.

3.2. Maize Yield Performance in Different Locations

The mean yield of 11 maize hybrids under 10 locations was assessed (Figures 1 and 2, Tables 4 and 5). The results showed that, in terms of the environment, whether it was in 2022, 2023, or over the two years, these locations (E4, E1, E8, E9, and E3) had higher maize yields (Tables 4 and 5). For the varieties, the yield ranged from 9398 kg/ha to 11,194 kg/ha, where G8, G6, G4, G5, and G9 were the five most productive varieties in 2022, while G1 performed the best, followed by G3, G9, G2, and G8 in 2023 (Table 5). Moreover, the two years of data showed that G8, G1, G6, G9, and G5 were the top five performers, which was in great agreement with the yield results of the two years alone (Table 4). Moreover, the 10 tested hybrids had higher average yields than the control (Figure 1, Table 4). In order to reflect the yield fluctuation more clearly, a clustering heat map of the yield was made (Figure 2). All these results showed that G8, G1, G9, G6, and G5 were more productive, and E4, E8, E3, E1, and E9 were suitable for breeding high-yielding varieties.

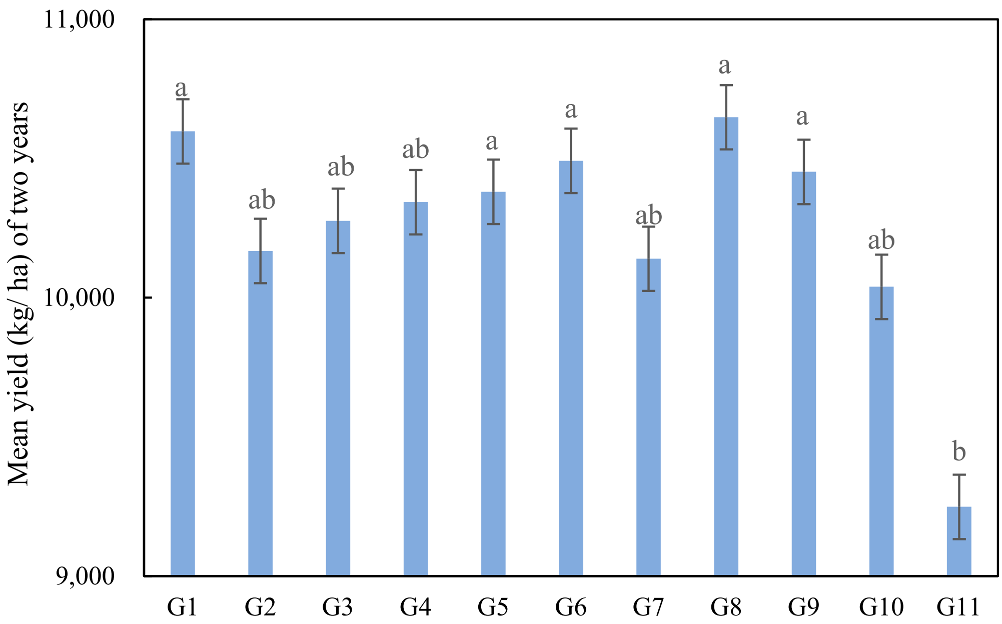

Figure 1. Mean yield (kg/ha) of 11 maize hybrids over two years. Different letters indicate significant differences ($p < 0.05$).

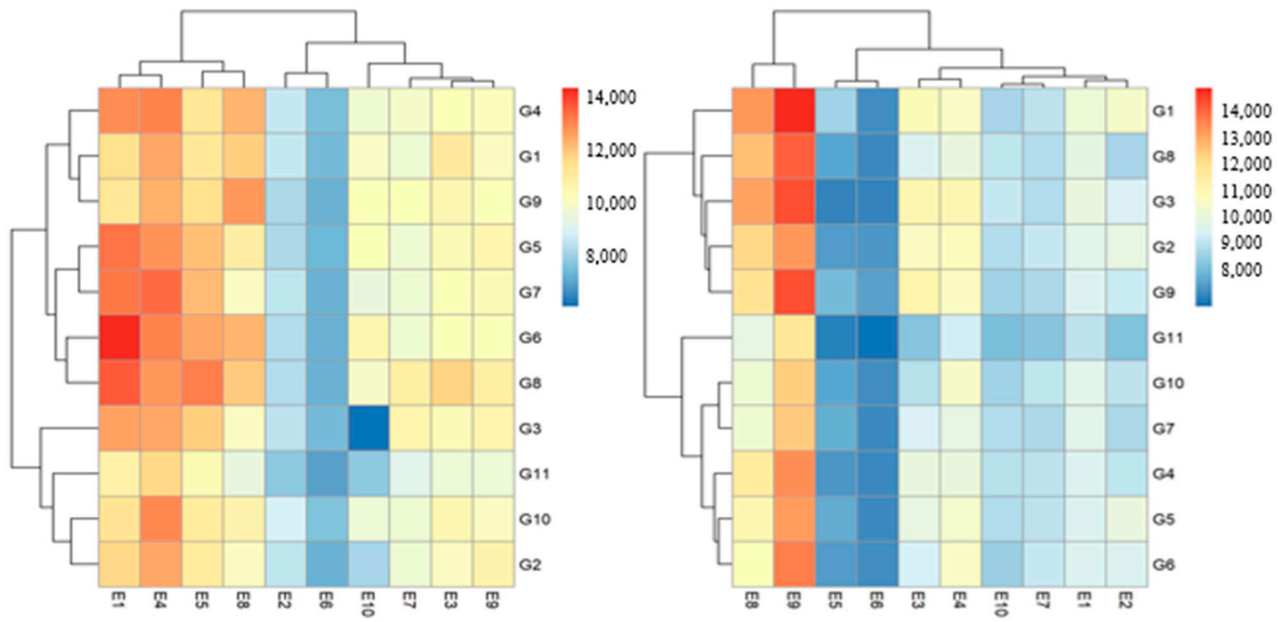

Figure 2. Clustering heat map of yield: horizontal coordinate is the hybrid, vertical coordinate is the test site, (**left**) is 2022, (**right**) is 2023. Environmental and genotypic codes are given in Tables 1 and 2.

Table 4. Average yield performance of 11 varieties in 10 sites over two years.

Hybrids	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	Mean	Rank
G1	11,017	9664	11,152	11,742	10,139	7556	9586	12,630	12,425	9581	10,549 a	2
G2	10,946	9359	10,508	11,810	9544	7594	9665	11,223	11,984	8662	10,130 ab	8
G3	11,502	9122	10,832	11,941	9767	7513	9955	11,644	12,436	7768	10,248 ab	7
G4	11,469	9025	10,331	11,812	9645	7567	9700	12,055	11,790	9567	10,296 ab	6
G5	11,693	9262	10,339	11,824	10,216	7490	9570	11,154	11,951	9806	10,331 a	5
G6	12,263	9100	10,059	12,005	10,319	7533	9663	11,707	11,959	9797	10,441 a	3
G7	11,730	8826	10,091	11,896	10,267	7443	9480	10,360	11,454	9393	10,094 ab	9
G8	11,992	8674	10,876	11,619	10,720	7469	10,079	12,381	12,440	9751	10,600 a	1
G9	10,675	8880	10,947	11,675	10,079	7642	9756	12,431	12,263	9675	10,402 a	4
G10	10,756	9118	9982	11,968	9599	7650	9579	10,644	11,299	9332	9993 ab	10
G11	10,122	8201	9180	10,738	9003	7067	8983	9861	10,795	8167	9212 b	11
mean	11,288 ab	9021 d	10,391 bc	11,730 a	9936 cd	7502 e	9638 cd	11,463 ab	11,891 a	9227 cd		
rank	4	9	5	2	6	10	7	3	1	8		

Note: Different letters indicate significant differences ($p < 0.05$).

The correlation analysis of yield and other traits showed (Figure 3) that yield and hundred seed weight had a highly significant positive correlation; hundred seed weight and plant height had a significant positive correlation in 2022; yield and ear tip were significantly negatively correlated; and ear tip and kernel ratio were significantly negatively correlated in 2023.

Table 5. Average yield performance of 11 hybrids across 10 sites in 2022 and2023.

Locations/ Hybrids	Year	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11
E1	2022	11,636 ± 220	11,865 ± 292	12,781 ± 403	13,105 ± 288	13,559 ± 139	14,653 ± 695	13,447 ± 669	13,908 ± 549	11,455 ± 554	11,520 ± 179	10,896 ± 108
	2023	10,397 ± 828	10,028 ± 492	10,222 ± 142	9833 ± 297	9828 ± 305	9873 ± 227	10,013 ± 406	10,075 ± 453	9894 ± 1469	9993 ± 312	9349 ± 87
E2	2022	8678 ± 300	8531 ± 103	8478 ± 596	8631 ± 217	8194 ± 314	8314 ± 547	8550 ± 177	8281 ± 449	8217 ± 332	8911 ± 230	7772 ± 162
	2023	10,650 ± 1611	10,188 ± 1448	9766 ± 452	9419 ± 211	10,330 ± 1250	9885 ± 798	9102 ± 473	9068 ± 505	9544 ± 428	9324 ± 845	8629 ± 399
E3	2022	11,244 ± 261	10,214 ± 79	10,444 ± 258	10,350 ± 238	10,489 ± 470	10,372 ± 162	10,403 ± 91	11,908 ± 524	10,639 ± 239	10,667 ± 312	9692 ± 198
	2023	11,060 ± 735	10,801 ± 701	11,219 ± 745	10,312 ± 673	10,189 ± 672	9745 ± 647	9779 ± 632	9844 ± 655	11,256 ± 737	9297 ± 599	8669 ± 301
E4	2022	12,751 ± 268	12,713 ± 201	12,691 ± 90	13,332 ± 390	13,024 ± 201	13,285 ± 317	13,643 ± 429	13,003 ± 272	12,501 ± 122	13,221 ± 220	11,855 ± 241
	2023	11,060 ± 735	10,801 ± 701	11,219 ± 745	10,312 ± 673	10,189 ± 672	9745 ± 647	9779 ± 632	9844 ± 655	11,256 ± 737	9297 ± 599	8669 ± 301
E5	2022	11,329 ± 190	11,167 ± 46	11,996 ± 112	11,423 ± 1127	12,267 ± 217	12,727 ± 494	12,331 ± 154	13,385 ± 448	11,711 ± 493	11,117 ± 337	10,536 ± 220
	2023	8949 ± 438	7921 ± 320	7538 ± 791	7866 ± 247	8164 ± 376	7911 ± 117	8203 ± 207	8054 ± 707	8446 ± 432	8081 ± 236	7470 ± 324
E6	2022	7422 ± 246	7308 ± 211	7425 ± 41	7525 ± 54	7331 ± 205	7317 ± 72	7258 ± 80	7289 ± 171	7250 ± 198	7592 ± 65	6900 ± 56
	2023	7689 ± 46	7881 ± 207	7600 ± 143	7608 ± 89	7650 ± 105	7750 ± 116	7628 ± 96	7650 ± 114	8033 ± 160	7708 ± 422	7233 ± 105
E7	2022	9806 ± 703	9814 ± 67	10,689 ± 958	10,061 ± 867	9828 ± 86	9850 ± 303	9803 ± 429	10,969 ± 766	10,361 ± 863	9765 ± 55	9269 ± 363
	2023	9366 ± 290	9516 ± 463	9221 ± 388	9338 ± 1000	9313 ± 406	9477 ± 472	9157 ± 196	9188 ± 107	9152 ± 452	9394 ± 471	8696 ± 317
E8	2022	12,050 ± 512	10,242 ± 660	10,226 ± 138	12,447 ± 1026	11,084 ± 479	12,424 ± 155	10,177 ± 522	12,146 ± 221	12,933 ± 246	10,854 ± 274	9558 ± 141
	2023	13,210 ± 1189	12,204 ± 584	13,063 ± 1467	11,662 ± 621	11,223 ± 679	10,990 ± 657	10,543 ± 1209	12,617 ± 1456	11,928 ± 312	10,433 ± 471	10,165 ± 156
E9	2022	10,208 ± 205	10,778 ± 350	10,689 ± 958	10,253 ± 792	10,750 ± 767	10,375 ± 270	10,433 ± 647	10,969 ± 766	10,361 ± 863	10,225 ± 116	9706 ± 309
	2023	14,641 ± 426	13,191 ± 220	14,184 ± 131	13,328 ± 999	13,151 ± 661	13,543 ± 286	12,474 ± 201	13,911 ± 1785	14,164 ± 344	12,374 ± 513	11,883 ± 252
E10	2022	10,123 ± 261	8102 ± 332	6025 ± 140	9879 ± 502	10,386 ± 269	10,661 ± 255	9625 ± 607	10,080 ± 652	10,379 ± 172	9703 ± 138	7799 ± 163
	2023	9039 ± 505	9223 ± 957	9511 ± 176	9255 ± 674	9225 ± 360	8934 ± 576	9161 ± 498	9422 ± 120	8971 ± 770	8962 ± 163	8535 ± 251

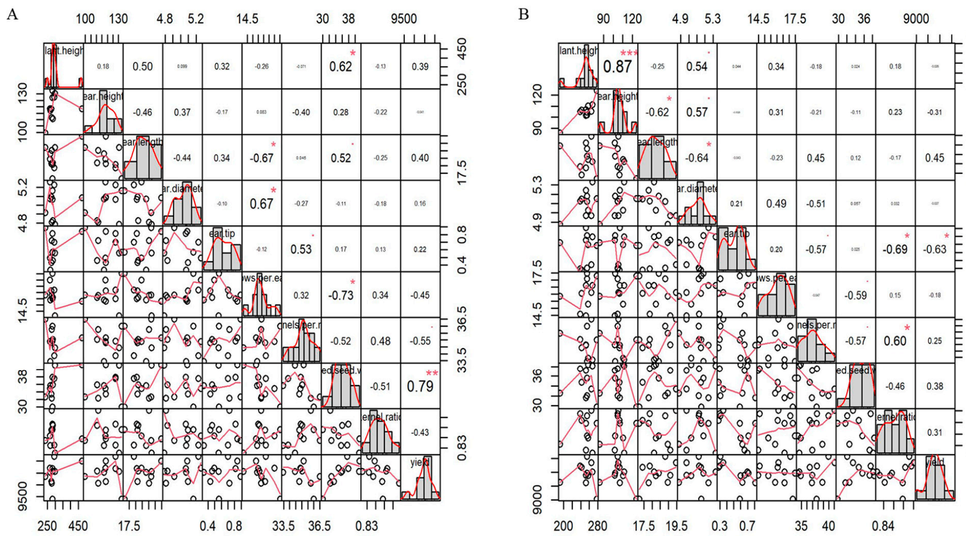

Figure 3. Description and correlation analysis of each trait. Note: (**A**), 2022; (**B**), 2023. ***, ** and * represent $p < 0.00$, $p < 0.01$ and < 0.05 in the upper panel, respectively. The lower panel shows scatter plots for each pair of traits. The distribution of each phenotype is shown along the diagonal.

3.3. AMMI Model for Analyzing Variety Yield and Stability

The AMMI biplot is shown in Figure 4, where the average yield is the x-axis and the GE decomposition of IPCA1 is the y-axis. And when the coordinate is farther to the right and closer to the x-axis, the variety yield is higher and more stable; when the environment is farther from the x-axis, the more discriminative it is. In this study, the stable varieties were G7, G10, G8, G5, and G4 in 2022 (Figure 4A), while they were G4, G2, G5, G6, and G9 in 2023 (Figure 4B). Additionally, sites E8, E9, E7, and E6 are well-discriminated environments in both 2022 and 2023 (Figure 4). Therefore, combined with the yield results, we found that G8, G4, and G5 (in 2022) and G2 and G9 (in 2023) were the ideal varieties (with both high yield and stability).

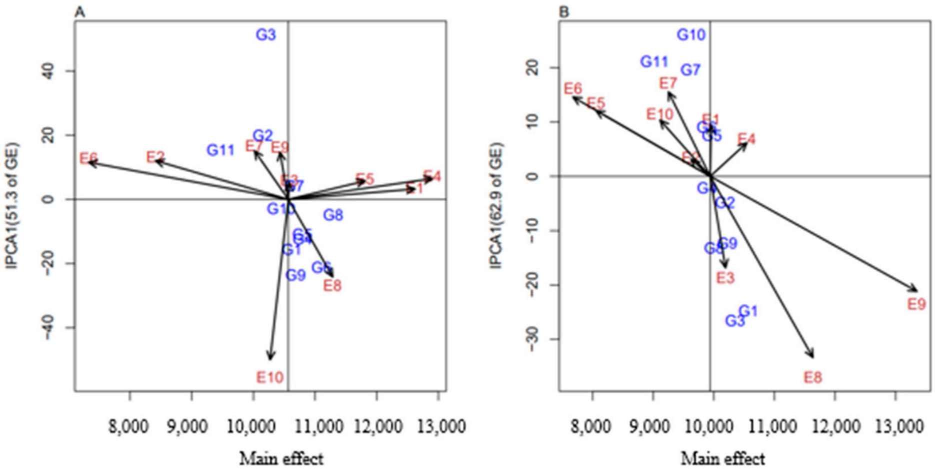

Figure 4. AMMI1 biplot. (**A**) AMMI1 biplot in 2022; (**B**) AMMI1 biplot in 2023. Environmental codes are in Table 1 and genotypic codes are given in Table 2.

The AMMI1 biplot represented only 51.3% and 62.9% of the varietal–environmental variance information, which was not sufficiently comprehensive to infer varietal stability and environmental discrimination. But, the AMMI2 biplot showed the scores of the varieties of IPCA1 and IPCA2, which can explain most of the intercropping variance (Figure 5). In the AMMI2 biplot, the closer to the origin of the coordinates, the more stable the species is, and the worse the ambient discriminatory power is, so G4 had the best performance in terms of stability, and E1 and E8 had the highest discriminatory power.

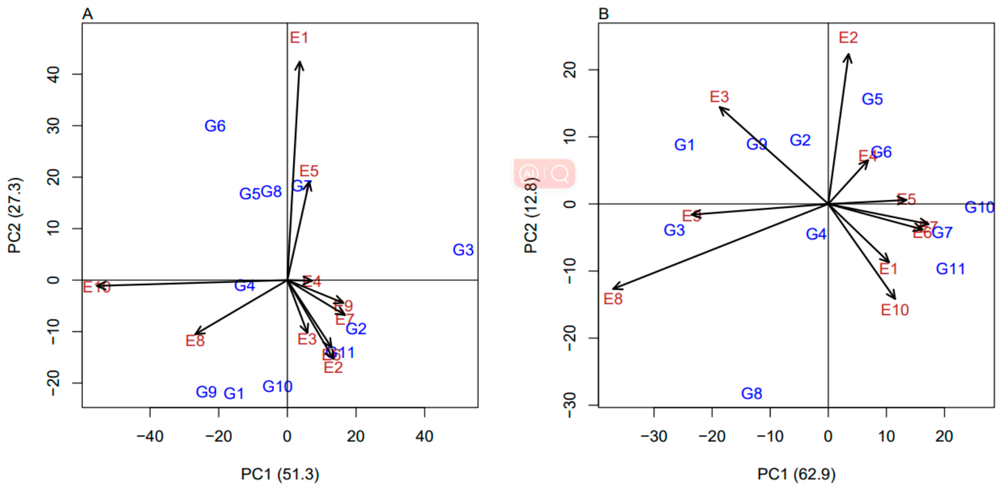

Figure 5. AMMI2 biplot. (**A**) AMMI2 biplot in 2022; (**B**) AMMI2 biplot in 2023. Environmental codes are in Table 1 and genotypic codes are given in Table 2.

3.4. GGE Biplot Analysis

The results of the GGE analysis were displayed by different biplot patterns, where the horizontal coordinate is the PC1 score and the vertical coordinate is the PC2 score, explaining 80.58% of the variance in the environment and 86.04% of the variance in the GEI, respectively.

3.4.1. "Which Won Where" Biplot

In the "which won where" GGE biplot (W-W-W), varieties in the top corners of the polygon were the most productive. Specifically, hybrids were distributed into five sections, with G8 (DY-519) and G6 (JG-18) being the best hybrids in multiple environments in 2022 (Figure 6A). Moreover, G1(ZF-2208) and G3 (ZF-2210) were the most productive in 2023 (Figure 6B). Furthermore, hybrids located at vertices exhibited greater responsiveness compared to those located within polygons. Additionally, varieties outside the polygon performed poorly in some or all of the environments.

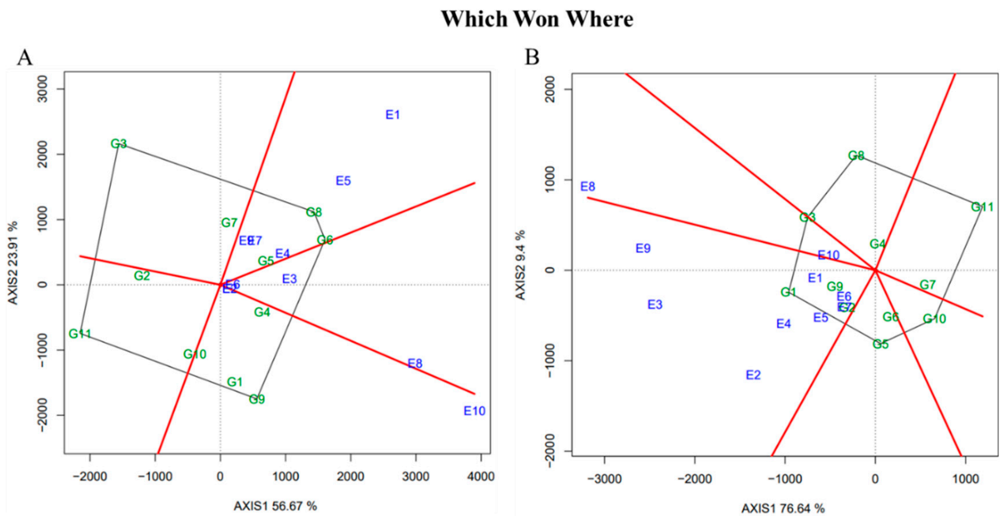

Figure 6. "Which won where" model of GGE biplot for 11 maize hybrids (G1–G11) evaluated in 10 environments. (**A**) GGE biplot in 2022; (**B**) GGE biplot in 2023. Environmental codes are in Table 1 and genotypic codes are given in Table 2.

3.4.2. "Mean vs. Stability" Biplot

The analysis of "mean vs. stability" was conducted by the GGE biplot with an average environmental correction (AEC). The shorter the vertical segment between the variety and the AEC axis, the more stable the variety is. In the study, G6, G8, G5, G4, and G9 were more productive, while G11, G5, G6, G2, and G4 and were more stable in 2022 (Figure 7A); additionally, G1, G3, G9, G2, and G8 had high yields, while G9, G11, G1, G2, and G4 were more stable in 2023 (Figure 7B). Hence, these results showed that G5 (DY-519), G6 (JG-18), and G4 (DY-213) were the best varieties with excellent yield performance and wonderful stability in 2022, while they were G1 (ZF-2208), G9 (LX-24), and G2 (ZF-2209) in 2023.

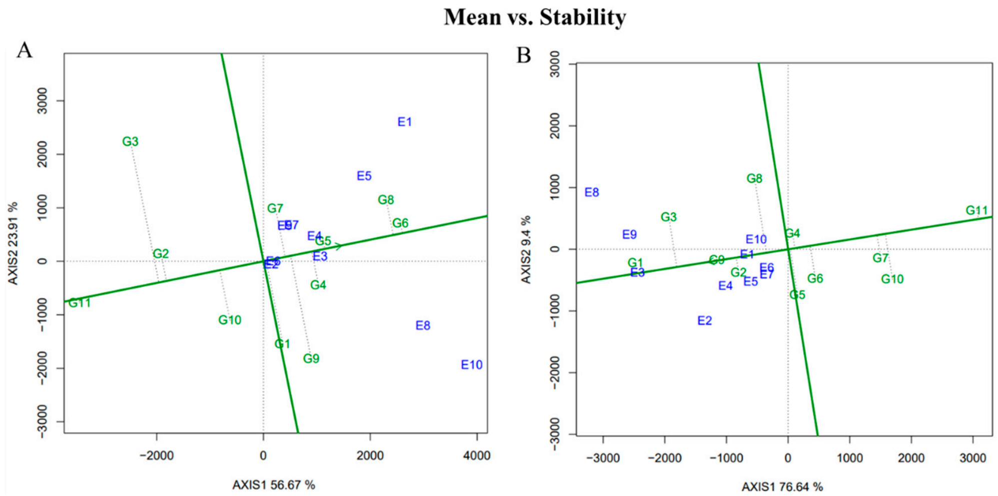

Figure 7. The productivity and stability of 11 maize hybrids were assessed in 10 environments using GGE biplot analysis. (**A**) GGE biplot in 2022; (**B**) GGE biplot in 2023. Environmental codes are in Table 1 and genotypic codes are given in Table 2.

3.4.3. "Discriminativeness vs. Representativeness" Biplot

The discriminative power and representativeness of the environment were assessed by the GGE biplot in Figure 8. A site with a long vector length and a small angle to the ACE axis can be considered as an ideal environment for variety selection. In this study, E10, E1, E8, and E5 were highly discriminative, while E6, E2, E3, and E4 were more representative in 2022 (Figure 8A); E8, E9, E3, and E2 were highly discriminative, while E3, E1, E9, and E4 were highly representative in 2023 (Figure 8B). Therefore, these results indicated that E3 (Gengma) and E9 (Yongsheng) were the best environments with good discrimination and representation in 2023.

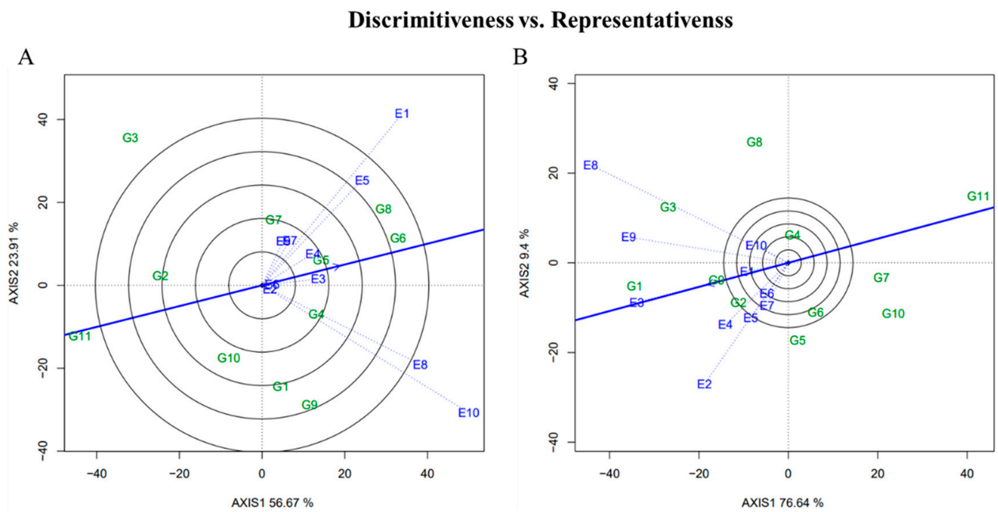

Figure 8. GGE biplot for the evaluation of the differentiating power and representativeness of 10 environments. (**A**) GGE biplot in 2022; (**B**) GGE biplot in 2023. Environmental codes are in Table 1 and genotypic codes are given in Table 2.

3.4.4. "Ranking Genotypes" and "Ranking Environments" Biplot

In the ranking GGE biplot, if the variety or site was located closer to the first concentric circle, they were considered for selection. From Figure 9, G6 and G1 were in the first concentric circle of their respective biplot; followed by G8, G5, G4, and G7 in 2022 (Figure 9A); and G3, G9, G2, and G8 in 2023 (Figure 9B). Thus, the results declared that G6, G1, G8, G3, G9, and G5 were the pretty satisfying genotypes.

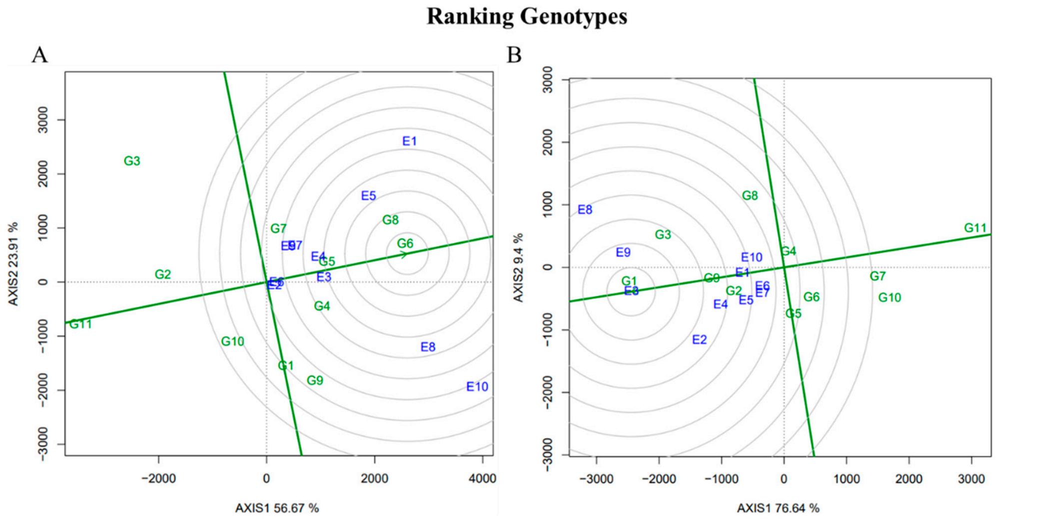

Figure 9. Ranking of genotypes by the GGE biplot. (**A**) GGE biplot in 2022; (**B**) GGE biplot in 2023. Environmental codes are in Table 1 and genotypic codes are given in Table 2.

Additionally, E1, E8, E5, and E10 in 2022 and E3, E9, E8, and E2 in 2023 could be considered as the ideal environments (Figure 10). Therefore, the above sites can be considered ideal environments for their respective years, which were more conducive to screening excellent maize hybrids. Interestingly, this result is consistent with the result found in the discriminativeness and representativeness section (Figure 8).

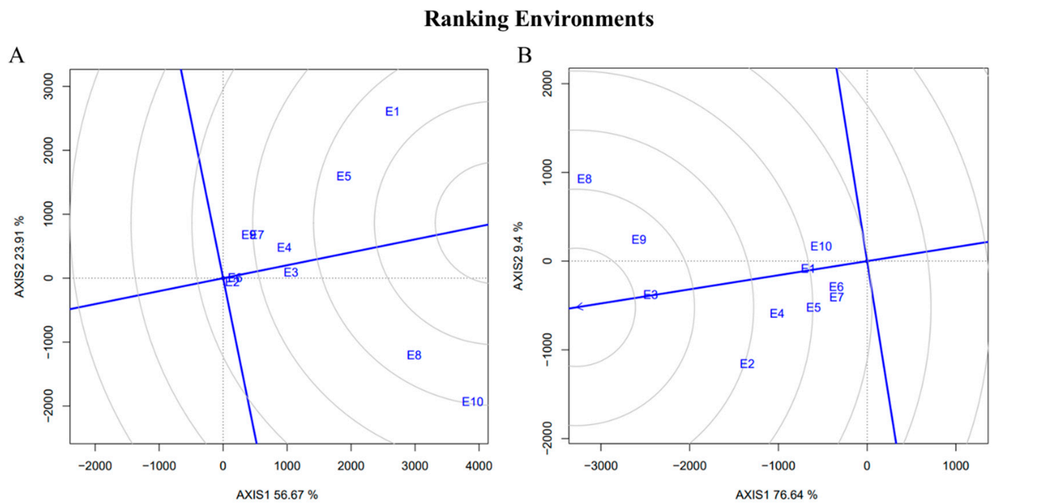

Figure 10. Ranking of environments under the GGE biplot. (**A**) GGE biplot in 2022; (**B**) GGE biplot in 2023. Refer to Table 1 for the environment codes.

4. Discussion

4.1. Yield Performance Evaluation

Genotype and environment interaction is a complex question involved in preparing high-yielding and stable genotypes for breeding [16]. In this study, the effects of environment, genotype, and GEIs on maize yield were significant ($p < 0.01$), and the environmental factor contributed more variation (49.96%) than genotypes and GEIs, reflecting that there was a greater variability in the environment (Table 3). Similar results were found in Adham et al., Alizadeh et al., and Ansarifard et al. that the environment accounted for most of the variance [16,35,36]. Additionally, the GEI effect is largely a response to environmental factors, not genotypic factors [37]; thus, the significant GEI factors demonstrated that the use of AMMI and the GGE biplot was appropriate in yield evaluation [38].

4.2. Yield and Stability of 11 Maize Hybrid Varieties

The AMMI1 biplot was mainly used to identify high-yielding varieties with stable performance potential [7,39]. Firstly, in the AMMI model, varieties G4, G5, and G8 had high yield and stability in 2022, whereas G2 and G9 had the same in 2023 (Figure 4). Secondly, the "mean vs. stability" biplot indicated that G6, G5, and G4 were the ideal varieties in 2022, while G1, G9, and G2 were the optimal varieties in 2023 (Figure 7). And the above results were consistent, which is similar to the findings of Esan et al. and Memon et al. [7,40]. In addition, G1 shows a better yield and stability in the GGE biplot but a better yield and worse stability in the AMMI model. The slight difference between the two methods may be related to the fact that GGE considered GEI in addition to G [39,41].

4.3. Evaluation of Hybrids in Mega-Environments

The GGE biplot model elucidated a substantial proportion of the variance, enabling meaningful inferences to be made. The "W-W-W" biplot can be visualized using a polygon view. To identify the optimal performance in a particular environment, Mehareb et al., Kona et al., and Silva et al. employed a similar method to divide mega-environments [42–44]. In this study, the GGE biplot was divided into five or six parts with two large environments (Figure 6), and the apex hybrid was the highest-yielding hybrid in its region. Genotypes G3 and G11 (2022) and G5, G10, G8, and G11 (2023) did not fall into sectors, meaning that these varieties performed poorly in some/all environments [15,45,46]. To improve the accuracy of the test, it is recommended to increase the test period or test environment to better evaluate the varieties [27]. And in previous studies, the GGE biplot has been used to screen ideal varieties, such as in potato [19], sweet maize [47], baby corn maize [48], and sugar beet [45]. Thus, in the study, G8 and G6 (in 2022) and G1 and G3 (in 2023) performed well in general environments.

4.4. Ideal Genotypes and Ideal Environments

Genotype assessment is only relevant in a particular environment. Ideal genotypes should have high yield and stability in that environment, and the ideal environment should be both strongly discriminating and representative [49,50]. Accordingly, in this study, G6, G8, G5, G4, and G7 were closer to the ideal genotypes in 2022, while they were G1, G3, G9, G2, and G8 in 2023; and E1, E8, E5, and E10 in 2022 and E3, E9, E8, and E2 in 2023 could be considered as the ideal environments (Figure 10), which was similar to the studies by Yousaf et al., Kona et al., and Kendal et al. [15,43,51]. Liu et al. found that GengMa was an ideal environment for selecting varieties, which agreed with this study [52]. Additionally, the results of the ranking biplot were in good accordance with the results of the yield performance (Tables 4 and 5), AMMI model (Figure 4), W-W-W biplot (Figure 6), "Mean vs. Stability" biplot (Figure 7), and "Discriminativeness vs. Representativeness" biplot (Figure 8). There were differences in yield performance between the two years due to the environmental conditions (rainfall and temperature were the main influences), and Ureta also found that rising temperatures and changes in rainfall can affect maize yields [53]. Therefore, G6, G8, G1, and G9 are the varieties with good comprehensive performance (high yield and stability), and E1, E3, E8, and E9 are perfect environments for variety breeding.

5. Conclusions

Genotypes, environments, and GEI had significant effects on maize yield, and the combined ANOVA results showed that environment contributed the most to yield. The

AMMI model showed high yield and stability for G8, G4, and G5 in 2022 and G2 and G9 in 2023. The W-W-W biplot showed the existence of optimal varieties (G8 and G6 in 2022; G1 and G3 in 2023). The mean vs. stability biplot indicated that G6, G5, and G4 (in 2022) and G1, G9, and G2 (in 2023) were the optimal varieties with relatively high yield and stability. Therefore, the G8 (DY-519), G6 (DY-605), G1 (ZF-2208), and G9 (LX-24) hybrids could be used for variety promotion. Moreover, E1 (BinChuan), E8 (ShiDian), E3 (GengMa), and E9 (YongSheng) were the perfect environments to choose varieties based on the discrimination and representative biplot and the ranking biplot. The combination of the two analyses provided a comprehensive and reliable approach for evaluating the yield and stability of maize hybrids, and the selected hybrids and environments were conducive to guiding the production in southwest China and bringing economic and social benefits.

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Conflicts of Interest: Author Chaorui Liu was employed by the company Yunnan Zu Feng Seed Industry Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The authors declare that they have no conflicts of interest.

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