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Article

Research on Regional Adaptability and Stability of Maize Varieties in Mid-to-High Altitude Areas of Yunnan Province Based on GGE Biplot Analysis

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Abstract

Identifying superior genotypes in multi-environment trials is crucial for accelerating cultivar improvement and breeding innovation. This study evaluated the yield potential of 29 maize hybrids (including the control) across 10 trial locations in mid-to-high altitude regions of Yunnan Province from two growing seasons (2023-2024), aiming to recommend high-yielding, stable, and widely adapted maize varieties. Analysis of variance indicated that genotype, environment, and their interaction all had highly significant effects ($p < 0.001$) on maize yield, with environ-mental factors accounting for the primary source of variation. Yield mean analysis identified the top-performing hybrids annually: in 2023, these were G28, G13, G22, G3, G10, G9, and G27; in 2024, they included G5, G13, G4, G2 G27, G22 and G26. The GGE biplot analysis identified E2 (Binchuan), E5 (Lijiang), E7 (Shilin), and E8 (Xuanwei) as optimal testing environments. Among elite genotypes, G22 (LS-2305), G9 (LS-2303), and G13 (YR-399) exhibited consistent high yields and stability across years, with G13 (YR-399) emerging as the most outstanding. Therefore, these findings confirm that the GGE biplot method is effective for screening high-yielding, stable varieties and identifying representative test environments, thereby providing a scientific foundation for maize breeding work in the region.

Keywords: maize; GGE biplot; G×E interaction; adaptability; stability

1. Introduction

Maize (*Zea mays* L.) originated in Central America and was introduced to Europe and other continents following Columbus's voyages in the late 15th century [1]. With an annual global planting area of about 197 million hectares, positioning it as the world's second most widely planted crop after wheat [2]. China contributes 23% of the global maize supply while accounting for 21% of the world's maize cultivation area [3]. Maize yield serves as a critical indicator of a country or region's economic performance and is closely linked to national and regional food security [4]. Given the widespread issues of cropland occupation and fragmentation[5,6], selecting suitable maize varieties and improving yield per unit area are essential for ensuring food security [7].

In multi-site trials for crop breeding, evaluating yield potential and stability plays a decisive role in assessing and promoting new varieties [8]. Variety stability primarily stems from genotype-by-environment (G × E) interaction effects[9]. However, significant G×E interaction limits single-environment variety recommendations, requiring multi-environment testing for yield stability evaluation [10-12]. Therefore, G × E analysis can effectively assess the stability and adaptability of genotypes in terms of yield and yield-related traits [13,14]. Currently, the AMMI model and the GGE biplot are widely used for investigating and interpreting G×E interaction [15-17]. The AMMI model can estimate the contributions of genotype (G), environment (E), and genotype-by-environment interaction (GEI) effects on yield [18]. Compared to the AMMI model, the GGE biplot offers superior interpretability and is specifically designed to visualize and dissect GEI patterns in multi-environment studies [19]. And it is widely considered a preferred method for analyzing large-scale environmental impacts, assessing genotypes, associating traits, and examining hybridization pattern [20,21]. The GGE biplot was employed to visualize the GEI, with the goal of identifying high-yielding varieties and selecting genotypes that exhibit both ability and adaptability to the target environments [22,23]. And the GGE biplot model has been widely used to analyze high yield and yield stability in crops, like maize, rice, oats, wheat, and sugarcane in recent years [24-30]. Hence, in large-scale environmental analyses and genotype evaluations, the GGE biplot offers advantages over the AMMI biplot [30].

Yunnan is characterized by a complex and heterogeneous ecological landscape, where diverse maize varieties have adapted to distinct regional conditions. Consequently, understanding the performance of various genotypes and their interactions with the environment is paramount for shaping future breeding initiatives. This study employed the GGE biplot to conduct a detailed analysis of multi-environment yield trials across Yunnan, with the goal of identifying representative and stable varieties as well as optimal cultivation environments. These findings will not only support the advancement and dissemination of improved maize cultivars but also serve as a valuable guide for farmers in making informed planting decisions.

2. Materials and Methods

2.1. Experimental Materials, Sites, and Design

The trial involved 29 maize genotypes (Table 1) and was conducted over two years (2023–2024) at 10 experimental sites in mid-to-high altitude regions of Yunnan Province (Table 2, Figure 1). The experiment used a randomized complete block design with three replications. Management aligned with local farmers' practices. Each 20 m² plot had alternating wide (0.9 m) and narrow (0.4 m) rows, with plant spacing at 0.25 m, giving a density of 4,105 plants per hectare. Maize was seeded in late April to early May. Fertilization included 30 kg of compound fertilizer per mu as base, mixed with 1.4 kg of phoxim for pest control, and 30 kg of urea per mu was top-dressed later.

Table 1. 29 maize varieties and their codes.

Hybrids	Code	Hybrids	Code	Hybrids	Code
ZHY-103	G1	ZF-2304	G11	LS-2304	G21
ZF-2302	G2	ZF-2305	G12	LS-2305	G22
ZF-2303	G3	YR-399	G13	JG-1356	G23
YR-17	G4	DY-801	G14	JG-1865	G24
YR-18	G5	YBY-202	G15	SS-2203	G25
DY-604	G6	SS-2201	G16	SS-2204	G26
YBY-201	G7	SS-2202	G17	SS-2205	G27
LS-2301	G8	JG-1872	G18	SS-2206	G28
LS-2303	G9	JG-1881	G19	WG-3861(CK)	G29
MS-2301	G10	MS-2302	G20		

Table 2. Ten test sites and their codes.

Location	Code	Latitude (N)	Longitude (E)	Altitude (m)
Baoshan	E1	25°09′	99°13′	1592

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Binchuan	E2	25°48′	100°35′	1430
ChuXiong	E3	25°08′	101°18′	1767
Gengma	E4	23°74′	99°62′	1340
Lijiang	E5	100°3′	26°58′	1819
Mile	E6	24°27′	103°31′	1543
Shilin	E7	24°41′	103°27′	1927
Xuanwei	E8	26°15′	104°8′	1980
Yanshan	E9	23°07′	104°34′	1490
Zhaotong	E10	27°19′	103°42′	1920

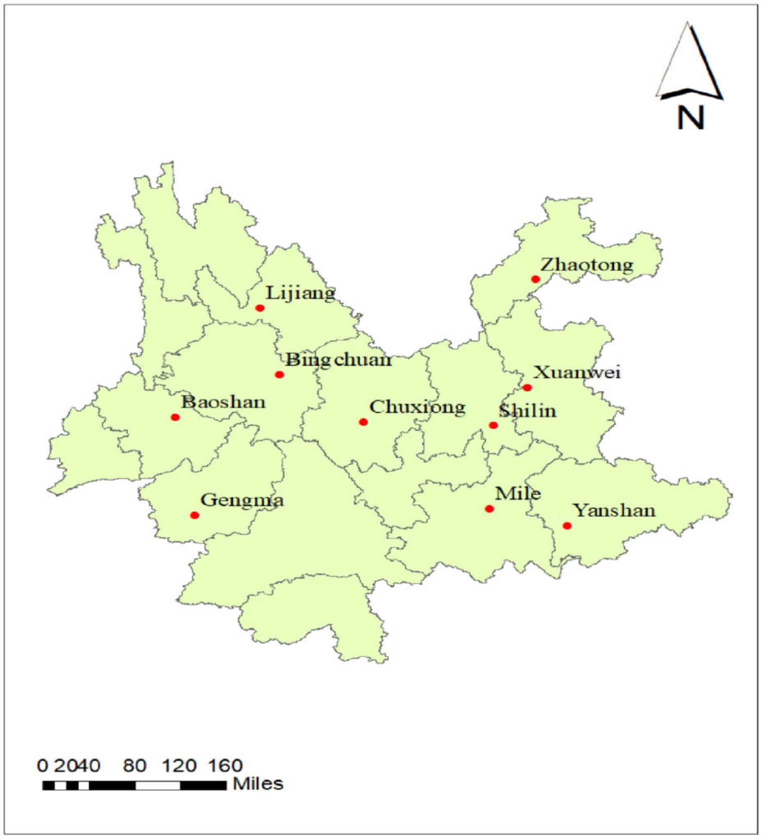

Figure 1. The location of 10 test sites in mid-to-high altitude areas of Yunnan Province.

2.2. Trait measurement

During the growing seasons of 2023 and 2024, data was collected on the yield and agronomic traits of 29 maize varieties in 10 sites. Traits included ear length, ear diameter, bald tip length, Kernels per row, hundred-kernel weight, kernel output rate, ear kernel weight, growth duration, plant height, and ear height. For plant height and ear height, healthy and disease-free plants were prioritized. Plant height was measured at the full maturity using a tape from the ground to the tassel top, while the ear height was recorded from the ground to the primary ear's node. Ear height was measured from the ground to the node where the primary ear is located. Growth duration was counted as the days from emergence to the maturity. Traits such as ear length, ear diameter, bald tip length, and kernel per row were manually measured post-examination, while the kernel output rate and yield were calculated according to the following formulas.

kernel output rate = (Grain dry weight / Fresh ear weight) × 100%; (1)

$$\text{Maize yield (kg/ha)} = (\text{Yield per unit area (kg)} / \text{Unit area (m}^2\text{)}) \times 10{,}000\ (\text{m}^2/\text{ha}) \quad (2)$$

2.3. Data Analysis

We managed data and performed descriptive statistics in Microsoft Excel. All analyses were conducted in R version 4.2.3. We utilized the *agricolae* package for ANOVA and *GGEBiplotGUI* package for GGE biplot analysis. The GGE biplot, generated via PCA, visualized genotypes (G) effected and G×E interactions based on the first two principal components [13].

3. Results

3.1. Variance Analysis (ANOVA) for Maize Yield

The combined ANOVA for 29 maize hybrids across 10 locations showed that the genotype (G), environment (E), and their interaction (GEI) had highly significant impacts ($p < 0.001$) on maize yield in both evaluation years (Tables 3 and 4). Furthermore, the trial environments explaining 63.79% and 64.15% of the total variation in 2023 and2024, respectively.

Table 3. Variance analysis for maize yield (kg/ha) in 2023.

Source of Variation	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Squares	F-Calculated	Proportion of SS (%)
Environments(E)	9	2386119	265124355.8	576.3844***	63.79
Genotypes(G)	28	4921447	17576597.05	38.2117***	13.16
G×E Interaction	252	5684386	2255708.6	4.9039***	15.2
Replication	2	2246726	22467.26	0.0488	0
Residuals	639	2939261	459978.29		7.86
Total	929	3740651			100

Note: **, $p < 0.01$; ***, $p < 0.001$.

Table 4. Variance analysis for maize yield (kg/ha) in 2024.

Source of Variation	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Squares	F-Calculated	Proportion of SS (%)
Environments(E)	9	2386119	265124355.8	576.3844***	63.79
Genotypes(G)	28	4921447	17576597.05	38.2117***	13.16
G×E Interaction	252	5684386	2255708.6	4.9039***	15.2
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Residuals	639	2939261	459978.29		7.86
Total	929	3740651			100

Note: **, $p < 0.01$; ***, $p < 0.001$.

3.2. Comprehensive Visualization of Yield Bar Chart and Yield-Environment-Cultivar Relationships Heatmap

Maize yield performance was assessed in Figure 2 and Figure 3. In 2023, the highest-yielding varieties were G28, G13, G22, G3, G10, G9 and G27 (Figure 2a), while in 2024, G5, G13, G4, G2, G27, G22 and G26 emerged as the top performers (Figure 2b). The heatmap of the two-year average yield revealed significant environmental variations in yield (Figure 3). Among the varieties, G3, G10, G2, G11, G9, G22, G27, G13 and G28 had the highest yields. Locations E5, E8, E1and E7 were identified as optimal for cultivating high-yield maize.

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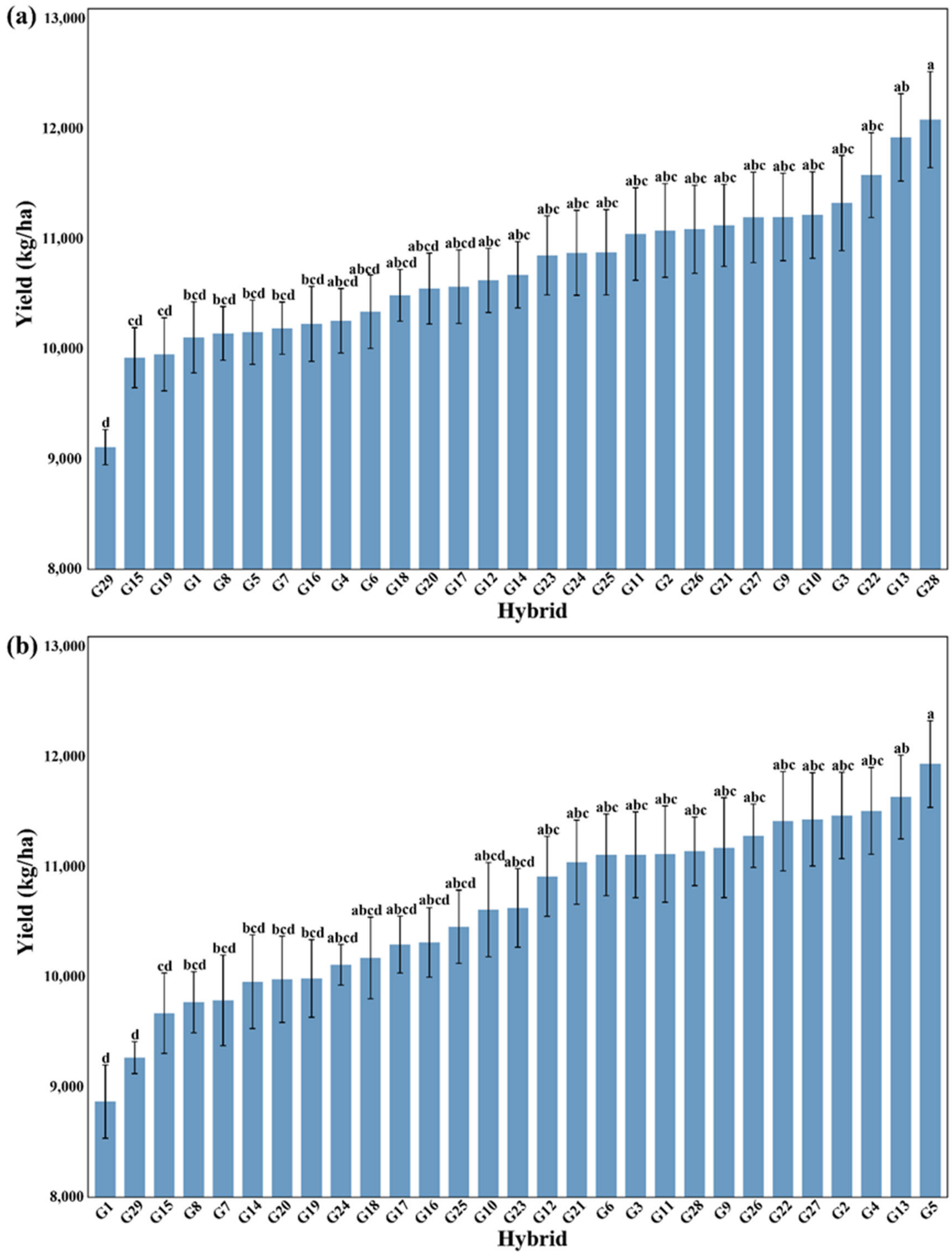

Figure 2. (a) Maize yield performance in 2023; (b) Maize yield performance in 2024.

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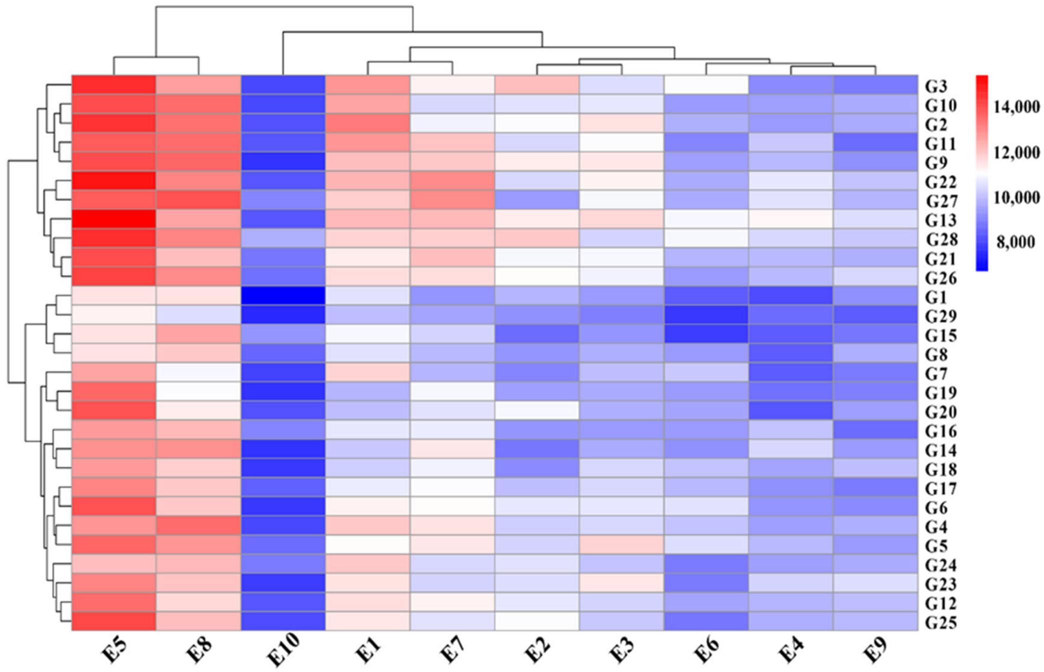

Figure 3. Heatmap of two-year average yield from 2023 to 2024.

3.3. Analysis of Correlation Between Agronomic Traits and Yield

In 2023, grain weight per ear showed a strong positive correlation with yield, and a positive correlation with plant height, while kernel output rate, growth period, and plant height exhibited weak correlations with yield (Figure 4a). In 2024, yield demonstrated weak correlations with ear diameter, hundred-kernel weight, growth duration, and plant height, whereas kernel output rate was positively correlated with ear length (Figure 4b). However, most agronomic traits generally demonstrated weak or negligible correlations with yield, suggesting that these traits may have limited direct influence on yield.

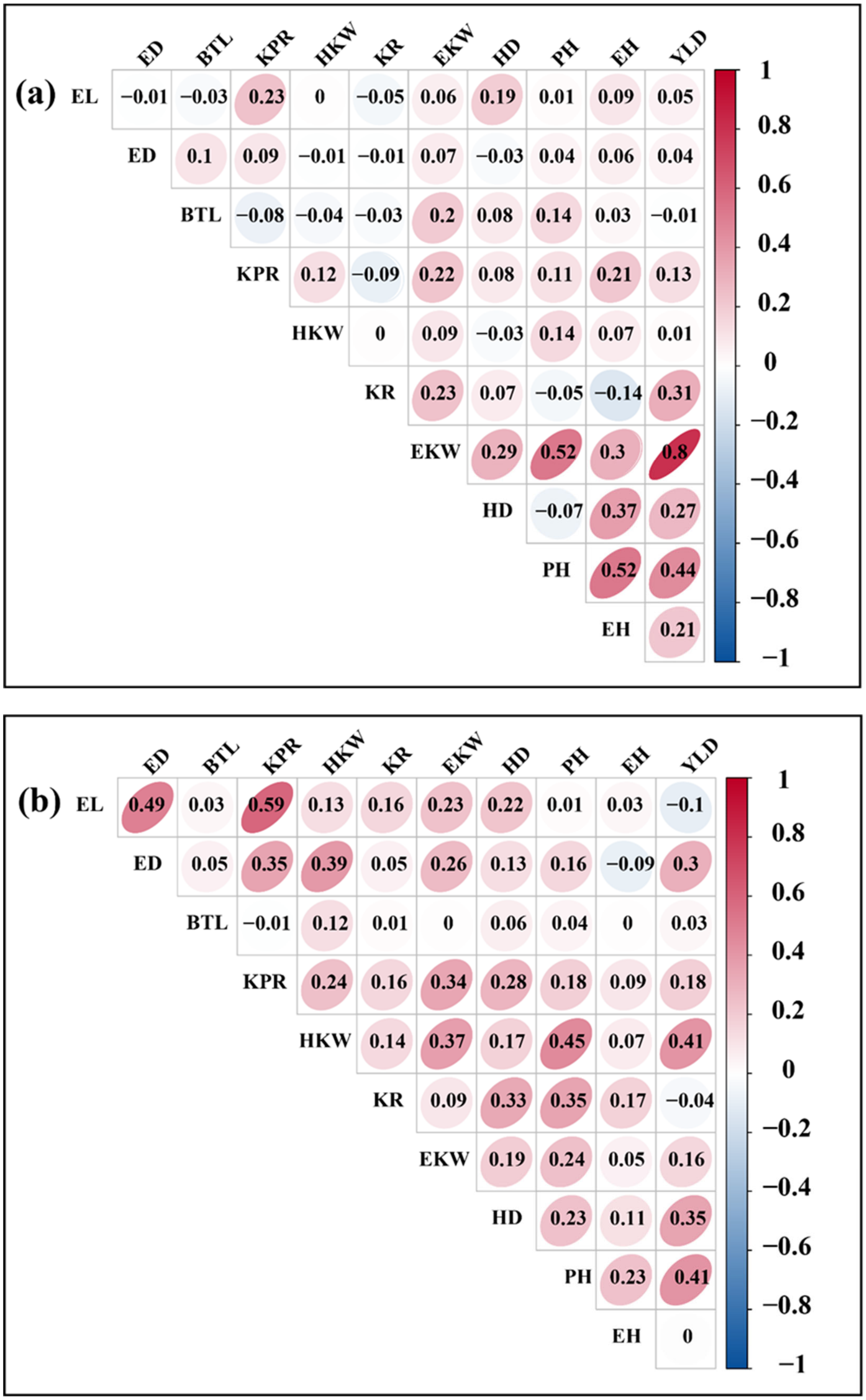

Figure 4. (a) Correlation analysis of agronomic traits in 2023; **(b)** Correlation analysis of agronomic traits in 2024. EL: Ear length; ED: Ear diameter; BTL: Bald tip length; KPR: Kernels per row; HKW: Hundred-kernel weight; KR: Kernel output rate; EKW: Ear kernel weight; HD: Growth duration; PH: Plant height; EH: Ear height.

3.4. GGE Biplot Analysis

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3.4.1. Relationship among test environments

In the Figure 5, AXIS1 and AXIS2 represent the first two principal components, which account for the variation in maize hybrid yield across 10 environments in 2023 (61.98%) and in 2024 (63.62%). The GGE biplot evaluates the relationships among environments. Small angles (E4 and E7, E2 and E5, and E3 and E8) indicated strong environmental correlations, suggesting similar rankings of maize genotypes within these paired environments. In contrast, the angle between E6 and E8 was greater than 90°, indicating uncorrelated genotypic performance between these two environments (Figure 5a). Similarly, the smallest angles were observed between E1 and E5, as well as among E7, E6, and E8, reflecting the highest environmental correlations. Conversely, the angle between E2 and E10 was more than 90° indicating weak genotypic correlation between these environments (Figure 5b).

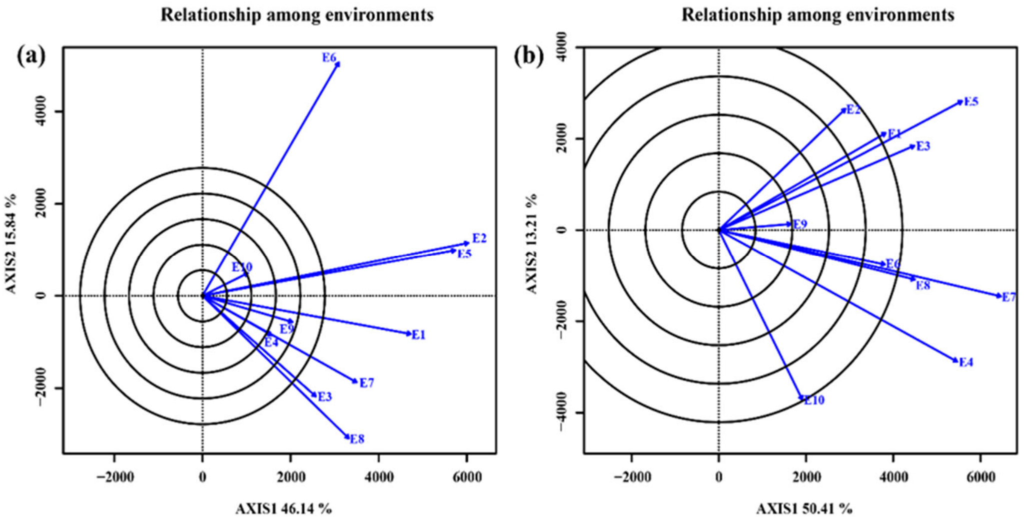

Figure 5. Relationships among test environments revealed by GGE biplot analysis across 10 trial environments. **(a)** GGE biplot for 2023; **(b)** GGE biplot for 2024.

3.4.2. Selection of ideal test environments

The GGE biplot of "Discriminating Ability vs. Representativeness" view and environmental ranking view across 10 test environments were displayed in Figure 6 and Figure 7, respectively. In 2023, Environments E6, E2, and E5 had the longest vectors, indicating the strongest discriminative power. Relative to the AEC abscissa, E1, E2, and E5 showed the smallest angles, suggesting their high environments representativeness (Figure 6a). And E1, E2, and E5 were in a smaller concentric circle and could be identified as the top-ranked test environments (Figure 7a). Therefore, E2 (Binchuan) and E5(Lijiang) were identified as ideal test environments with both strong discriminative power and high representativeness in 2023. In 2024, E5 and E7 displayed the longest vectors, indicating the strongest discriminative power, while E8 showed relatively weaker genotype differentiation compared to E5 and E7 but remained a suitable test environment. E6, E7, and E8 had the smallest angles relative to the AEC abscissa, indicating their high representativeness (Figure 6b). And E7 and E8 were the top-ranked test environments because the concentric circles closest to the center of the circle. Consequently, E7(Shilin) and E8(Xuanwei) were identified as ideal test environments in 2024.

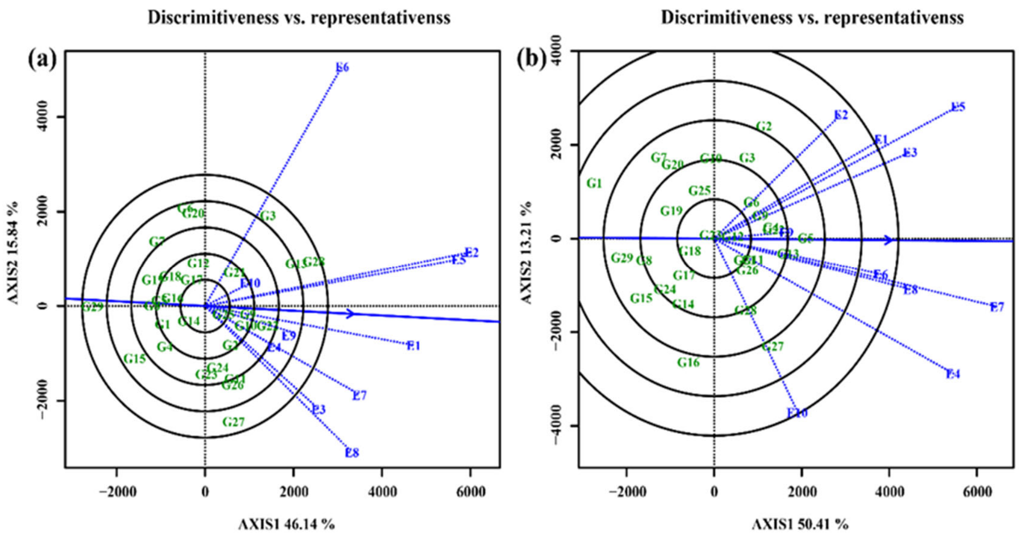

Figure 6. GGE biplot of "Discriminating Ability vs. Representativeness" view across 10 test environments. **(a)** GGE biplot for 2023; **(b)** GGE biplot for 2024.

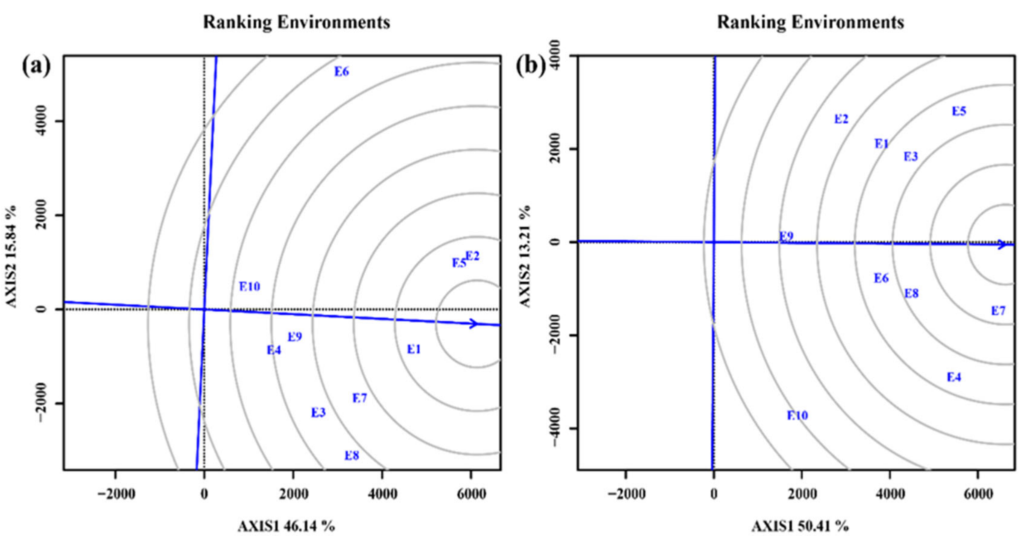

Figure 7. GGE biplot of environmental ranking view across 10 test environments. **(a)** GGE biplot for 2023; **(b)** GGE biplot for 2024.

3.4.4. Screening of elite cultivars under test environments

The polygon view of the GGE biplot revealed the "which-won-where" pattern of yield performance among 29 maize varieties, with the vertices of the polygon representing the winning genotypes in their respective environmental groups (Figure 8). In 2023, G27, G28, and G3 demonstrated optimal performance in their respective test environments. Moreover, the location of G13 was infinitely close to that of G28, so it can also be regarded as the most promising variety. In 2024, genotypes G27, G5, and G2 exhibited superior performance, with G13 and G22 continuing to show excellent potential in specific sectors. This indicated that G27(SS-2205) and G13(YR-399) had ultimately emerged victorious, emerging as the key candidate for further research and potential commercialization.

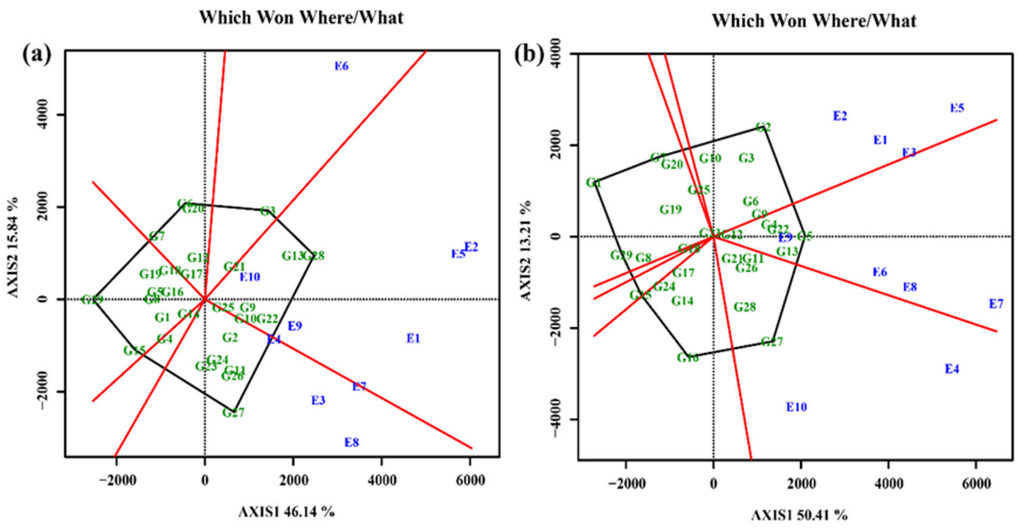

Figure 8. GGE biplot of "Which-won-where" view among 29 maize varieties across 10 test environments. **(a)** GGE biplot for 2023; **(b)** GGE biplot for 2024.

3.4.5. Selection of varieties with high stability and productivity

The stability view reflects varietal productivity and stability. Shorter perpendicular distances from the varieties to the AEC indicate higher stability, while smaller concentric circles in the ranking view signify superior varieties (Figure 9). In 2023, G28, G13, G22, G9 and G10 demonstrated the optimal balance between productivity and stability (Figure 9a, 10a). In 2024, G5, G13, G22, G4 and G9 exhibited excellent stability and productivity (Figure 9b, 10b). Therefore, G13(YR-399), G22(LS-2305) and G9 (LS-2303) displayed relatively high stability and productivity over two years.

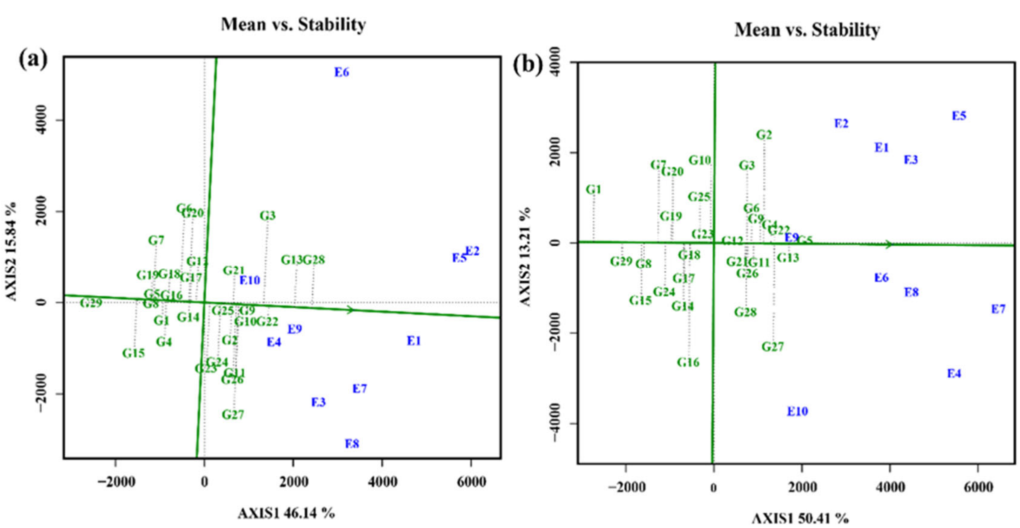

Figure 9. GGE biplot displaying the "Means vs. Stability" view for the average yield of 29 maize varieties across 10 test environments. **(a)** GGE biplot of "Means and Stability" view for 2023; **(b)** GGE biplot of "Means and Stability" view for 2024.

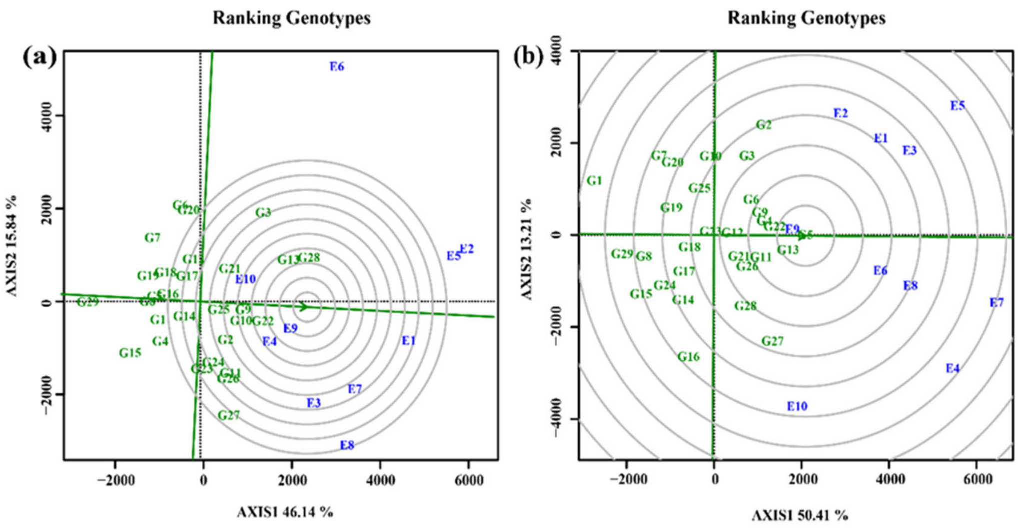

Figure 10. GGE biplot displaying the "Ranking Genotype" view for the average yield of 29 maize varieties across 10 test environments. **(a)** GGE biplot of ranking genotype view for 2023; **(b)** GGE biplot of ranking genotype view for 2024.

4. Discussion

4.1. Yield Variance Analysis

The environmental factors accounted for a larger proportion of variation compared to genotypic effects and genotype-by-environment interaction effects, highlighting the paramount role of the environmental condition in shaping yield performance. And this also underscored the necessity of evaluating genotypes across diverse environments to ensure the robustness and reliability of results (Tables 3, 4). Similar findings have been documented in previous studies by Ma et al. (2024), Taak et al. (2025), Gonçalves et al. (2025) and Liu et al. (2022) [17,31-33]. Furthermore, the effects of environment, genotype, and their interaction on maize yield were all statistically significant at the extremely high levels ($p < 0.001$). These results aligned with recent research by Zendrato et al. (2025), Neelam et al. (2025), and Nišavić et al. (2025) [34-36], confirming that the performance of maize genotypes was strongly modulated by specific environmental conditions. Consequently, the application of the GGE biplot analysis for yield evaluation is methodologically validated.

4.2. Evaluation of Ideal Test Environments

Heatmap analysis identified E5 (Lijiang), E8 (Xuanwei), E1 (Baoshan), and E7 (Shilin) as optimal environments for evaluating high-yielding genotypes (Figure 3). It was worth noting that the three locations E5 (Lijiang), E8 (Xuanwei) and E7 (Shilin) were highly consistent with the ideal environment results obtained by the GGE biplot (Figures 6,7). This mutual validation of analytical methods has also been confirmed in the studies by Zhang et al. (2016) and Nišavić et al. (2025) [20,37]. Yan et al. (2021) and Li et al. (2023) emphasized that the efficacy and precision of cultivar selection were markedly influenced by the discriminating discriminatory capacity of test environments[38,39], reinforcing the importance of selecting appropriate trial locations. In this study, E2 (Binchuan) and E5 (Lijiang) in 2023, alongside E7 (Shilin) and E8 (Xuanwei) in 2024, were identified as the most suitable ideal test environments for cultivar evaluation (Figures 6, 7). Furthermore, Ma et al. (2024) and Liu et al. (2022) validated that Binchuan, Shilin, and Xuanwei were relatively ideal environments [17,33], which was highly consistent with the ideal environments identified in our study. As highlighted by Mullualem et al. (2024), Kona et al. (2024) and Tiwari et al. (2025) the delineation of representative environments necessitated multi-year experimental validation [40-42].

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4.3. Evaluation of Ideal Genotypes

The results of high-yielding varieties obtained from the analysis of yield performance and the polygon view of GGE biplot showing a very high degree of overlap (Figure 2 and Figure 8). The high-yielding varieties with complete overlap were as follows: G3(ZF-2303), G27(SS-2205), G28(SS-2206) and G13(YR-399) in 2023, and G27(SS-2205), G5(YR-18), G2(ZF-2302) and G13(YR-399) in 2024. Notably, the mutual validation of analytical approaches has been further confirmed in studies by Liu et al. (2022), Ma et al. (2024), Ruswandi et al. (2022) and BaduApraku et al. (2023) [17,33,43,44]. Otherwise, a mature tool for genotype-by-environment interaction analysis, the GGE model has demonstrated good applicability in selecting ideal genotypes for various important crops, including rice (Li et al., 2023)[29], wheat (Mullualem et al., 2024)[40], and sugarcane (Chaudhary et al., 2025)[45], and oats (Sanadya et al., 2025)[46] in variety adaptation evaluation. However, yield potential alone cannot ensure temporal or spatial stability[47], high and stable yields performance remains a fundamental criterion for determining a variety's suitability for large-scale commercial promotion [48,49]. In this study, G13 (YR-399), G22 (LS-2305), and G9 (LS-2303) were identified as the most desirable genotypes due to their consistently high grain yield and strong stability (Figures 9, 10). This analysis of high-yield and stable varieties based on the GGE model has been validated in studies by Gonçalves et al. (2025), Kumar et al. (2024), and Nagesh et al. (2025)[32,50,51].

5. Conclusions

A multi-environment maize yield trial, analyzed via the GGE biplot model, revealed significant effects of genotypes, environments, and their interactions on yield, with environmental factors accounting for the primary source of variation. The optimal testing environments were E2 (Binchuan), E5 (Lijiang), E7 (Shilin), and E8 (Xuanwei). For superior genotypes, G22 (LS-2305), G9 (LS-2303), and G13 (YR-399) exhibited consistently high and stable yields across years, with G13 (YR-399) emerging as the most exceptional. The GGE biplot approach proved highly effective for screening high-yielding, stable varieties and identifying optimal test environments, thereby offering scientific guidance for maize breeding programs in mid-to-high elevation regions of Yunnan Province.

Author Contributions: Q.Z.: original draft, writing—review and editing, visualization, validation, methodology, investigation, formal analysis, data curation, project administration. Z.Y.: writing—review and editing, supervision, resources, conceptualization, project administration, funding acquisition. C.M.: writing—review and editing, investigation, project administration. C.L.: writing—review and editing, investigation, supervision, project administration. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Dataset available on request from the authors.

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