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Yield Stability Analysis in Maize Hybrids of Southwest China under Genotype by Environment Interaction Using GGE Biplot

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Abstract: Selecting superior genotypes across different environments is vital for varietal release, crop planting, and commercial use. Therefore, the objectives of this research were to appraise the performance of hybrids approved in recent years in diverse environments, and recommend high-yielding and stable genotypes for wider adaptation. Fourteen single cross maize hybrid genotypes (G), including a check, were implemented across ten environments (E) in two crop seasons (2020 and 2021). The combined analysis of variance revealed that G, E, and their interactive (GEI) significantly ($p < 0.01$) affected the grain yield. Moreover, the mean grain yield ranged from 9333 kg ha^{-1} for HH-2 (2021) to 13,195 kg ha^{-1} for LD-18 (2020). The "which won where" GGE biplot revealed the existence of mega environments with their own best hybrids (LD-18 and LD-29 in 2020; LD-18, LD-19, and YY-1506 in 2021). The "mean vs. stable" GGE biplot suggested that LD-18 and ZY-811, with highest/middle productive and high stability across 10 environments, were closest to the ideal genotype. Furthermore, the "discriminating power vs. representativeness" GGE biplot showed that Xuanwei, Yanshan, Gengma, and Shiling were the most the ideal test environments for hybrid selecting, based on their discriminative ability and representativeness. Therefore, the GGE biplot analysis allowed for an efficient selection of high-yielding and stable maize hybrids to guide ecological planting and commercial use.

Keywords: maize hybrids; grain yield; G × E interaction; stability; GGE biplot

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1. Introduction

Maize (*Zea mays* L.) is one of the most predominant crops in China, especially in the Southwest. It is the source of carbohydrates, protein, oil, iron, minerals, alcohol, vitamin B, and essential fatty acids [1,2]. Developing countries are the major consumers of maize. In China, maize is the largest crop, mainly used for feed production, and has a pivotal role in agriculture and animal husbandry. However, the average grain yield of maize in China was lower than that of other countries, i.e., the USA, Canada, Turkey, the European Union, and Argentina [3]. Therefore, selecting appropriate and productively stable maize hybrids for cultivation is an effective solution for increasing the grain yield of maize. Moreover, we can select ideal maize hybrids in diverse sites by evaluating genotype and environment interaction (GEI) and their stability [4,5].

GEI commonly exists and is associated with the performance and stability of varieties planted in different environments. Therefore, a variety that performs well in one site or period may not grow well in other conditions [6]. Hence, therefore, it is very important to analyze the yield and stability of new maize cultivars through multi-environment trials (METs) [7,8]. However, in the absence of appropriate analytical methods, breed selection may be inefficient. With the application of stability analysis models, and the genotype main effect plus genotype by environment interaction (GGE) biplot, the problem has been effectively solved [8–10].

The GGE biplot, which is a modification of the best linear unbiased prediction (BLUP), and the additive main effects and multiplicative interaction analysis (AMMI), is more superior because it displays both the effects of the genotypes and the GEI, which are the two sources of variation [11,12]. In other words, the GGE biplot analysis is a method in analyzing GEI and MET data for identifying and selecting the superior genotypes in specific environments [13,14]. Nowadays, GGE biplot analysis is the more widely used for integrating genotype main effect with the GEI effect [7], since it could benefit grouping mega environments [11], identify ideal environments with high representative and discriminative [15], and select genotypes with high grain yields and stability [16]. Additionally, GGE biplot analysis has been widely used in the study of maize [7,17–20], cotton [21], potato [14,22], sweet potato [23], wheat [24,25], and pigeon pea [26].

Therefore, the purposes of this study were to (a) evaluate the performance of 14 maize hybrid genotypes under 10 diverse environments through the GGE biplot, and (b) identify high-yielding and stable varieties across environments to help in the ecological planting and commercial use of maize cultivar.

2. Materials and Methods

2.1. Experimental Material

The experimental material in this study consisted of a check and thirteen single cross maize hybrids, which were approved by Yunnan province in recent years. The code and the source of these hybrids were given in Table 1. Among them, HH-2 hybrid was approved to control hybrids while the others (ZY-811, ZY-607, ZY-609, YY-1503, YY-1506, DY-201, DY-502, DY-602, LD-18, LD-19, LD-29, LX-1, and JL-118) were under evaluation.

Table 1. Description of 14 maize hybrids used in the study.

Hybrids	Abbreviation	Code	Source
Zuyu-811	ZY-811	G1	Yunnan Zu Feng Seed Industry Co., Ltd.
Yuanyu-1503	YY-1503	G2	Yunnan Yun Dan Seed Industry Co., Ltd.
Diyu-201	DY-201	G3	Yunnan Di Yu Seed Industry Co., Ltd.
Ludan-18	LD-18	G4	Yunnan Shi Feng Seed Industry Co., Ltd.
Linxin-1	LX-1	G5	Yunnan Lin Feng Seed Industry Co., Ltd.
Ludan-19	LD-19	G6	Yunnan Shi Feng Seed Industry Co., Ltd.
Ludan-29	LD-29	G7	Yunnan Shi Feng Seed Industry Co., Ltd.
Diyu-502	DY-502	G8	Yunnan Di Yu Seed Industry Co., Ltd.
Diyu-602	DY-602	G9	Yunnan Di Yu Seed Industry Co., Ltd.
Zuyu-607	ZY-607	G10	Yunnan Zu Feng Seed Industry Co., Ltd.
Zuyu-809	ZY-809	G11	Yunnan Zu Feng Seed Industry Co., Ltd.
Yuanyu-1506	YY-1506	G12	Yunnan YUN Dan Seed Industry Co., Ltd.
Jinli-118	JL-118	G13	Yunnan Jin li Seed Industry Co., Ltd.
Haihe-2 (CK)	HH-2	G14	Liaoning Haihe Seed Industry Co., Ltd.

2.2. Experimental Site

The 14 maize hybrids were performed in 10 environments in two crop seasons (2020 and 2021). The code and the characteristics of these 10 test environments were given in Table 2. Moreover, test accuracy analysis showed that the error coefficient of variation (CV) and the genetic coefficient of variation (GCV) in each test site were less than 10%, except for Yanshan in 2021 (Table S1), which indicated that pilot selection was reasonable, field operation was standardized, observation and measurement records were consistent, the test accuracy was high, and the results were reliable.

Table 2. The characteristics of test environments.

Location	Code	Latitude (N)	Longitude (E)	Altitude (m)
Shiling	SL	24°41′	103°27′	1927
Binchuan	BC	25°48′	100°35′	1430
Lijiang	LJ	100°3′	26°58′	1819
Yanshan	YS	23°07′	104°34′	1490
Mile	ML	24°27′	103°31′	1543
Chuxiong	CX	25°08′	101°18′	1767
Zhaotong	ZT	27°19′	103°42′	1920
Xuanwei	XW	26°15′	104°8′	1980
Gengma	GM	23°74′	99°62′	1340
Baoshan	BS	25°09′	99°13′	1592

2.3. Experimental Design

The experiments were arranged by a randomized complete block design with three replications. Five-row experimental plots of 5 m length, spaced 0.8 m apart were used. The grain yield trait was used to check the productivity and stability of maize hybrids, which was calculated by the three central rows of each plot during harvest. Five protective rows were set up around the plot using the corresponding hybrids. Standard agronomic practices were carried out at all locations. Grain was timely harvested, and later measured for yield using the following formula:

$$\text{Grain yield (kg ha}^{-1}\text{)} = \text{(Unit grain yield (kg)/unit area (m}^2\text{))} \times 10{,}000\ \text{(m}^2\ \text{ha}^{-1}\text{)}$$

where 10,000 m^2 = area of 1 hectare plot.

2.4. Statistical Analysis

The experimental data were preliminarily organized and analyzed by Excel. Variance analysis (ANOVA) was conducted by using statistical analysis software "Zone Test 99" (China Agricultural University). Additionally, the GGE biplot software (GenStat software Version 21.1) was used to graph the data [16].

3. Results

3.1. Variance Analysis for Grain Yield

The combined analysis of variance across 10 locations for 14 maize hybrids showed that G, E, and GEI significantly ($p < 0.01$) affected the grain yield in both two seasons (Tables 3 and 4). In addition, the environment's contribution to the total variation (SS) was high, explaining 73.49% and 66.74% of the SS in 2020 and 2021, respectively (Tables 3 and 4). Hence, it was necessary to further analyze the GEI using GGE analysis.

Table 3. Mean squares for hybrid grain yield under genotype by environment interaction study in 2020.

Source of Variation	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Squares	F-Calculated	Proportion of SS (%)
Block (B)	20	52,315.42969	2615.77148		0.68
Environments (E)	9	5,665,275.5	629,475.0625	83.47784 **	73.49
Genotypes (G)	13	577,943.4375	44,457.1875	5.89569 **	7.50
G × E Interaction	117	882,253.0625	7540.62451	3.68901 **	11.44
Error	260	531,460.5625	2044.0791		6.89
Total	419	7,709,248			100.00

Table 4. Mean squares for hybrid grain yield under genotype by environment interaction study in 2021.

Source of Variation	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Squares	F-Calculated	Proportion of SS (%)
Block (B)	20	774,893.6875	38,744.68359		10.81
Environments (E)	9	4,780,375	531,152.75	97.98611 **	66.74
Genotypes (G)	13	414,385.0625	31,875.77344	5.88039 **	5.79
G × E Interaction	117	634,221.25	5420.69434	2.52029 **	8.85
Error	260	559,213	2150.81934		7.81
Total	419	7,163,088			100.00

3.2. Performance of Maize Grain Yield across the Environments

The yield performance of 14 maize hybrids across 10 environments was evaluated with their mean grain yield (Tables 5–7). For environments, grain yield ranged from 9222 kg ha^{-1} in Zhaotong to 15,065 kg ha^{-1} in Binchuan, while it was from 11,138 kg ha^{-1} (HH-2) to 13,195 kg ha^{-1} (LD-18) among hybrids in 2020 (Table 5). Meanwhile, in 2021, the lowest- and highest-yielding for environments was 8066 kg ha^{-1} (Zhaotong) and 13,113 kg ha^{-1} (Shilin), respectively. The yields ranged from 9333 kg ha^{-1} (HH-2) to 11,404 kg ha^{-1} (LD-18) among 14 maize hybrids (Table 6). Hybrids LD-18, LD-29, ZY-811, and LD-19 were found as the top four productive genotypes in 2020. Among these four hybrids, LD-18 was the highest-yielding genotype across six different environments in 2020, i.e., Xuanwei, Binchuan, Shilin, Lijiang, Mile, and Yanshan. Moreover, situation in 2021 was similar to that in 2020, where LD-18 performed best across five different environments followed by LD-19, ZY-811, and LX-1 (Table 6). Additionally, over the data of two years (Table 7), the best performing four hybrids were LD-18, LD-19, ZY-811, and LD-29, with LD-18 having the highest yield.

Table 5. Mean yield (kg ha^{-1}) of 14 maize hybrids across 10 environments in 2020.

Locations/ Hybrids	Gengma	Binchuan	Lijiang	Yanshan	Mile	Chuxiong	Baoshan	Zhaotong	Xuanwei	Shiling	Mean
ZY-811	**11,352**	**15,733**	13,444	13,070	11,751	**13,698**	10,307	**9593**	14,949	**14,343**	12,824
YY-1503	10,224	15,395	13,223	**13,136**	12,047	12,620	10,512	9429	14,027	13,551	12,416
DY-201	10,226	14,914	12,016	12,092	10,178	11,987	11,306	**9663**	13,865	11,885	11,813
LD-18	9506	**16,543**	**14,023**	**13,500**	**13,287**	12,703	10,529	9495	**17,703**	**14,660**	13,195
LX-1	9125	14,444	12,686	12,867	11,042	12,876	11,423	8978	13,979	13,575	12,099
LD-19	**11,516**	14,528	**13,522**	12,642	9869	**13,578**	11,534	**9690**	**15,183**	**14,775**	12,684
LD-29	**10,926**	15,529	11,485	12,775	**13,913**	**13,806**	**12,384**	9573	**15,611**	12,825	12,883
DY-502	9054	13,323	12,548	12,333	10,901	12,851	11,087	9045	14,099	13,676	11,892
DY-602	9564	14,175	11,411	11,836	11,192	11,873	10,839	8493	13,526	12,368	11,528
ZY-607	10,793	**16,409**	13,520	**13,581**	11,240	13,065	11,853	8832	14,782	13,926	12,800
ZY-809	9423	15,694	**13,612**	12,889	10,928	13,026	**11,990**	9417	14,960	13,526	12,546
YY-1506	9245	14,943	13,403	12,767	12,209	12,998	11,834	9465	12,223	13,476	12,256
JL-118	9437	14,877	12,140	11,242	**12,974**	13,484	**12,192**	8798	12,517	12,959	12,062
HH-2 (CK)	8042	14,398	11,709	11,356	10,370	11,326	10,459	8637	12,976	12,109	11,138
Mean	9888	15,065	12,767	12,577	11,564	12,849	11,303	9222	14,314	13,404	12,295

Note: values in bold and underlined are the top three highest grain yield (kg ha^{-1}) of maize hybrids at each test environment.

Moreover, the multiple comparison results showed that the mean yield of 13 evaluated hybrids were all higher than the control hybrid HH-2 (Figure 1 and Table S2). Moreover, there were no significant differences among the top 7 varieties, LD-18, LD-19, ZY-811, LD-29, YY-1503, ZY-607, and ZY-609. Additionally, LD-18 had over 20.16% yield advantage over HH-2 (Table S2). These results indicated that LD-18, LD-19, and ZY-811 were the more productive genotypes in 2020 and 2021.

Table 6. Mean yield (kg ha^{-1}) of 14 maize hybrids across 10 environments in 2021.

Locations/ Hybrids	Gengma	Binchuan	Lijiang	Yanshan	Mile	Chuxiong	Baoshan	Zhaotong	Xuanwei	Shiling	Mean
ZY-811	**10,115**	11,869	12,095	**11,696**	9153	12,168	9284	8054	11,342	13,584	10,936
YY-1503	8389	11,854	**13,259**	11,001	**9956**	12,152	9233	**8484**	11,147	12,938	10,841
DY-201	9011	**12,420**	12,269	11,168	9509	12,227	9328	7835	11,789	12,543	10,810
LD-18	8996	**13,817**	**12,459**	**13,001**	9414	12,393	9234	7920	**12,681**	**14,126**	11,404
LX-1	8606	11,574	**12,822**	11,084	9231	**12,875**	9172	7890	11,114	**14,187**	10,855
LD-19	**10,324**	11,690	11,973	**12,195**	9153	**13,175**	9183	**8745**	10,876	13,490	11,080
LD-29	**9584**	11,646	12,300	10,584	8898	11,609	7800	8348	**12,381**	**14,120**	10,727
DY-502	8402	11,677	11,998	9557	**9515**	**12,792**	9117	7668	9738	12,032	10,249
DY-602	8178	11,651	10,905	9890	9287	11,717	9134	7853	10,764	12,459	10,184
ZY-607	8999	11,762	10,954	9501	9392	12,302	**9634**	7968	10,822	12,978	10,431
ZY-809	8232	11,599	12,399	10,751	9381	12,251	**9851**	8108	9955	13,620	10,614
YY-1506	8606	11,712	11,944	10,473	9234	12,726	**11,051**	7754	9988	13,310	10,680
JL-118	8532	**12,982**	10,860	10,334	**9935**	11,534	9234	**9248**	**12,056**	12,717	10,743
HH-2 (CK)	7234	11,234	9939	9167	8262	11,095	8825	7048	9042	11,487	9333
Mean	8800	11,963	11,870	10,743	9308	12,215	9291	8066	10,978	13,113	10,635

Note: values in bold and underlined are the top three highest grain yield (kg ha^{-1}) of maize hybrids at each test environment.

Table 7. Mean yield (kg ha^{-1}) of 14 maize hybrids across 10 environments over two years.

Locations/ Hybrids	Gengma	Binchuan	Lijiang	Yanshan	Mile	Chuxiong	Baoshan	Zhaotong	Xuanwei	Shiling	Mean
ZY-811	**10,733**	13,801	12,769	**12,383**	10,452	**12,933**	9795	8823	**13,145**	**13,964**	11,880
YY-1503	9307	13,624	**13,241**	12,069	11,001	12,386	9873	8957	12,587	13,244	11,629
DY-201	9618	13,667	12,142	11,630	9843	12,107	10,317	8749	12,827	12,214	11,311
LD-18	9251	**15,180**	**13,241**	**13,250**	**11,351**	12,548	9881	8708	**15,192**	**14,393**	12,299
LX-1	8865	13,009	12,754	11,975	10,136	**12,875**	10,297	8434	12,547	13,881	11,477
LD-19	**10,920**	13,109	12,747	**12,418**	9511	**13,376**	10,358	**9218**	13,029	**14,132**	11,882
LD-29	10255	13,587	11,893	11,680	**11,405**	12,707	10,092	**8960**	**13,996**	13,472	11,805
DY-502	8728	12,500	12,273	10,945	10,208	12,821	10,102	8357	11,918	12,854	11,070
DY-602	8871	12,913	11,158	10,863	10,239	11,795	9986	8173	12,145	12,413	10,856
ZY-607	**9896**	**14,085**	12,237	11,541	10,316	12,683	**10,743**	8400	12,802	13,452	11,616
ZY-809	8827	13,647	**13,005**	11,820	10,154	12,638	**10,920**	8762	12,458	13,573	11,580
YY-1506	8925	13,328	12,673	11,620	10,721	12,862	**11,442**	8609	11,106	13,393	11,468
JL-118	8984	**13,929**	11,500	10,788	**11,454**	12,509	10,713	**9023**	12,287	12,838	11,402
HH-2 (CK)	7638	12,816	10,824	10,262	9316	11,210	9642	7842	11,009	11,798	10,236
Mean	9344	13,514	12,318	11,660	10,436	12,532	10,297	8644	12,646	13,259	11,465

Note: values in bold and underlined are the top three highest grain yield (kg ha^{-1}) of maize hybrids at each test environment.

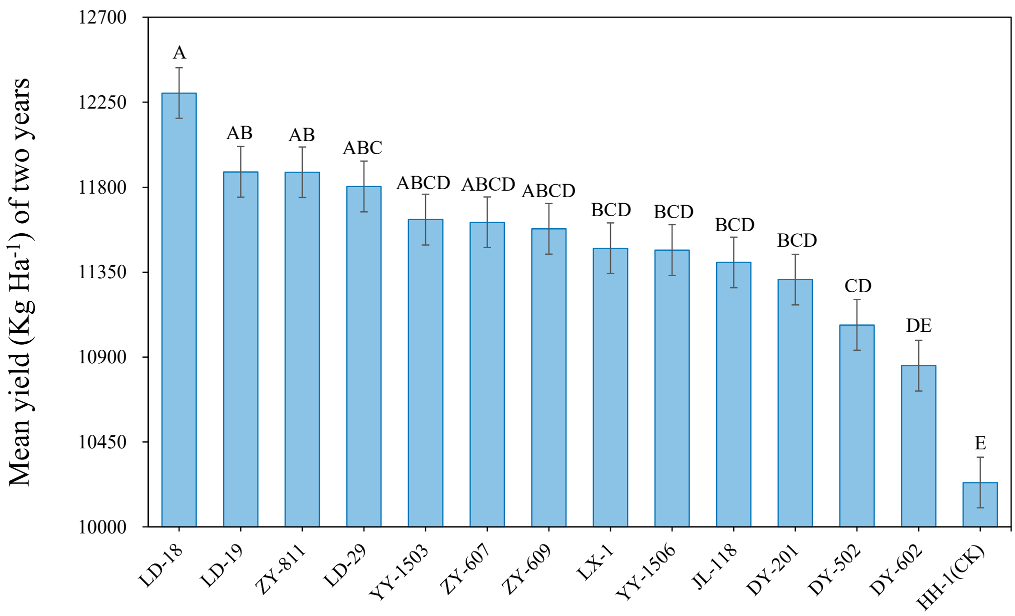

Figure 1. Mean yield (kg ha^{-1}) of 14 maize hybrids over two years. Different letters indicate significant differences ($p < 0.01$).

3.3. Selection of Ideal Hybrids across 10 Test Environments Based on GGE Biplot

"Which-won-where" GGE biplot is shown in Figure 2. The vertices of the polygon were the best varieties in their own sectors. In detail, 14 genotypes were distributed in five sectors in 2020, and LD-18 and LD-29 were the best hybrids in the two mega environments (Figure 2A). Additionally, LD-18, LD-19, and YY-1506 were the best performing varieties in their respective mega environment zones in 2021 (Figure 2B). Moreover, hybrids in vertex were more responsive than those within the polygon, and some hybrids, which were not in any of the mega environments, performed poorly across some or all of the test environments (Figure 2).

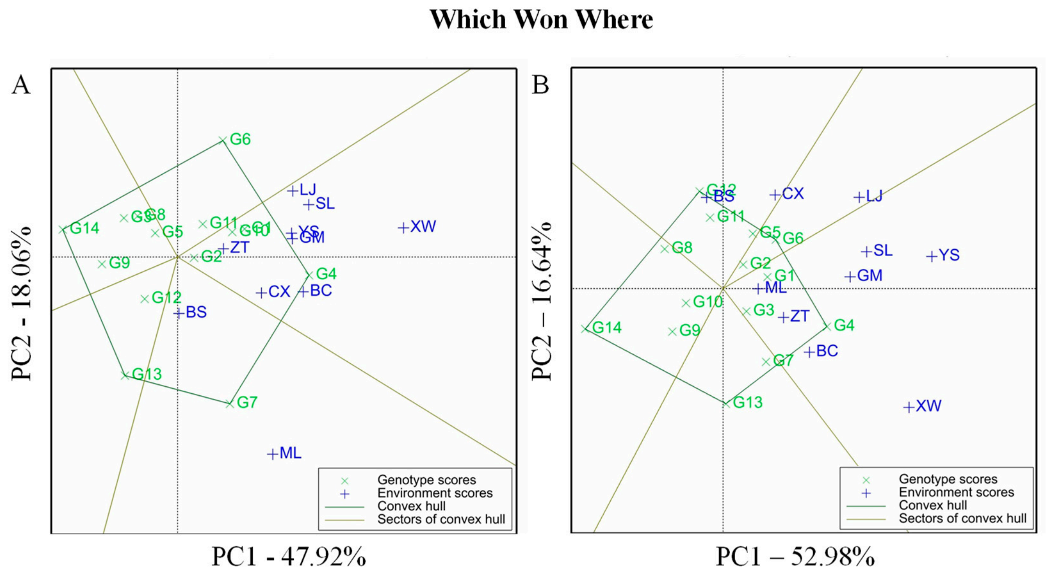

Figure 2. "Which-won-where" pattern of GGE biplot for 14 maize hybrids (G1-G14) evaluated across 10 environments. Genotypes at the vertices of the polygon are responsive to a particular environment: (**A**) GGE biplot in 2020; (**B**) GGE biplot in 2021. See genotype and environment codes in Tables 1 and 2, respectively.

3.4. Selection of Ideal Hybrids across 10 Test Environments Based on GGE Biplot

The mean yield and stability of hybrids were evaluated by GGE biplot with average environment coordination (AEC) (Figure 3). The vertical foot position of each variety on the ACE axis represented the variety yield, while the vertical line segment indicated the stability of the variety. In this study, LD-18 was highest-yielding, followed by LD-29, ZY-811, ZY607, LD-19, ZY-809, and YY-1503 in 2020 (Figure 3A), and followed by LD-19, ZY-811, LX-1, LD-29, YY-1503, and DY-201 in 2021 (Figure 3B). Moreover, YY-1503 was found as the most stable hybrid followed by LD-18, DY-602, and HH-2 in 2020. ZY-811 was the most stable genotype followed by ZY-607, HH-2, and YY-1503 in 2021 (Figure 3B). Thus, the above results further revealed that LD-18 and ZY-811 were the best hybrids with outstanding yield performance (the most productive or middle productive) and excellent stability (higher or best) across the environments.

3.5. Representativeness and Discriminating Ability of the Test Environments

The discriminating ability and representativeness of tested environments were displayed in Figure 4. Test environments with long vectors' length (most discriminative), and small angles with the AEC abscissa (most representative), were considered as the ideal environments for the selection of superior varieties. The results revealed that Xuanwei was the relatively most discriminative and representative environment, which appeared to be similar to Yanshan, Gengma, and Zhaotong, based on the small angle between them in 2020 (Figure 4A). Accordingly, Yanshan was the ideal environment associated with Shiling and

Gengma for the small angle between them in 2021 (Figure 4B). Hence, Xuanwei, Yanshan, Gengma, and Shiling were the desirable environments for selecting superior maize hybrids.

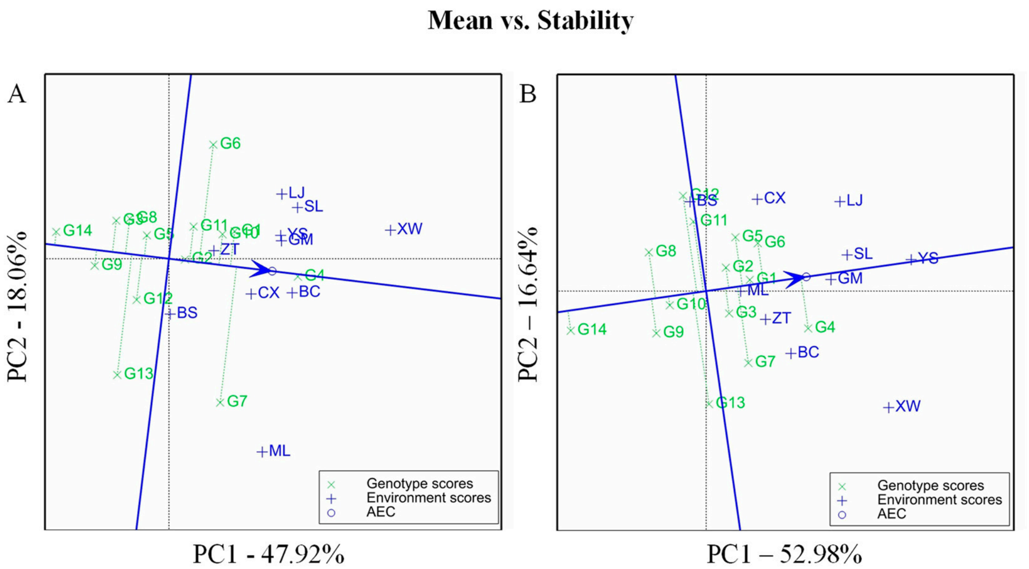

Figure 3. GGE biplot showing mean and stability of 14 maize hybrids for yield across 10 locations. Genotypes on the extreme right are highest-yielding; those having smaller projection on the ordinate are relatively stable: (**A**) GGE biplot in 2020; (**B**) GGE biplot in 2021. See genotype and environment codes in Tables 1 and 2, respectively.

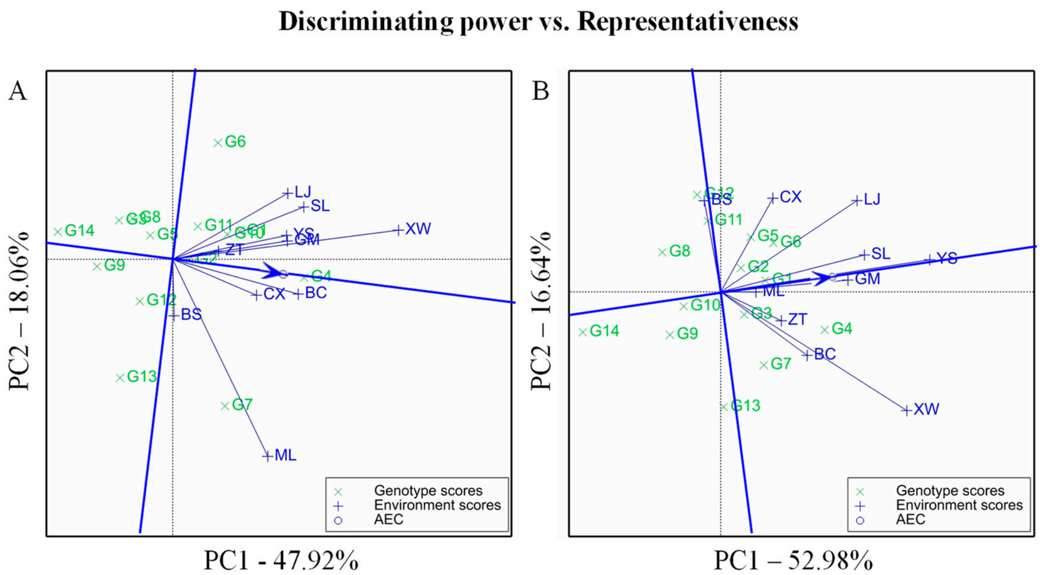

Figure 4. GGE biplot for the evaluation of the relationships among the 10 test environments. Environmental vectors having smaller angles are closely related. Environments having longer vectors are discriminating: (**A**) GGE biplot in 2020; (**B**) GGE biplot in 2021. See genotype and environment codes in Tables 1 and 2, respectively.

3.6. Evaluation of Ideal Varieties and Ideal Environments

From the comparison biplot (Figure 5), the ideal genotypes are lying in the first concentric circle, and varieties closer to the ideal spot are desirable. In the current study, LD-18 was an outstanding hybrid located on the first concentric circle followed by ZY-811 and ZY-607 in 2020 (Figure 5A), and by ZY-811 and LD-19 in 2021 (Figure 5B). Therefore, these results revealed that LD-18 and ZY-811 were the relatively desirable genotypes (Figure 5).

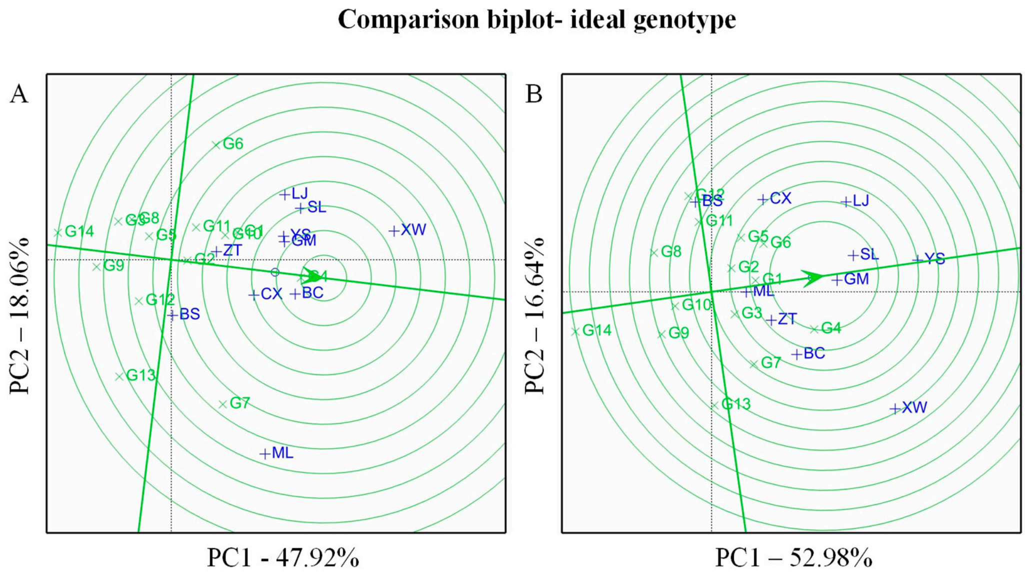

Figure 5. Visualization of 'ideal genotype' using GGE biplot. Concentric circles show the location of ideal genotypes. Genotypes closer to the ideal spot are ideal genotypes. GGE biplot of ideal hybrids and ranking of hybrids: (**A**) GGE biplot in 2020; (**B**) GGE biplot in 2021. See genotype and environment codes in Tables 1 and 2, respectively.

According to the above analysis method, the ideal/desirable environments can be easily found (Figure 6). Obviously, Xuanwei was identified as an excellent environment, as it was lying in the first concentric circle followed by Binchuan, Yanshan, Gengma, and Shiling in 2020 (Figure 6A). Additionally, a desirable environment was Yanshan in 2021, followed by Shiling, Gengma, Linxing, and Xuanwei (Figure 6B). Generally speaking, test environments Yanshan, Xuanwei, Shiling, and Gengma were more reliable and worthy of consideration (Figure 6), and this finding was consistent with the results identified by representativeness and discriminating ability of the 10 environments (Figure 4).

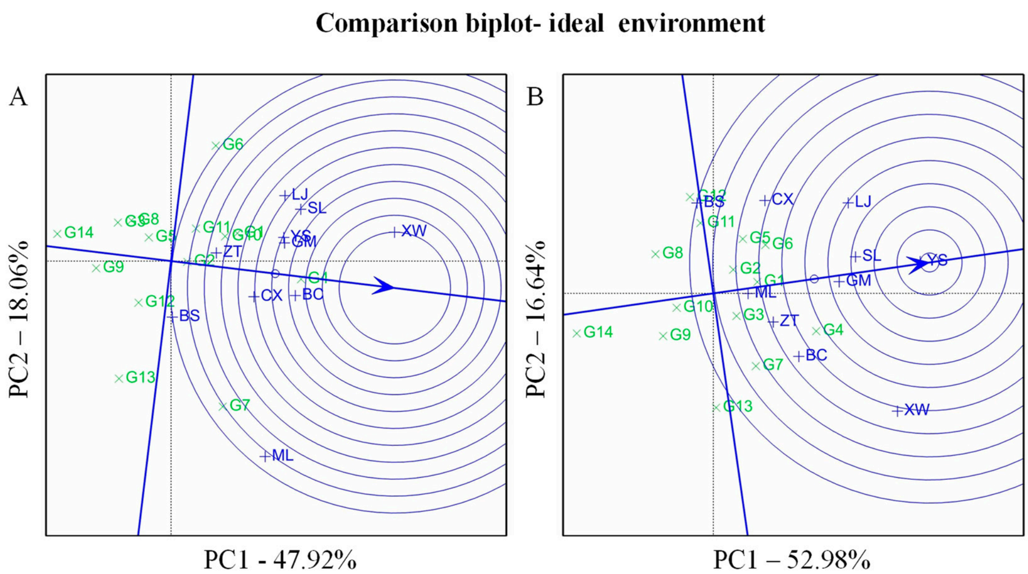

Figure 6. Visualization of 'ideal environment' using GGE biplot. Concentric circles show the position of ideal environments. Environments closer to the ideal spot are ideal environments. GGE biplot of ideal hybrids and ranking of hybrids: (**A**) GGE biplot in 2020; (**B**) GGE biplot in 2021. See genotype and environment codes in Tables 1 and 2, respectively.

4. Discussion

4.1. Performance of 14 Maize Hybrids under 10 Diverse Environments

In this study, the environment component created more variation than genotype and GEI, indicating that there was high variability among test environments (Tables 3 and 4). This was similar to the results found by Agyeman and Ewool, Badu-Apraku et al., and Yousaf et al., who observed that environment was the largest part of the total variation [7,17,18]. The GEI was highly significant for grain yield, suggesting the use of the GGE biplot analysis to evaluate grain yield performance, and stability was feasible. This finding was similar with the results described by previous studies [18,27–30].

4.2. Mega-Environment Analysis Based on GGE Biplot

Figure 2 showed the "which-won-where" polygon view, and each environment group had the same best genotype [16,31]. Therefore, we could visually identify some mega environments from Figure 2. In detail, LD-18 and LD-29 performed well under the first and second mega-environment in 2020, respectively. LD-18, LD-19, and YY-1506 were the highest-yielding hybrids adapted to their own mega environment zones in 2021. Generally, the polygon view exposed the most productive hybrids in each environmental group [14,32,33], and further demonstrated that these varieties could guide the ecological planting, and were recommended for widespread commercial use. However, further evaluation is required under more multi-environments over seasons.

4.3. Ideal Maize Hybrids' Evaluation

Previous studies suggested that the ideal hybrid should have the highest yield and stability across test environments [16,34,35]. However, the ideal genotype served only as a reference for variety selection, since few existed in reality [36]. Following this suggestion, we found that LD-18 and ZY-811 were close to the ideal genotype because of their relatively higher grain yield and stability. This was similar to the findings discovered by Badu-Apraku et al. and Yousaf et al [7,37].

4.4. Ideal Test Environment Evaluation

Identifying an ideal test environment is considered very essential for selecting superior maize hybrids and crop improvement [31]. An ideal test environment should be most discriminative (the differentiation power) and most representative (illustrates its competence) across the target environments [12]. Hence, the GGE biplot revealed that these environments, Yanshan, Xuanwei, Shiling, and Gengma, were the closest to the ideal environment, thanks to their long vector length and small angles with AEC abscissa. Moreover, some previous studies had evaluated ideal test environments in optimizing maize genotype selection based on discriminating ability and representativeness of the test environment [1,17,18,21,32]. Therefore, these four environments could be used to evaluate maize hybrids in Southwestern China for variety selection and crop production.

5. Conclusions

Significant ($p < 0.01$) differences were observed between environments, genotypes, and their interaction. The GGE biplot analysis revealed the existence of mega environments with their own best varieties (LD-8 and LD-29 in 2018; LD-18, LD-19, and YY-1506 in 2019). In these hybrids, LD-18 was the most productive hybrid with relatively higher stability; additionally, ZY-811 was the other ideal genotype for middle productive hybrid and highest stability. Hence, LD-18 and ZY-811 maize hybrids can be used for crop production. Furthermore, Yanshan, Xuanwei, Gengma, and Shiling were considered as the ideal test environments for hybrid selecting, based on their discriminative ability and representativeness. Therefore, the GGE biplot methodology was effectively identified, in terms of high-yielding and stable varieties, to guide the ecological planting of maize and for its commercial use, and the two varieties and the four environments provided guidance for maize variety selection and planting in Southwest China.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agronomy12051189/s1, Table S1: Test accuracy analysis in 2020 and 2021, Table S2: Multiple comparison results by the LSD method over two years.

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