

## EFFECTS OF GENOTYPE-BY-ENVIRONMENT INTERACTION ON THE MAIN AGRONOMIC TRAITS OF MAIZE HYBRIDS

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**Abstract.** The additive main effects and multiplicative interaction (AMMI) model and genotype main effects and genotype-by-environment interaction (GGE) biplot are commonly used to analyze multi environmental trial data. This study adopted the AMMI model and GGE biplot to comprehensively analyze the data on genotypes tested in the 2016–2017 Zhongcheng combined regional maize trial in China. Results showed that the traits highly and significantly differed across different genotypes (G) and environments (E). Significant or very significant genotype-by-environment interactions (GEI) were also found. With the exception of 100-kernel weight, the ratio of GEI for the remaining three traits was lower than that of E and higher than that of G. GEI was decomposed, and the interaction information of PCA1 and PCA2 in the interaction of four traits was significant. Hengyu1587 and Shiyu 1503 performed better than the other hybrids and were identified as excellent varieties across locations because of their outstanding performances according to a 2-year observation. The comprehensive utilization of the AMMI model and GGE biplot can enable the scientific and objective judgment of the high yield, stability, and adaptability of tested maize hybrids and provides theoretical support for the rational layout of maize hybrids in the environments of Hebei Province.

**Keywords:** *yield, stability, adaptability, AMMI model, GGE biplot*

### Introduction

Maize (*Zea mays* L.) is an important industrial, feed, and food crop in China and plays an important role in the national economy (Yue et al., 2018a). The three major maize-producing areas in China are northeast spring, southwest mountainous, and Huanghuaihai summer, which has the largest maize concentration. The wheat–maize double cropping system is the planting mode in this region which accounts for approximately 1/3 of the planting area and output of the country and frequently experiences natural disasters, such as high winds, heavy rainfall, drought, mites, high temperatures, and low temperatures during the filling period (Zhang et al., 2015; Zhao and Yang, 2018). In addition, the continued occurrence of maize pests and diseases destabilizes the production from this area and results in a massive difference between the actual field yield and genetic yield potential of maize hybrids (Yue et al., 2018b). These problems have seriously hindered the healthy development of the maize industry. Breeding high-yielding and stable hybrids suitable for environmental conditions in various regions is necessary to achieve high and stable maize yields.

The combined regional trial of crop varieties is an important form of national and provincial regional trial that has emerged in the past 2 years and is an inevitable outcome of the modern seed industry. The combined regional trial of maize hybrids is the comprehensive evaluation of the yield, adaptability, stress resistance, quality, and representativeness of newly cultivated hybrids according to standard specifications (Bao et al., 2017; Zhao et al., 2018). Combined regional trials are performed to screen out genotypes with excellent performance, determine the best adaptation areas for the tested varieties, and maximize the yield potential in accordance with local conditions. Discriminative analysis between locations is an important aspect of combined regional trials. The scientific and effective selection of locations and the improvement of screening services for new hybrids are difficult problems encountered by agricultural researchers (Zhang et al., 2016; Blanche and Myers, 2016).

Yield and other important agronomic traits of maize hybrids are represented by genotype (G), environment (E), and genotype main effects and genotype–environment interaction effects (GEI). The GEI effect occurs when different hybrids face different Es. E affects G because of the GEI effect, which in turn causes changes in different hybrids (Ma’ali, 2008; Abakemal et al., 2016). A high interaction effect degrades the stability of maize hybrids. In general, maize hybrids that exhibit high and stable yields under different environmental conditions have good adaptability, a large promotion value, and an outstanding productivity but poor stability in local areas. Genotypes with special adaptability also have a high production promotion. Therefore, understanding the connotation and essence of the interaction effect is helpful for studying the stability of maize yields and agronomic traits under different environmental conditions.

Agricultural researchers have proposed numerous research methods, including ANOVA (Lin et al., 1992), principal component analysis (Perkins, 1972), high stability coefficient (Berzsenyi and Dang, 2008), coefficient of variation (Döring and Reckling, 2018), additive main effects and multiplicative interaction (AMMI model) (Zobel et al., 1988), and genotype main effects and GEI effect (GGE) biplot (Yan et al., 2000), for the analysis of crop genotype and environment interaction. The AMMI model and the GGE biplot have been commonly used for GEI analysis. The AMMI model, also known as the additive main effect product interaction model, is the combination of ANOVA and principal component analysis for maximizing the interaction between G and E and separating the sum of product terms with different values from additive model interactions. This technique can also maximize assessment accuracy (Thillainathan and Fernandez, 2001; Dehghani et al., 2016). The results of AMMI model analysis can be intuitively and concisely expressed and interpreted, thus aiding the stability analysis of varieties and the screening of G with special GEI effects and providing valuable information for the breeding of special varieties adapted for a particular environment (Lal, 2012). Several scholars have used the AMMI model for the GEI analysis of crops, such as maize (Ndhlela et al., 2014), wheat (Sareen et al., 2012), rice (Suwaero and Nasrullah, 2011), millet (Bashir et al., 2014), barley (Bocianowski et al., 2019) and potato (Thiyagu et al., 2012). The genotype main effect plus GEI (GGE) biplot method was first proposed by Yan to analyze the regional test data of wheat varieties (Yan et al., 2000). This method analyzes the data in the regional experiment in a 2D map, and the results only show the G effect and GEI related to variety evaluation. This technique has become an ideal tool for studying crop genotype stability and location discrimination (Kaya et al., 2006; Baxevanos et al., 2008; Laurie and Booyse, 2015; Rea et al., 2016; Dehghani et al., 2017). Nevertheless, any analytical method is

imperfect and has its own shortcomings. The AMMI model mainly considers the interaction between G and E. Comprehensively evaluating the G effect in the breeding and promotion of genotypes is necessary. Analysis results often focus on genotypes that are stable and high yielding or stable and low yielding while ignoring genotypes with high yields but poor stability and thus are subjected to certain restrictions during application (Akinwale et al., 2014). The GGE biplot reveals the GEI information in the form of maps and reflects the cultivar's environmental adaptability. Relying only on 2D plane mapping in the analysis will lead to a loss of a part of the GE's mutation information. Therefore, this approach has a certain risk. The AMMI model and the GGE biplot method can be combined for the regional trials of crop genotypes, to screen out genotypes with good yield and poor stability and apply them in specific regions, thus greatly improving the accuracy of results (Muthoni, 2015; Erdemci, 2018).

Here, the AMMI model and the GGE biplot were used to comprehensively evaluate the stability, adaptability, and discrimination in the Zhongcheng combined regional maize trial in Hebei province from 2016 to 2017. This work aims to provide a theoretical basis for the selection and utilization of maize hybrids in the Huanghuaihai summer maize area of China.

## Materials and methods

Experimental data were derived from the Zhongcheng combined regional maize trial of Hebei Province, China. Thirteen hybrids from private and public companies were tested in 2016 and 2017, and Zhengdan 958 was used as a control hybrid. Information on the tested hybrids is shown in *Table 1*. The numbers of locations in 2016 and 2017 were 13 and 16, respectively. The latitude, longitude, altitude, and annual rainfall differed between locations as shown in *Table 2*.

### *Experimental design*

Each location was designed by randomized complete block design (RCBD) with three repetitions. Each experimental plot contained 5 rows with dimensions of 6.7 m for each genotype, 6–8 rows were surrounded by protected areas, and 3 rows of each plot were harvested on time. The field management of each plot was slightly more intense than the field level and involved timely chemical weeding and pest control. Field management and measurements were completed on the same day in case of special weather. Integrated pest management methods, including the use of bait to trap rats. Thrips and armyworm are the most important pests in maize seedling stage, and the control measure is to use 4.5% high efficiency cypermethrin 15000 times liquid spray per hectare. The control of weeds is carried out in two stages. In the first stage, weeds are controlled by chemical agents (methalamin 3000 ml/ha plus 450 kg/ha) at pre-emergence stage. The second stage is to use 225 ml/ha of nitrocellulose at a concentration of 225 kg/ha of nitrocellulose in the 3-5 leaves of the post-emergence stage. Both pre-emergence and post-emergence weeding are directed sprayed under windless conditions. The sowing date was carried out on 10<sup>th</sup>-20<sup>th</sup> of June of each location, and the harvest period was controlled from 1<sup>th</sup> to 10<sup>th</sup> of October during 2016-2017. Each location was reasonably arranged for fertilizer application according to the respective soil measurement conditions, 150-200 kg N ha<sup>-1</sup> and 100-130 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> were applied at the time of sowing date. The plant height and ear position of the hybrid were investigated during the milk maturity period, and lodging and folding were

investigated during the waxy stage. The traits of 100-grain weight, ear length, and kernel weight were investigated after harvest and the grain yield has been corrected for 14% moisture at each location.

**Table 1.** Basic information of the hybrids in the Zhongcheng maize combined regional trial in 2016–2017

Hybrid	Abbreviation	Growth period (d)	Breeding institute	Year
Jiyu 974	J974	106	Institute of Cereal and Oil Crops, Hebei Academy of Agriculture and Forestry Sciences	2016
Jiyu 610	J610	108	Institute of Cereal and Oil Crops, Hebei Academy of Agriculture and Forestry Sciences	2016
Jiyu 906	J906	106	Institute of Cereal and Oil Crops, Hebei Academy of Agriculture and Forestry Sciences	2016-2017
JL 658	JL658	105	Jifeng Seed Industry, Hebei	2016
Xingyu 26	X26	105	Xingtai Agricultural Science Research Institute	2016
Xingyu 375	X375	108	Xingtai Agricultural Science Research Institute	2016
Hengyu 1587	H1587	106	Dryland Farming Institute, Hebei Academy of Agriculture and Forestry Sciences	2016-2017
Hengyu 12	H12	106	Dryland Farming Institute, Hebei Academy of Agriculture and Forestry Sciences	2016
Shiyu 1501	S1501	108	Shijiazhuang Academy of Agricultural and Forestry Sciences	2016
Shiyu 1503	S1503	107	Shijiazhuang Academy of Agricultural and Forestry Sciences	2016-2017
Cangkeyu 1	C1	106	Cangzhou Academy of Agriculture and Forestry Sciences	2016
Tangyu 5115	T5115	108	Tangshan Academy of Agricultural and Forestry Sciences	2016
Zhengdan 958 CK	Z958	108	Henan Academy of Agriculture and Forestry Sciences	2016-2017
RT 3321	RT3321	107	Hebei Banghao Agricultural Development Co., Ltd.	2017
Cangyu 168	C168	108	Cangzhou Academy of Agriculture and Forestry Sciences	2017
Cangyu 268	C268	107	Cangzhou Academy of Agriculture and Forestry Sciences	2017
Hengyu 6084	H6084	106	Dryland Farming Institute, Hebei Academy of Agriculture and Forestry Sciences	2017
Jiyu 202	J202	107	Institute of Cereal and Oil Crops, Hebei Academy of Agriculture and Forestry Sciences	2017
Jiyu 7176	J7176	106	Institute of Cereal and Oil Crops, Hebei Academy of Agriculture and Forestry Sciences	2017
Tangyu 6925	T6925	108	Tangshan Academy of Agricultural and Forestry Sciences	2017
Xingyu 1511	X1511	106	Xingtai Agricultural Science Research Institute	2017
Xingyu 1799	X1799	106	Xingtai Agricultural Science Research Institute	2017

**Table 2.** Basic information of the locations and its code in the trials in 2016-2017

Location	Abbreviation	Longitude E	Latitude N	Altitude (m)	Annual rainfall (mm)	Year
Mancheng	MC	114°48'	38°52'	137	547	2016-2017
Handan	HD	114°54'	36°63'	55	515	2016-2017
Gaocheng	GC	114°85'	38°02'	59	494	2016-2017
Dingxing	DX	115°80'	39°20'	28	551	2016-2017
Shenzhou	SZ	115°56'	38°01'	29	482	2016-2017
Botou	BT	115°91'	38°09'	16	547	2016-2017
Luquan	LQ	114°20'	38°05'	90	540	2016-2017
Zhaoxian	ZX	114°76'	37°48'	42	351	2016-2017
Renxian	RX	114°40'	37°15'	33	498	2016-2017
Longyao	LY	114°46'	37°22'	35	524	2016-2017
Cangzhou	CZ	116°49'	38°18'	78	581	2016
Qingxian	QX	116°79'	38°58'	6	618	2016
Fengnan	FN	118°08'	39°34'	20	675	2016-2017
Qianying	QY	116°26'	38°21'	10	620	2017
Houying	HY	116°38'	38°44'	15	617	2017
Luanxian	LX	118°42'	39°45'	33	697	2017
Langfang	LF	116°42'	39°34'	27	554	2017
Yongnian	YN	114°38'	36°44'	48	583	2017

## Data analysis

### AMMI model

The formula for the AMMI model is as follows:

$$y_{ge} = \mu + \alpha_g + \beta_e + \sum_{n=1}^N \lambda_n \gamma_{gn} \delta_{en} + \theta_{ge} \quad (\text{Eq.1})$$

where  $y_{ge}$  represents the yield of genotype ( $g$ ) in the environment ( $e$ ),  $\mu$  is the grand mean,  $\alpha_g$  represents the average deviation of  $g$  from  $\mu$ ,  $\beta_e$  represents the average deviation of  $e$  from  $\mu$ ,  $\lambda_n$  is the  $n$ th eigenvalue of interaction effect principal component axis,  $\gamma_{gn}$  is the  $G$  principal component score representing the  $n$ th principal component,  $\delta_{en}$  represents the environmental principal component score of the  $n$ th principal component, and  $\theta_{ge}$  is the error term.

### GGE biplot method

The yield and ear trait data in the regional trials of the Zhongcheng combined regional maize trial were compiled into a two-way table with  $G$  and  $E$ . Each test value was the average value of each hybrid in the corresponding location, and the calculation formula is as follows:

$$Y_{ge} - y_e = \lambda_1 \xi_{g1} \eta_{e1} + \lambda_2 \xi_{g2} \eta_{e2} + \varepsilon_{ge} \quad (\text{Eq.2})$$

where  $Y_{ge}$  is the yield of genotype  $g$  in environment  $e$ ;  $y_e$  is the yield performance of all varieties in environment  $e$ ;  $\lambda_1\xi_{g1}\eta_{e1}$  and  $\lambda_2\xi_{g2}\eta_{e2}$  represent the first and second principal component scores of genotype  $g$  in the environment  $e$ , respectively;  $\lambda_1$  and  $\lambda_2$  are the eigenvectors of the first and second principal components, respectively;  $\xi_{g1}$  and  $\xi_{g2}$  are the first and second eigenvector scores of environment  $e$ , respectively; and  $\varepsilon_{ge}$  represents the residuals in the model (Balestre et al., 2009). AMMI model and GGE biplot analyses were performed using DPSV18.0 edition (Tang and Zhao, 2013).

## Results

### *Ear traits and yield performance of maize hybrids*

#### *100 kernel weight*

As shown in *Figure 1*, in 2016, the average 100-kernel weight was 39.03 g for Xingyu 26 and 38.85 g for Hengyu 12. These values were significantly higher than that of the control hybrid Zhengdan 958. The 100-kernel weight of Shiyu 1501 had a minimum value of 31.89, which was significantly lower than that of Zhengdan 958.

In the 2017 Zhongcheng combined regional maize trial, the average 100-kernel weights of Xingyu 1799, Jiyu 7176, Hengyu 6084, Tangyu 6925 and Hengyu 1587 were 39.21, 39.20, 37.38, 35.99, and 35.89 g, respectively. These values were significantly higher than that of Zhengdan 958. The average of 100-kernel weights of Jiyu 906, Jiyu 202, and RT3321 were lower than those of Zhengdan 958, but the differences between these values were not significant. The 100-kernel weights of other varieties were significantly lower than that of Zhengdan 958.

#### *Grain yield*

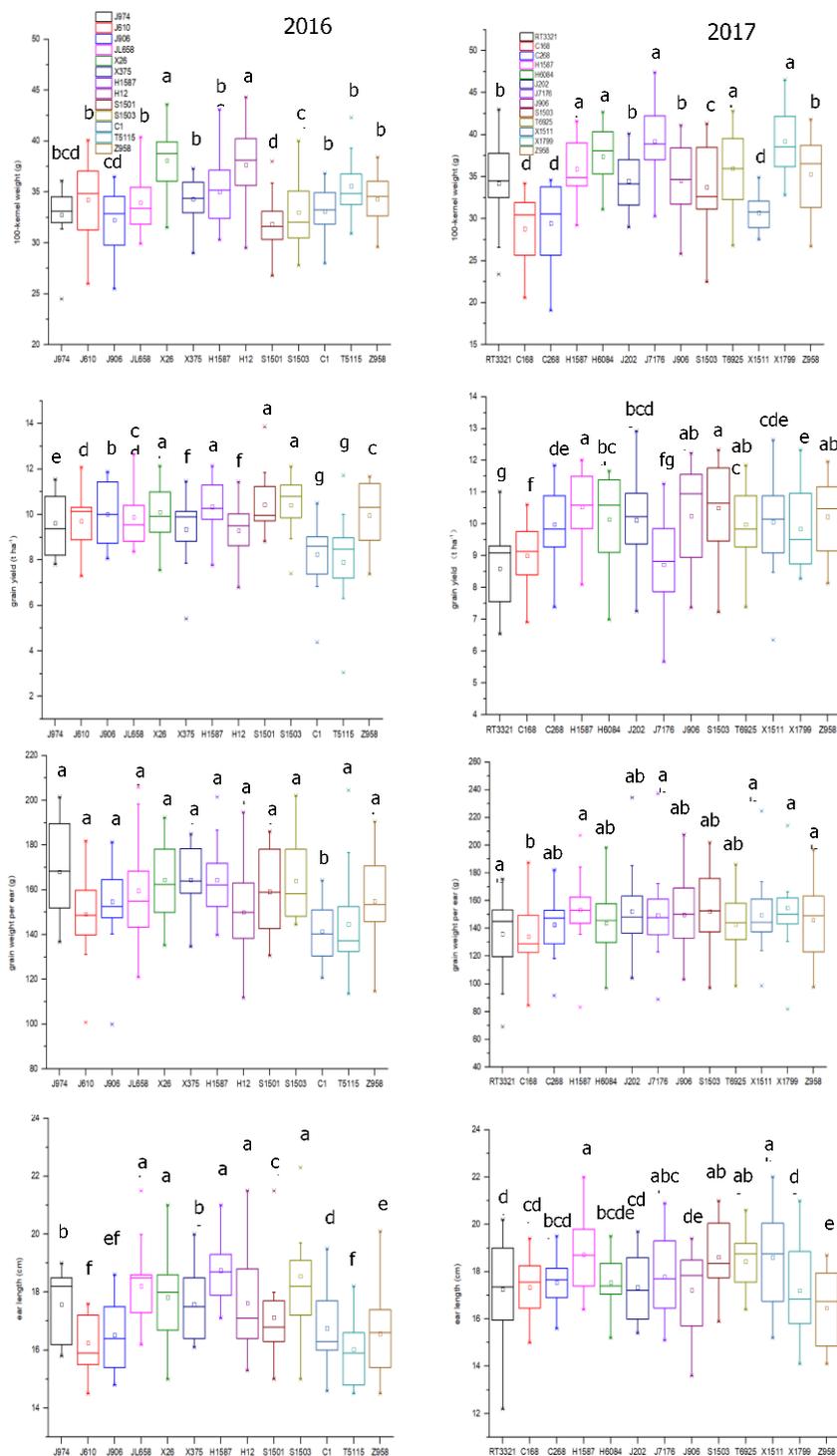
In the 2016 Zhongcheng combined regional maize trial, the highest average grain yield of Shiyu 1501 was 10.44 t ha<sup>-1</sup>. The average grain yields of Shiyu 1502 and Hengyu 1587 were 10.41 and 10.33 t ha<sup>-1</sup>, respectively, which ranked second and third, respectively. The highest average grain yields of Xingyu 26 and Jiyu 906 were 10.10 and 10.01 t ha<sup>-1</sup>, respectively. The average grain yields of the above hybrids increased significantly compared with those of the control hybrid Zhengdan 958. JL658 and the control Zhengdan 958 had the same yield, and the average grain yields of other hybrids were significantly reduced compared with those of the control.

In the 2017 Zhongcheng combined regional maize trial, the grain yields of Hengyu 1587, Shiyu 1503, Tangyu 6925 and Jiyu 906 were higher than those of Zhengdan 958 and were 10.53, 10.50, 10.40, and 10.26 t ha<sup>-1</sup>, respectively. No significant differences existed between these varieties and Zhengdan 958. The yields of Hengyu 6084, Jiyu 202 and Xingyu 1511 were 10.14, 10.12, and 10.06 t ha<sup>-1</sup>, respectively, and were insignificantly lower than those of the control. The grain yield of the other varieties was significantly lower than that of Zhengdan 958.

#### *Grain weight per ear*

In 2016, Jiyu 974 had the highest average grain weight per ear of 167.96 g, followed by Xingyu 375 (164.53 g) and Hengyu 1587. The average grain weight per ear of Xingyu 26 and Shiyu 1503 was 164.48 g. The average grain weights per ear of JL658 and Shiyu 1501 ranked fourth and seventh, respectively, and were insignificantly higher

than those of the control. The average grain weights per ear of Jiuyu 906, Hengyu 12, Tangyu 5115, and Cangkeyu 1 were lower than those of control hybrid. The average grain weight per ear of Cangkeyu 1 was the lowest (141.59 g) and was significantly different from that of Zhengdan 958.



**Figure 1.** Traits average performance of maize hybrids in 2016-2017. The lowercase letters indicate significant difference at the 0.05 level

In the 2017 test, Xingyu 1799 had the highest average grain weight per ear of 154.96 g, followed by Hengyu 1587 at 153.58 g and Jiyu 202 at 152.53 g. The average grain weights per ear of Hengyu 6084, Tangyu 6925, Cangyu 268, RT3321, and Cangyu 168 were lower than that of the control hybrid Zhengdan 958.

#### *Ear length*

In 2016, Hengyu 1587 had the highest average ear length of 18.75 cm, followed by Shiyu 1503 and JL 658. The average ear lengths of Xingyu 26, Hengyu 12, Shiyu 1501, and Cangkeyu 1 ranked fourth, fifth, sixth, and seventh, respectively, and were significantly higher than that of the control. The average ear lengths of Jiyu 906, Jiyu 610, and Tangyu 5115 were lower than that of the control. Significant difference was found between Jiyu 906 and Zhengdan 958 but not between the two hybrids and the control hybrid Zhengdan 958.

In 2017, the average ear length of all tested hybrids was higher than that of the control. Among them, Hengyu 1587 had the highest with 18.72 cm, followed by Shiyu 1503, Xingyu 1511, and Jiyu 7176 with 18.62, 18.61, and 17.78 cm, respectively. The differences between the above hybrids and the control were significant. The values for other hybrids did not reach significant levels.

#### *Analysis of AMMI model for various traits of maize hybrids*

##### *100-kernel weight*

Variance analysis for 100-kernel weight in 2016 showed that G, E, and GEI were extremely significant (*Table 3*). The squared sum of G accounted for 39.39% of the sum of squares. The square of the GEI had a total squared sum of 36.40%. The ratio of square sum to the sum of squares for E was the smallest at 24.21%. The interaction between G and GEI had a greater impact on 100-kernel weight than E. GEI was 1.5 times higher than E, indicating that the former is crucial for the reasonable evaluation of 100-kernel weight. GEI was decomposed by the AMMI model, and the interaction effects of the first two principal component axes (PCA1 and PCA2) reached extremely significant levels. The square sums of PCA1 and PCA2 accounted for 33.01% and 21.34% of the sum of the interaction effects, respectively.

Variance analysis for 100-grain weight in the 2017 trial showed that the squared sum of G and E accounted for 36.19% and 35.66% of the sum of squares, respectively (*Table 4*). GEI squared accounted for 28.15% of the sum of squares, and G effects and E effects reached extremely significant levels. However, GEI effect was not significant. AMMI model analysis showed that the *P*-value of the GEI effect expressed by PCA1 and PCA2 was less than 0.01 and reached a very significant level, and the sum of the squares accounted for 31.02% and 20.77% of the square of the interaction effect.

##### *Grain yield*

Variance analysis of grain yield in the 2016 regional trial showed that the square sum of the E accounted for 46.67% of the total squared sum, that of GEI accounted for 31.06%, and the square of G accounted for 22.26%. G, E, and GEI effects reached a very significant level. E effect accounted for the largest proportion of the total effect. The variations of E and GEI were 2.10 times and 1.40 times that of genotype variation,

respectively. Therefore, analyzing the stability of grain yield was necessary. PCA1 and PCA2 accounted for 41.04% and 23.55% of the sum of the GEI effects, respectively, and both reached extremely significant levels.

**Table 3.** Results of each trait analysis of variance and AMMI model analysis in 2016

Items	Source of variation	Degree of freedom	Sum of squares	Mean square	F value	P value	Percentage of total sum of squares (%)
100-kernel weight	Total	168	1907.70	11.36			
	Genotype	12	751.35	62.61	17.60**	< 0.0001	39.39
	Environment	12	461.95	38.50	10.82**	< 0.0001	24.21
	Genotype and environment interaction (G×E)	144	694.39	4.82	1.36*	0.0431	36.40
	PCA1	23	229.21	9.97	2.80**	0.0002	33.01
	PCA2	21	148.20	7.06	1.98*	0.0114	21.34
	Error	119	423.33	3.56			
Grain yield	Total	168	433.20	2.58			
	Genotype	12	96.45	8.04	14.53**	< 0.0001	22.26
	Environment	12	202.19	16.85	30.45**	< 0.0001	46.67
	Genotype and environment interaction (G×E)	144	134.56	0.93	1.69**	0.0016	31.06
	PCA1	23	55.22	2.40	4.34**	< 0.0001	41.04
	PCA2	21	31.69	1.51	2.73**	0.0003	23.55
	Error	119	65.84	0.55			
Grain weight per ear	Total	168	76763.01	456.92			
	Genotype	12	11106.85	925.57	4.94**	< 0.0001	14.47
	Environment	12	35443.89	2953.66	15.75**	< 0.0001	46.17
	Genotype and environment interaction (G×E)	144	30212.27	209.81	1.12	0.2636	39.36
	PCA1	23	7530.63	327.42	1.75*	0.0286	24.93
	PCA2	21	5992.86	285.37	1.52	0.0827	19.84
	Error	119	22317.71	187.54			
Ear length	Total	168	449.73	2.68			
	Genotype	12	120.15	10.01	12.79**	< 0.0001	26.72
	Environment	12	169.18	14.10	18.02**	< 0.0001	37.62
	Genotype and environment interaction (G×E)	144	160.41	1.11	1.42*	0.0233	35.67
	PCA1	23	53.34	2.32	2.96**	0.0001	33.25
	PCA2	21	36.94	1.76	2.25**	0.0033	23.03
	Error	119	93.13	0.78			

**Table 4.** Results of each trait analysis of variance and AMMI model analysis in 2017

Items	Source of variation	Degree of freedom	Sum of squares	Mean square	F value	P value	Percentage of total sum of squares (%)
100-kernel weight	Total	207	5761.09	27.83			
	Genotype	12	2084.88	173.74	26.05**	< 0.0001	36.19
	Environment	15	2054.31	136.95	20.54**	< 0.0001	35.66
	Genotype and environment interaction (G×E)	180	1621.90	9.01	1.35*	0.0278	28.15
	PCA1	26	503.11	19.35	2.90**	< 0.0001	31.02
	PCA2	24	336.86	14.04	2.10**	0.0037	20.77
	Error	152	1013.58	6.67			
Grain yield	Total	207	433.36	2.09			
	Genotype	12	79.77	6.65	14.32**	< 0.0001	18.41
	Environment	15	208.74	13.92	29.97**	< 0.0001	48.17
	Genotype and environment interaction (G×E)	180	144.86	0.80	1.73**	0.0003	33.43
	PCA1	26	58.51	2.25	4.85**	< 0.0001	40.39
	PCA2	24	33.12	1.38	2.97**	< 0.0001	22.87
	Error	152	70.58	0.46			
Grain weight per ear	Total	207	153812.95	743.06			
	Genotype	12	8316.55	693.05	3.58**	0.0001	5.41
	Environment	15	99346.57	6623.10	34.24**	< 0.0001	64.59
	Genotype and environment interaction (G×E)	180	46149.83	256.39	1.33*	0.0366	30.00
	PCA1	26	15342.13	590.08	3.05**	< 0.0001	33.24
	PCA2	24	8937.10	372.38	1.93**	0.0095	19.37
	Error	152	29399.43	193.42			
Ear length	Total	207	581.60	2.81			
	Genotype	12	92.25	7.69	9.01**	< 0.0001	15.86
	Environment	15	296.43	19.76	23.15**	< 0.0001	50.97
	Genotype and environment interaction (G×E)	180	192.92	1.07	1.26	0.0738	33.17
	PCA1	26	49.37	1.90	2.22**	0.0015	25.59
	PCA2	24	47.94	2.00	2.34**	0.0010	24.85
	Error	152	129.76	0.85			

Variance analysis for 2017 showed that G, E, and GEI accounted for 18.41%, 48.17% and 33.43% of the total squared sum, respectively, and all of them reached extremely significant levels. The variations in E and GEI were 2.62 and 1.82 times

higher than those of G. GEI was decomposed by the AMMI model, and the interaction information between PCA1 and PCA2 reached a very significant level. PCA1 and PCA2 accounted for 40.39% and 22.87% of the sum of square effects, respectively.

#### *Grain weight ear*

Variance analysis of regional trials in 2016 and 2017 showed that G and E differences reached extremely significant levels. GEI did not reach significant levels in 2016 but was significantly different in 2017. Environmental variation accounted for the majority of the variation in the 2-year regional trial. In 2016 and 2017, the sum of the squared environmental variances accounted for 46.17% and 64.59% of the total squared sum, respectively. The variations in GE and GEI were 2.72 and 5.55 times those of G effects, respectively. In 2016, PCA1 and PCA2 explained 44.77% and 52.61% of the square of the interaction effect. In 2016, the PCA1 interaction information reached a significant level, and PCA2 did not reach a significant level. PCA1 and PCA2 reached a very significant level in 2017.

#### *The ear length*

The variance analysis of ear length in 2016 showed that the squared sums of G, E, and GEI accounted for 26.72%, 37.62%, and 35.67%, respectively. G and E reached extremely significant differences. GEI effect reached a significant difference. AMMI model analysis showed that the square sum of PCA1 and PCA2 accounted for 33.25% and 23.03% of the sum of the square effects of the interaction, respectively. Both reached extremely significant levels. The AMMI model provided a thorough analysis of GEI effects.

Variance analysis revealed a significant difference between G and E in 2017. The sum of the squares accounted for 15.86% and 50.97% of the total squared sum, respectively, and the square of the interactions accounted for 33.17% of the total square but did not reach a significant level. The results of AMMI model analysis showed that PCA1 and PCA2 accounted for 50.44% of the sum of squares of interactions and reached extremely significant differences.

#### ***Adaptability analysis of tested varieties based on GGE biplot***

The GGE biplot visually represents the varieties with outstanding performance in different environments with different traits. Each of the “vertex” hybrid in the biplot is sequentially connected by a straight line to form a polygon, which is divided into a plurality of sectors from its origin. Each test environment is embedded in the sector. The “top angle” hybrid in each sector is the best-performing genotype in a certain environment (Yue et al., 2019a).

#### *100-kernel weight*

Adaptive analysis showed that the biplot map for 100-kernel weight in 2016 was divided into six sectors (*Fig. 2-A1*). Shenzhou, Fengnan, and Renxian were in the first sector. Xingyu 26 performed best in this sector. The remaining locations were divided into the second sector, and Hengyu 12 was the best performing hybrid. Adaptive analysis showed that the biplot map for 100-kernel weight in 2017, and the biplot map was divided into four sectors (*Fig. 2-B1*). The first sector included three locations in Shenzhou, Gaocheng, and Dingxing. Tangyu 6925 performed best in this sector. Hengyu 6084 had

good adaptability in Zhaoxian, Botou, Qixian, and Luquan, and Hengyu 6084 showed the best performance in the second sector. The remaining locations were distributed in the third sector, wherein Xingyu 1799 and Jiyu 7176 showed the best performance. The fourth sector did not show a location, indicating that Cangyu 168, Cangyu 268, and Xingyu 1511 in this sector were not satisfactory in all locations.

### *Grain yield*

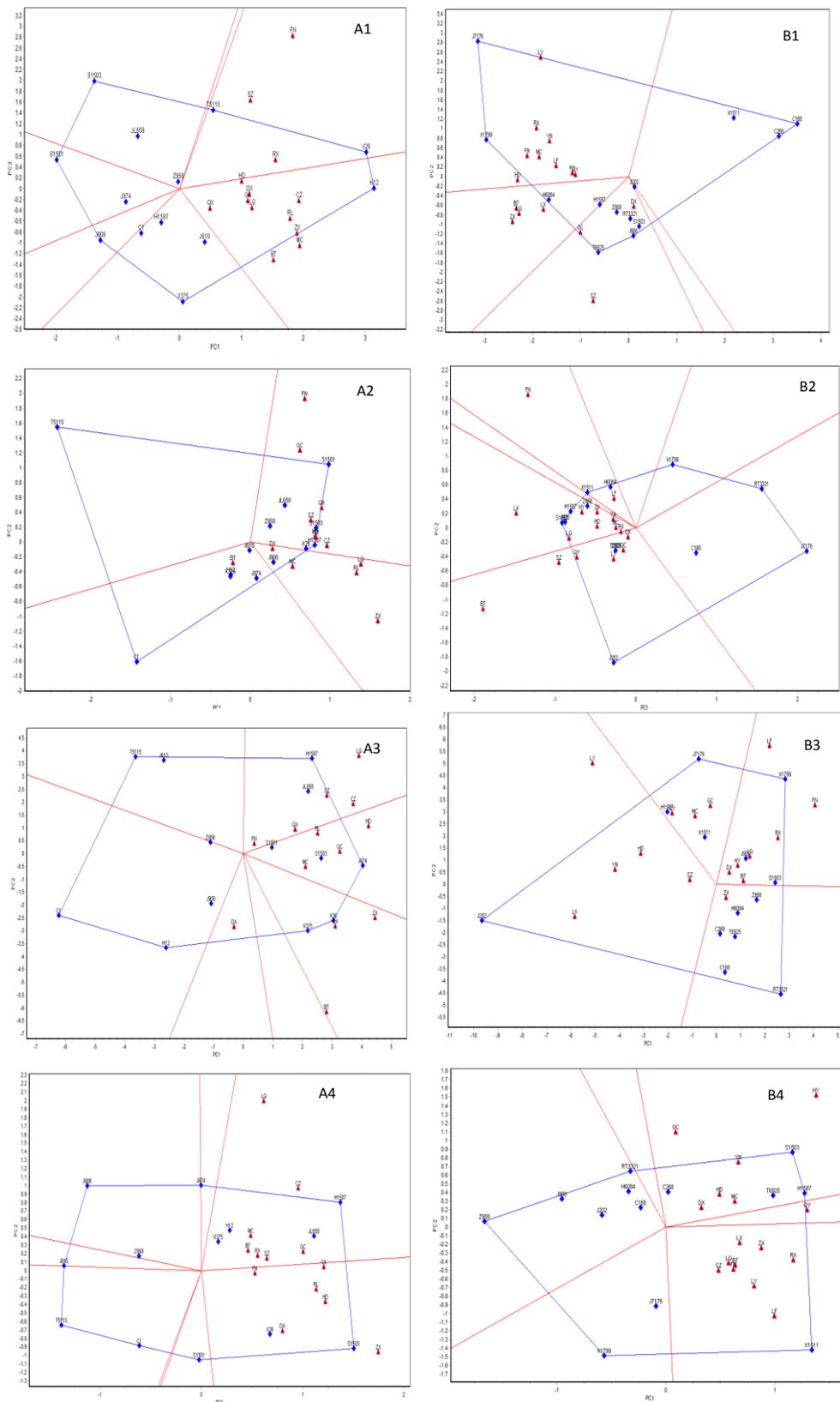
The 13 locations of the 2016 regional trial were divided into three sectors (*Fig. 2-A2*). Only Botou was located in the first sector, and Cangkeyu 1 showed the best performance. Zhaoxian, Longyao, Luquan, Mancheng, Dingxing, Cangzhou, Shenzhou, Gaocheng, Fengnan, and Qingxian were located in the second sector. Hengyu 1587 and Shiyu 1501 performed well in these locations. The third sector did not contain a location and included only Tangyu 5115. This result showed that Tangyu 5115 performed poorly in all locations. In 2017, the 16 plots of regional trial were divided into four sectors (*Fig. 2-B2*). Jiyu 202 exhibited outstanding performance in Botou, Shenzhou, Qianying, Gaocheng, Dingxing, and Longyao. Shiyu 1503 performed best in the remaining locations, and Hengyu 1587, Xingyu 1511, and Xingyu 1799 had strong adaptability.

### *Grain weight per ear*

In 2016, 13 plots were divided into five sectors (*Fig. 2-A3*). Luquan, Cangzhou, Shenzhou, Qingxian, and Fengnan were classified as the first sector, and Hengyu 1587 had good adaptability in the above locations. The second sector had four locations, namely, Handan, Gaocheng, Mancheng, and Longyao. Jiyu 974 performed best in this sector. Renxian, Zhaoxian, and Botou were located in the third sector, and Xingyu 26 performed best. The fourth sector had only one location, and Cangkeyu 1 and Hengyu12 performed well in the Dingxing location. A location drop was not observed in the fifth sector, indicating that Tangyu 5115 and Jiyu 610 in this sector did not perform well in all locations. In 2017, 16 plots of the regional trial were divided into four sectors (*Fig. 2-B3*). The first sector only had one location in Zhaoxian, and RT3321 performed best in this sector. Botou, Dingxing, Langfang, Fengnan, Houying, and Luquan belonged to the second sector, and Xingyu 1799 had good adaptability in these locations. Mancheng, Yucheng, and Qianying belonged to the third sector, and Jiyu 7176 performed best. The remaining locations belonged to the fourth sector, and Jiyu 202 performed best.

### *Ear length*

The adaptation analysis of the 2016 regional trial based on ear length showed that Shiyu 1503 performed best in the locations of Dingxing, Qingxian, Handan, and Zhaoxian. Hengyu 1587 had strong adaptability in Luquan, Zhangzhou, Yucheng, Shenzhou, Botou, Mancheng, and Renxian. Jiyu 974, Jiyu 906, Jiyu 610, Tangyu 5115, Shiyu 1501, and Cangkeyu 1 had unsatisfactory performances in all locations (*Fig. 2-A4*). The results of the adaptation analysis of the 2017 regional trial based on ear length were obtained (*Fig. 2-B4*). Xingyu 1511 showed good adaptability in Langfang, Longyan, Renxian, Zhaoxian, Qixian, Shenzhou, Luquan, and Botou locations. Shiyu 1503 and Hengyu 1587 had good adaptability in different locations, such as Gaocheng, Dingxing, Handan, Mancheng, Houying, and Yongnian. The performance of all varieties in Qianying was not satisfactory, and the performances of Zhengdan 958 and Xingyu 1799 were not satisfactory in all the locations.



**Figure 2.** Adaptability analysis of maize hybrids based on GGE-biplot analysis. A: field data in 2016; B: field data in 2017; 1: 100-kernel weight; 2: grain yield; 3: grain weight per ear; 4: ear length (similarly hereinafter, the same below)

### ***Analysis of the high yield and stability of the tested varieties based on GGE biplot***

The small diamond in *Figure 3* represents the average environment, and the central straight line represents the average environmental axis. The genotypes in the double plot is perpendicular to the average environmental axis, and the high yield of the hybrids can be determined in accordance with the position and length of the vertical line. Vertical lines close to the average environment indicate that traits have high average values and are superior. Short vertical lines are indicative of small deviations from the average environmental axis and high trait stability (Sujay et al., 2012).

#### ***100-kernel weight***

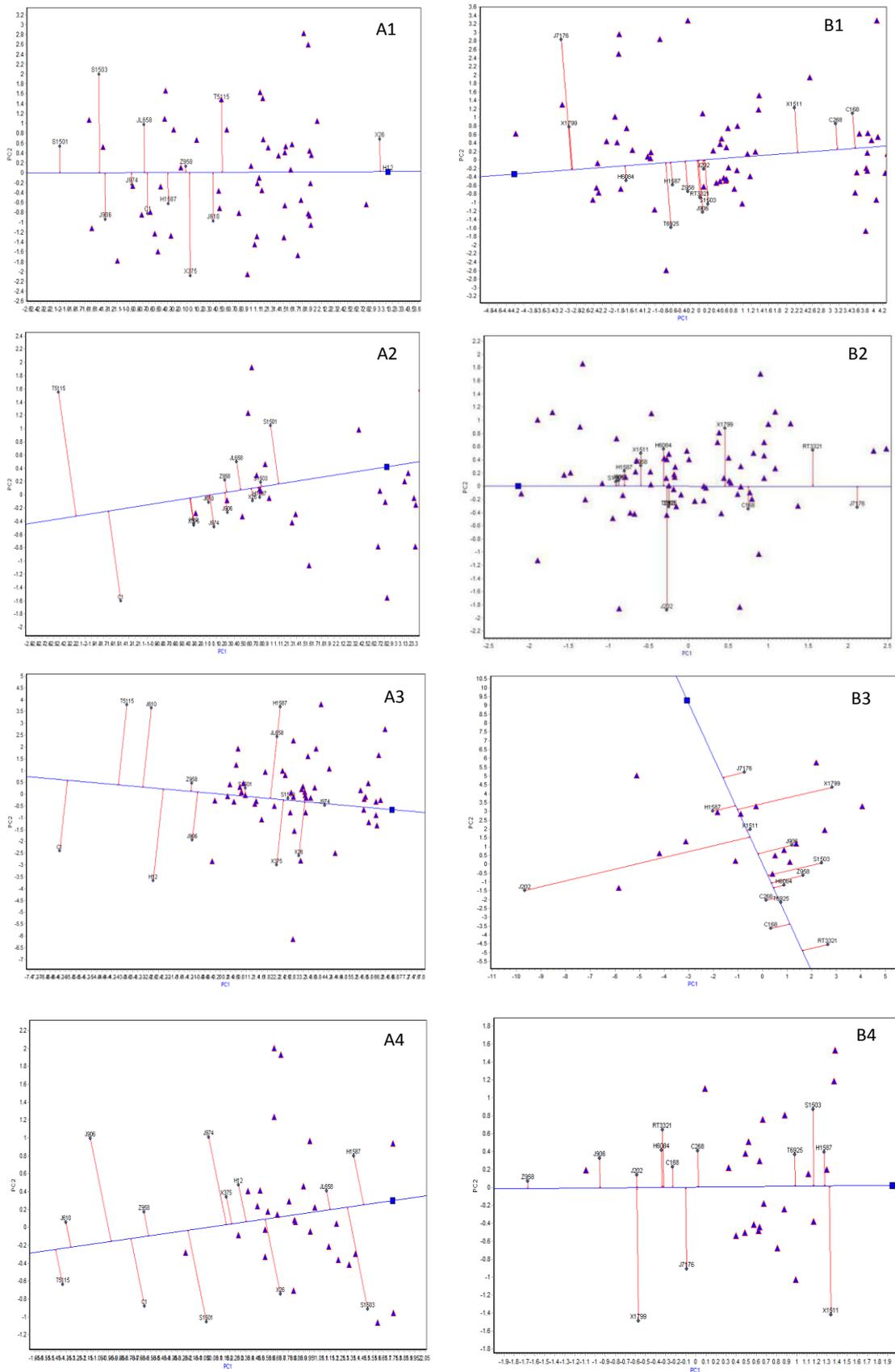
The analysis of 100-kernel weight and stability in the 2016 Zhongcheng combined regional maize trial revealed that Hengyu 12 had the highest weight, followed by Xingyu 26, Tangyu 5115, and Jiyu 610. Jiyu 906, Shiyu 1503, and Shiyu 1501 had poor performances in terms of 100-kernel weight. Hengyu 12, Zhengdan 958, Jiyu 974, Hengyu 1587, and Cangkeyu 1 had good stability, and Tangyu 5115, Xingyu 375, and Shiyu 1503 had poor performances (*Fig. 3-A1*). In the 2017 regional trial, Jiyu 7176 and Xingyu 1799 were closer to the average environment than other varieties. These two varieties had good 100-kernel weight performance. The performances of these varieties were followed by those of Hengyu 6084, Tangyu 6925, and Hengyu 1587. Xingyu 1511, Cangyu 268, and Cangyu 168 had low average 100-kernel weight. The stabilities of the 100-kernel weights of Jiyu 7176, Xingyu 1799, and Tangyu 6925 were poor, and those of the 100-kernel weights of Jiyu 202, Hengyu 6084, and Hengyu 1587 were good (*Fig. 3-B1*).

#### ***Grain yield***

The grain yield in 2016 was analyzed (*Fig. 3-A2*). The yields of Shiyu 1501, Shiyu 1503, Hengyu 1587, and Xingyu 26 exceeded those of the control Zhengdan 958, Tang 5115, Cangkeyu 1, and Shiyu 1501, and the stability of the three varieties was significantly lower than that of the remaining varieties. In the 2017 regional trial, the yields of Shiyu 1503, Hengyu 1587, and Jiyu 906 were superior to those of Zhengdan 958. Cangyu 168, Cangyu 268, Hengyu 1587, and Shiyu 1503 had good stability (*Fig. 3-B2*).

#### ***Grain weight per ear***

In the 2016 regional trial, the average grain weights per ear of Jiyu 974 were the highest, followed by those of Xingyu 26, Shiyu 1503, Xingyu 375, and Hengyu 1587. Cangkeyu1 had the lowest average grain weight per ear. The grain weight stabilities of Jiyu 974, Shiyu 1501, Shiyu 1503, and Zhengdan 958 were high, and those of other varieties were low (*Fig. 3-A3*). In the 2017 regional trial, the average grain weights of Jiyu 7176 were the highest, followed by those of Hengyu 1587, Xingyu 1799, Xingyu 1511, Jiyu 202, Jiyu 906, and Shiyu 1503. The average grain weights of the remaining varieties were lower than those of the control variety Zhengdan 958. The grain weight stabilities of Tangyu 6925, Xingyu 1511, Cangyu 268, and Hengyu 6084 were high, and those of Jiyu 202, Xingyu 1799, and Shiyu 1503 were poor (*Fig. 3-B3*).



**Figure 3.** The yielding and stability of each trait of maize hybrids based on GGE-biplot analysis

### *Ear length*

In the 2016 regional trial, the average ear length of Hengyu 1587 was the highest, and those of Shiyu 1503 and JL658 were ranked second and third, respectively. Those of Cangkeyu 1, Jiyu 906, Jiyu 610, and Tang 5115 were lower than those of the control. The ear lengths of Jiyu 658, Xingyu 375, Hengyu 12, Hengyu 1587, Tangyu 5115, and Zhengdan 958 were stable, and those of other varieties were unstable (*Fig. 3-A4*). In the 2017 regional trial, the average ear lengths of Xingyu 1511, Hengyu 1587, Shiyu 1503, and Tangyu 6925 were high, and Zhengdan 958 had the lowest average ear length. Zhengdan 958, Jiyu 202, Cangyu 168, and Hengyu 1587 had high stability, and Shiyu 1503, Jiyu 7176, Xingyu 1511, and Xingyu 1799 had poor stability (*Fig. 3-B4*).

### *Analysis of ideal varieties based on GGE biplot*

The GGE biplot can be used to visually and clearly determine the position of an ideal genotype. The ideal hybrid is the genotype with the highest average yield and the best stability in all test environments. The ideal hybrid is presented as the center of a multilayered concentric circle, and the pros and cons of the tested hybrids are judged on the basis of their distance from the ideal hybrid. Genotypes close to the center of the concentric circle have good performance, and those far from the center of the circle have poor performance (Kendal and Tekdal, 2019).

### *100-kernel weight*

As shown in *Figure 4-A1*, Hengyu 12 and Xingyu 26 were closer to the center of the concentric circle than other hybrids. These two hybrids had high 100-kernel weights and were stable. Jiyu 906, Shiyu 1503, and Shiyu 1501 were far from the center of the concentric circle and had low 100-kernel weights and poor stability. As shown in *Figure 4-B1*, Xingyu 1799 was closest to the center of the concentric circle, indicating that this hybrid had a high kernel weight and good stability. Xingyu 1511, Cangyu 268, and Cangyu 168 were far from the center of the concentric circle and had low 100-grain weights and poor stability.

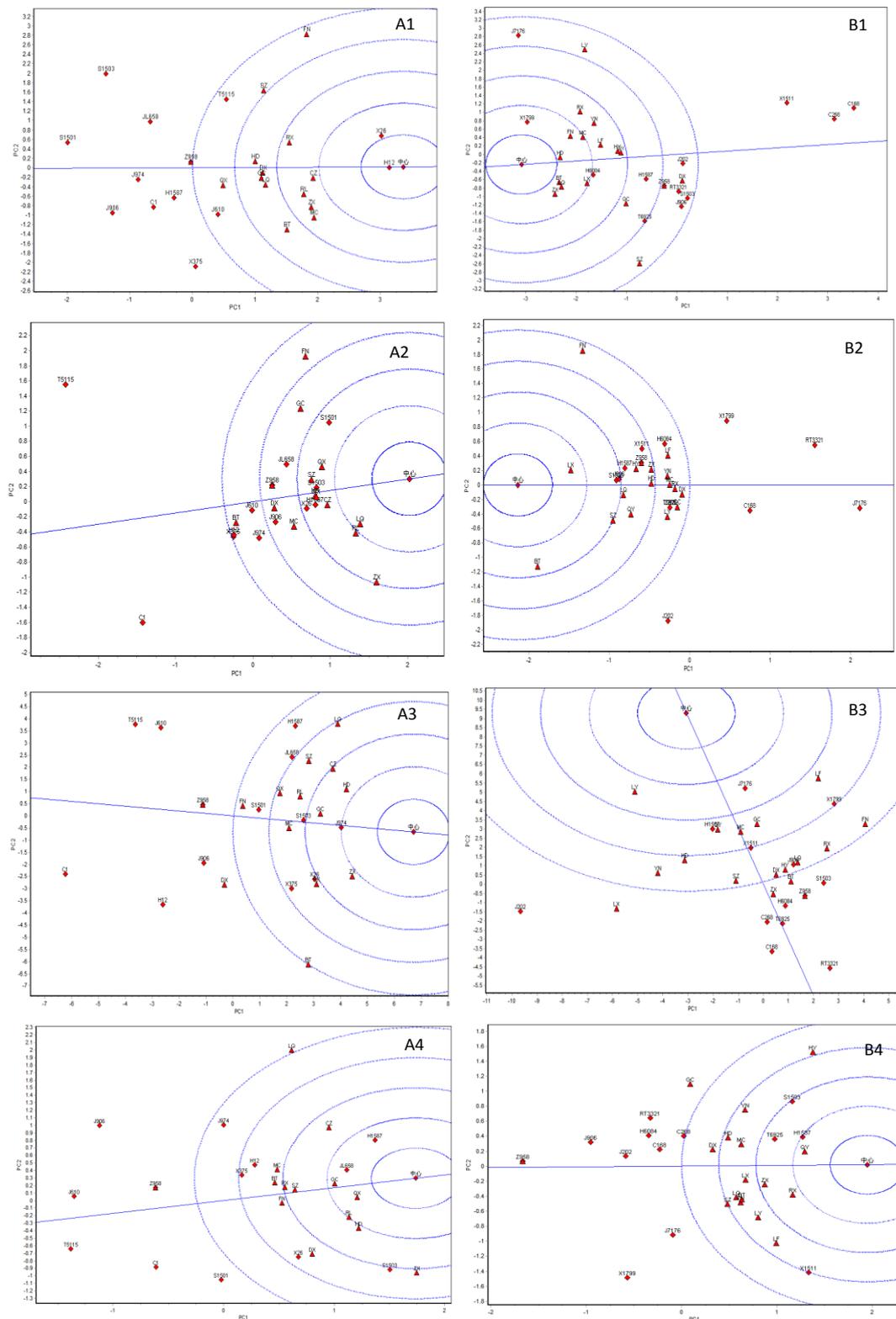
### *Grain yield*

As illustrated in *Figure 4-A2*, Shiyu 1501, Shiyu 1503, and Hengyu 1587 were close to the center of the concentric circle, indicating that these genotypes had good yield and stability. Cangkeyu 1 and Tangyu 5115 were far from the center of the circle and had low yield and poor stability. *Figure 4-B2* shows that Shiyu 1503, Jiyu 906, and Hengyu 1587 were closest to the center, indicating that these three varieties were high yielding and stable. Jiyu 202, Xingyu 1799, Cangyu 168, RT3321, and Xingyu 7176 were far from the center and had poor yield and stability.

### *Grain weight per ear*

In 2016, Jiyu 974 was the closest to the center of concentric circles, indicating that its grain weight per ear was the highest and its stability was the best. The grain weight per ear of Cangkeyu 1 was opposite to that of Jiyu 974 and was the worst (*Fig. 4-A3*). In the 2017 regional trial, the grain weight per ear of Jiyu 7176 was the closest to the ideal value. Jiyu 7176 was a genotype with high grain weight per ear and good stability. The

grain weights per ear of Hengyu 1587, Xingyu 1511, and Xingyu 1799 were ideal, and the comprehensive performances of Cangyu 168 and RT3321 were poor (Fig. 4-B3).



**Figure 4.** Comparisons of maize tested varieties with the ideal cultivar for each trait based on GGE biplot

### *Ear length*

It can be seen from *Figure 4-A4* that the closest ideal genotypes in 2016 were Hengyu 1587 and JL 658, and the overall performance of the ear length was better. Genotypes such as Shiyu 1501, Cangkeyu 1, Zhengdan 958, Jiyu 906, Jiyu 610 and Tang 5115 had poor overall performance and are not ideal genotype. In the 2017 regional trial, Hengyu 1587 was the closest to the center of concentric circles, indicating that its overall ear length was excellent and belongs to the ideal genotype. Jiyu 202, Xingyu 1799, Jiyu 906 and Zhengdan 958 were far away from the center of concentric circles. Among them, Zhengdan 958 was the farthest from the center, and the overall performance of ear length was the worst (*Fig. 4-B4*).

### **Discussion**

The traits of crop varieties are the results of G, E, and GEI. GEI directly affects the stability of varietal traits (Tekdal and Kendal, 2018). This study showed that in addition to 100-kernel weight, the effects of GEI on three agronomic traits were less than those of E, but had significant effects on traits that were greater than those of G. The GEI effect of three traits, such as grain yield, grain weight per ear, and ear length in 2016–2017 was 1.3-5.5 times that of G (Balestre et al., 2009; Badu-Apraku et al., 2012; Yue et al., 2019b). This result is consistent with previous results. Trait differences caused by crop G changes and GEI effects must be considered in the regional trial analysis of crop varieties. Only by fully studying and utilizing the effects of GEI can breeding efficiency be considerably improved. This requires us to promote corn production and rationally distribute of varieties. First, the appropriate promotion area must be selected in accordance with local light and heat resources. Then, suitable varieties must be screened on the basis of characteristics. The influence of GEI on varietal traits must be emphasized (Kandus et al., 2010). The 2-year analysis of variance showed that the 100-kernel weight of the tested varieties was less affected by external E and GEI. This indicates that 100-kernel weight is an inherent characteristic of the hybrid and is not easily affected by environmental changes. The expression of this trait is dominated by genotype effects.

The research and mastery of the variation in maize panicle traits are important bases for the breeding of high-yielding and stable maize hybrids and developing supporting cultivation techniques. Therefore, the stability analysis of important panicle traits and grain yield of maize genotypes can help fully understand the variation factors of varietal traits. The AMMI model can be used to calculate the AMMI stability value of the tested varieties in the form of a table and judge whether a genotype is high yielding and stable. The model focuses on GEI and enables the stability analysis of the genotypes. However, it fails to fully describe the adaptability of the varieties. The GGE biplot analysis compensates for this shortcoming. The GGE biplot map is a visual representation of the adapted area of the tested genotypes in a polygonal manner. This method focuses on the evaluation of varietal adaptability and yield (Erdemci, 2018; Malik et al., 2019). The GGE biplot analysis of the 2016 regional trial showed the adaptability of varieties on the basis of 100-kernel weight performance. Xingyu 26 and Hengyu 12 showed wide adaptability. The analysis of grain yield revealed that Hengyu 1587 and Shiyu 1501 had wide adaptability in 10 locations. The analysis of grain weight per ear revealed that Hengyu 1587, Jiyu 974, and Xingyu 26 had good adaptability in their respective regions. The analysis of ear length performance indicated that Shiyu 1503 and Hengyu

1587 had wide adaptability. According to the 100-kernel weight adaptation analysis of the GGE biplot of the regional trial in 2017, Tangyu 6925, Hengyu 6084, Xingyu 199 and Jiyu 7176 had strong adaptability. The analysis of grain yield showed that Jiyu 202, Shiyu 1503, Hengyu 1587, Xingyu 1511, and Xingyu 1799 were widely adaptable. The analysis of grain weight per ear indicated that Xingyu 1799, Jiyu 7176, and Jiyu 202 had wide adaptability. Ear length analysis revealed that Shiyu 1503 and Xingyu 1511 had wide adaptability.

Ideal genotypes have high yield, stability, and wide adaptability in different environments. In fact, this is an ideal assumption and is rare in actual agricultural production. The high yield, stability, and adaptability of crop varieties are important indicators in breeding. Breeders tend to focus on genotypes with good yield stability but often overlook varieties with high yield and outstanding stability but limited adaptability (Jain et al., 2019). The rational use of maize hybrids should be based on the premise of high yield, and some varieties with good stability and adaptability should be selected. Selecting hybrids with good stability and adaptability from genotypes with poor yield is inadvisable. The stability of maize hybrids must be based on the premise of high yield. The regional trials of maize hybrids revealed that some genotypes are suitable for specific regions. For example, in 2016, Cangkeyu 1 exhibited the best grain yield in the environment of Botou but showed general performance at other locations. It had the highest grain weight per ear in the Dingxing environment. In 2017, the grain yield of Jiyu 202 ranked first in the environments of Botou, Shenzhou, Qianying, Gaocheng, Dingxing, and Longyao but had general overall performance in the remaining locations. Cangkeyu 1 and Jiyu 202 had special adaptability and can be planted in suitable areas. Therefore, we should not only pay attention to genotypes with perfect characteristics, but also to the identification and utilization of special adaptive hybrids in production practice (Rakshit et al., 2012; Yue et al., 2019). Through the analysis of the results of AMMI and GGE in this study, the two analytical methods had similar results considering the specific adaptability to environmental conditions. Due to the GEI, both AMMI and GGE can effectively explore the variability in multi environmental trials (Mets) data, and both methods have been shown to be approximately equivalent, thus screening for genotypes with the highest yield and high stability (Neisse et al., 2018; Kendal et al., 2019).

## Conclusion

Multi environmental trials are an effective means to identify good or bad maize hybrids. The scientific evaluation of the stability, yield, and adaptability of maize genotypes is an important link before the promotion of hybrids. We evaluated important agronomic traits, such as 100-kernel weight, grain yield, grain weight per ear and ear length of maize hybrids using the AMMI model and GGE biplot analysis. We observed significant differences in agronomic traits between different genotypes and environments and significant or extremely significant GEIs. Combined with the performance of 2 years of experiments, Hengyu 1587 and Shiyu 1503 presented good comprehensive performance, while Cangkeyu 1 and Jiyu 202 showed special adaptability. The comprehensive application of AMMI and GGE biplot can more accurately and intuitively evaluate the high yield, stability and adaptability of each hybrid as well as the resolution and representativeness of each location. This research can provide valuable theoretical reference for the identification and promotion of new maize hybrids.

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