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COMPREHENSIVE ASSESSMENT OF REGIONAL TRIALS OF SORGHUM VARIETIES ACCORDING TO GGE BIPLOTS

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Abstract

As the primary multigrain crop in China, increased demand for sorghum poses great challenges to its high and stable yield. In this study, the stability and adaptation of seven sorghum varieties were assessed in seven sites over two years (2022-2023). ANOVA results showed that the yield, spike weight, plant height, and spike length were significantly different with respect to years (Y), environment (E), genotype (G), Y×E, Y×G, E×G, and Y×E×G, among which environment-related interaction terms contributed the largest variation to average yield and spike weight across all varieties. GGE biplot analysis based on these principal components showed that G2 ranked highest for yield and spike weight and was the most stable variety, outperforming the others and meeting the requirements of growers. E1 and E6 were best represented in the seven sites and served as the best-identified sites in the sorghum regional trials.

Key words: Sorghum; Yield; Stability; Adaptability; GGE biplots

Introduction

Sorghum constitutes a principal crop across arid and semi-arid areas on a global scale, and one of the earliest grain crops in China (Aruna *et al*., 2016; Al-Naggar *et al*., 2018; Omrani *et al.*, 2022). As a typical C4 crop, it has strong drought resistance, waterlogging tolerance, and salt-alkali tolerance (Bai *et al*., 2023). In 2022, the planting area of sorghum in China was 6.745 million hectares and its total production reached 3.094 million tons . According to geographical location, climatic conditions, and sowing time, sorghum cultivation in China is separated into four regions: early spring, late spring, spring-summer concurrent, and southern . Yield and yield-related traits are multifaceted quantitative traits controlled by multiple genes, manifesting the genotype (G), environment (E), and genotype-environment interaction (G×E) (Teodoro *et al*., 2016; Dariush *et al*., 2023; Fatemeh *et al*., 2023; Azon *et al*., 2023; Habtamu, 2024). Breeding high-quality, high-yielding varieties is an essential approach to increasing sorghum yield and is a major focus of breeders (Hasan *et al*., 2021; Gao *et al*., 2022; Gezahagn *et al*., 2023). Varieties with high and stable yields across different environments have the potential for promotion and utilization (Impa *et al*., 2019; Hou *et al*., 2024).

Using scientific methods to reduce and simplify multi-environment data can assist breeders in analyzing the performance of given varieties (Jeberson *et al*.,2017; Da *et al*., 2021; Ishola *et al*., 2023; Joshi *et al*., 2024). The GGE biplot analysis is commonly employed to study genotype (G), environment (E) and genotype × environment interaction (G×E), to assess yield stability across environments, and to identify ideal test environments (Kempton, 1984; Liu *et al*., 2022; Lal *et al*., 2023; Maria *et al*., 2023; Maulana *et al*., 2023). By partitioning the G×E effect graphically, the relative importance of G×E interaction and of genotype variance can be examined, providing an intuitive and quantitative description of the differences among varieties (Sujay *et al*., 2012; Sujay *et al*., 2014; Wubshet *et al*., 2023; Shakya *et al*., 2023). The GGE biplot analysis has been widely applied to regional trials in the United States, Canada and other countries (Hailemariam *et al*., 2017; Taryono *et al*., 2022). Kempton first employed the biplots to analyze the interaction between wheat varieties and environments in 1971. Al-Naggar used the models of AMMI and GGE-biplots to analyze the yield adaptability and stability of sorghum genotypes under different environments in Egypt (Al-Naggar *et al*., 2018; Wang *et al*., 2023). The GGE biplot analysis has also been used to examine the performance and stability of sorghum genotypes in western Ethiopia, showing that G×Y, G×E and G×Y×E interactions significantly affected genotype performance (Wardofa *et al*., 2019).

This study was based on the National Sorghum Regional Trial of China and used the test sites and varieties of 2022 and 2023; GGE biplot analysis, performed with the GGEBiplotGUI package in R, was used to evaluate the yield and yield-related traits of the different varieties. The results provide data support for optimizing the promotion and application of sorghum varieties and a scientific basis for sorghum breeding.

Although GGE biplot analysis has been widely applied to sorghum and other cereal crops, most earlier studies were based on a single year or on a small number of environments, and they seldom compared the discriminating ability and representativeness of individual test sites across consecutive cropping seasons; the few Chinese sorghum studies that used this approach focused mainly on yield and did not evaluate several agronomic traits simultaneously. The present study differs from these earlier analyses in three respects. First, it

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is based on the National Sorghum Regional Trial and includes seven test sites and seven varieties released by different breeding units, so that the results are directly relevant to variety release and site selection in China. Second, it combines two years (2022–2023) of data and analyses four traits (yield, spike weight, plant height and spike length) separately, so that the evaluation of the test sites is not restricted to yield alone. Third, it integrates the "which-won-where", "mean versus stability" and "discriminativeness versus representativeness" views of the GGE biplot to identify both the most stable and high-yielding varieties and the most informative test sites, which provides a more comprehensive assessment than the single-view analyses reported previously.

Materials and Methods

Planting material and testing sites: A total of seven trial sites were arranged in this study, with the designations E1 through E7 (Table 1), were planted for two consecutive years in 2022 and 2023. The experimental material consisted of seven sorghum varieties with distinct genotypes from different breeding units, defined as G1-G7 (Table 2).

Table 1. Testing sites and its codes.

Code	Testing sites	Latitude and longitude
E1	Baoji, Shaanxi Province, China	E107°37′, N34°26′
E2	Fenyang, Shanxi Province, China	E112°34′, N37°46′
E3	Jinzhou, Liaoning Province, China	E121°10′, N41°9′
E4	Chaoyang, Liaoning Province, China	E120°25′, N41°32′
E5	Jinzhong, Shanxi Province, China	E112°43′, N37°41′
E6	Zhengzhou, Henan Province, China	E113°40′, N34°47′
E7	Shenyang, Liaoning Province, China	E123°33′, N41°49′

Table 2. Name of the tested variety and breeding unit.

Code	Varieties	Breeding unit
G1	Jinza 117	Jinzhou Academy of Agricultural Sciences
G2	Fengza 88	Jilin Province Zhuangyi Seed Industry Co., Ltd
G3	Benliang 17	Shenyang Laoben Seed Company
G4	Jinza 7004	Sorghum Research Institute, Shanxi Agricultural University
G5	Tieza 24	Institute of Cereals, Tieling Academy of Agricultural Sciences
G6	Shenza 13	Shenyang Academy of Agricultural Sciences
G7	Liaonuo 11	Liaoning Academy of Agricultural Sciences

The seven sites covered contrasting agro-ecological conditions, and the weather of the two growing seasons differed both among sites and between years (Table 3). Averaged over May to October, the seasonal mean temperature in 2022 ranged from 18.9°C to 24.6°C and in 2023 from 19.8°C to 24.5°C, so the thermal regime of a given site was similar in the two years. Rainfall was much more variable. Total seasonal rainfall in 2022 ranged from 198.5 mm to 333.6 mm, and in 2023 from 199.7 mm to 860.4 mm; averaged over the seven sites it rose from 273 mm in 2022 to 471 mm in 2023. The change between the two years was very uneven: E6 received about 620 mm more rain in 2023 than in 2022 and E1 about 440 mm more, E3 about 230 mm more and E5 about 160 mm more, whereas E7 differed by less than 40 mm, E4 was almost unchanged, and E2 received about 110 mm less. At most sites the rain was concentrated in July and August, which coincides with rapid stem elongation and panicle differentiation: in 2022 the July rainfall alone supplied 46% of the seasonal total at E1, 63% at E3 and 65% at E6, and in 2023 the July to August rainfall dominated the seasonal total at E1, E3, E6 and E7. The genotype × environment interaction analysed below therefore mainly reflects the differences in temperature and rainfall among the sites.

Experimental methods: The trials were established using a two-factor randomized complete block design (RCBD) with three biological replications. The row length was 5 meters, row spacing was 0.60 meters, and the area was 15 square meters /15 m^2. The planting density was 1.2×10^5 plants/ha, and 600 kg/ha of compound fertilizer was applied once before sowing, other field management measures were consistent with the field planting. Ten consecutive plants per treatment were chosen to investigate plant height (PH), spike length (SL), and spike weight (SW) before harvest. During mature period, the middle three rows of each cell were harvested five days after natural air drying. The yield per unit area was computed according to the harvested area, and the standardized seed yield (14% water content) was determined. The standardized seed yield at 14% water content was calculated according to the formula: adjusted yield = actual grain yield × (100%-measured grain water content) / (100%-14%).

Statistical analysis

Data were processed and analysed using SPSS version 29.0.2. Analysis of variance (ANOVA) was performed to test the effects of year (Y), environment (E), genotype (G) and their interactions, and differences among genotype means were separated by Duncan's multiple range test at $p<0.05$. GGE Biplots, namely "What won Where," "Mean versus stability," and "Discriminativeness versus Representativeness," were implemented using R and its program package GGEBiplotGUI.

In the combined analysis of the two years, year was treated as a component nested within environment, so that each year–site combination was regarded as a distinct environment; consequently no separate GGE decomposition was performed for the year-to-year variation, and the implications of this treatment are discussed in disscussion.

Results and Analysis

Analysis of variance in yield and its related traits: As observed in Table 4, in 2022, G2 exhibited the highest average yield, spike weight, and spike length, reaching 9720.06 kg/ha, 94.05 g, and 36.99 cm, respectively. G4 produced the tallest plant height, which was 209.70 cm, while G3 had the shortest, at 148.13 cm. In 2023, G6 had the highest yield and spike length, reaching 8593.07 kg/ha and 34.58 cm, respectively. Correspondingly, G5 had the heaviest spike weight, which was 85.91 g. G4 had the tallest plant height, at 212.37 cm, while G3 had the shortest, which was 149.10 cm. The results of variance analysis suggested that traits like yield, grain weight per spike, plant height, and spike length showed extremely significant differences with respect to Years (Y), Environment (E), Genotype (G), Y×E, Y×G, E×G, and Y×E×G.

Table 3. Average temperature and rainfall during the growing season at the 2022-2023 trial site.

Code	Month	2022		2023	
		Average temperature (℃)	Rainfall (mm)	Average temperature (℃)	Rainfall (mm)
E1	May	20.0	84.6	18.0	126.8
	June	26.0	8.8	23.0	108.6
	July	26.5	133.8	25.5	113.1
	August	27.0	32.9	25.0	138.7
	September	20.0	12.4	20.5	79.6
	October	13.0	18.3	14.5	167.4
E2	May	17.5	16.3	17.5	46.6
	June	25.0	19.8	23.0	40.5
	July	24.0	55.7	25.0	25.8
	August	23.0	183.0	24.5	77.6
	September	18.5	0.7	20.0	27.1
	October	11.0	58.1	13.0	5.3
E3	May	17.5	86.0	18.5	87.6
	June	21.0	14.2	23.0	136.0
	July	25.5	204.7	26.0	219.2
	August	24.0	8.9	24.5	40.8
	September	20.0	8.7	21.0	32.1
	October	12.0	0	14.0	40.9
E4	May	18.5	29.2	18.5	29.6
	June	21.5	107.4	24.0	38.9
	July	25.5	21.8	26.0	85.5
	August	24.0	25.9	24.0	31.6
	September	19.5	4.3	20.0	17.6
	October	10.5	9.9	12.5	18.5
E5	May	16.5	7.5	17.5	23.9
	June	24.5	27.2	21.5	49.7
	July	24.0	35.0	25.0	66.5
	August	23.5	93.9	23.5	191.3
	September	17.5	16.4	19.5	24.8
	October	10.5	39.2	11.5	21.8
E6	May	22.5	0	21.0	201.7
	June	30.0	10.4	27.0	62.0
	July	27.5	155.9	29.5	391.3
	August	28.5	17.5	27.5	109.1
	September	24.0	50.8	23.5	73.7
	October	15.0	6.8	18.5	25.6
E7	May	17.5	18.7	18.0	63.8
	June	21.5	37.8	23.0	56.9
	July	25.5	113.6	26.0	132.1
	August	23.0	13.5	24.0	60.6
	September	18.5	102.0	20.0	10.6
	October	9.5	19.1	12.5	18.8

"What won where" perspective of GGE biplots: Assessing sorghum through a What won where pattern illustrates how individual genotypes adapt to a particular environment. Figures 1 and 2 depict polygonal views of the traits of the seven sorghum genotypes evaluated across seven locations during different years. The genotypes at the top of each sector represents the maximum value of the traits in the environment of that sector. Genotype and genotype-environment interaction together accounted for 82.2%, 82.7%, 97.2%, 83.6% (cumulative variation of PC1 and PC2 for yield, SW, PH, SL in 2022), and 77.6%, 60.8%, 94.5%, 85.6% (cumulative variation of PC1 and PC2 for yield, SW, PH, SL in 2023) of the total variation.

In 2022, the plant height was divided into four fan-shaped regions, and the yield, grain weight per spike, and spike length were all cut into five fan-shaped regions (Fig. 1). The yield of G2 was the most stable and high yielding in E1, E3, E5, E6, and E7 environments. The grain weight per spike of G2 was the most stable in E1, E2, E3, and E6, and the SW was the largest. The PH of G4 was the highest across all environments (E1-E7). The SL of G2 performed optimally in E1-E5 and E7 environments.

The GGE biplots from the extracted eigenvalues in 2023 was separated into 4 (SW), 5 (Yield, PH), and 6 (SL) fan-shaped regions. G2 exhibited the highest yield in E1, E3, E5, and E6, while G5 and G7 performed well in the E4 environment. The SW of the G4 genotype was the best in E3 and E7 environments, while the G5 and G3 genotypes were markedly more constant in E1, E4, and E6 environments. Similar to 2022, the PH of G4 was the highest in all environments (E1-E7). The SL of G6 and G2 genotypes performed best in the E1-E5 environments.

Table 4. Yield and main traits of different sorghum.

Years	Varieties	Yield (kg/ha)	Spike weight (g)	Plant height (cm)	Spike length (cm)
2022	G1	9115.31	73.09	172.23	30.57
	G2	9720.06	94.05	161.72	36.99
	G3	9039.54	82.92	148.13	33.83
	G4	8964.58	83.38	209.70	32.80
	G5	8262.96	81.84	184.97	29.79
	G6	9229.39	82.60	163.76	35.93
	G7	9130.76	76.56	165.42	31.85
2023	G1	8043.15	77.19	160.58	29.11
	G2	8443.80	81.25	160.81	33.91
	G3	8454.77	85.76	149.10	33.03
	G4	8347.86	77.50	212.37	32.00
	G5	8514.15	85.91	181.63	29.60
	G6	8593.07	73.82	156.24	34.58
	G7	8272.39	83.68	159.90	32.36
F-value					
Years (Y)		116,146.97**	2,979.03**	1834.45**	295.72**
Environment (E)		40,521.58**	75,383.79**	20,827.86**	692.32**
Genotype (G)		7,130.87**	34,740.36**	34,247.99**	870.85**
Y×E		8,516.12**	314,921.00**	4635.65**	125.16**
Y×G		8,392.50**	27,874.46**	506.49**	51.79**
E×G		4,664.12**	11,745.34**	508.85**	55.17**
Y×E×G		3,779.80**	15,984.09**	331.72**	29.87**

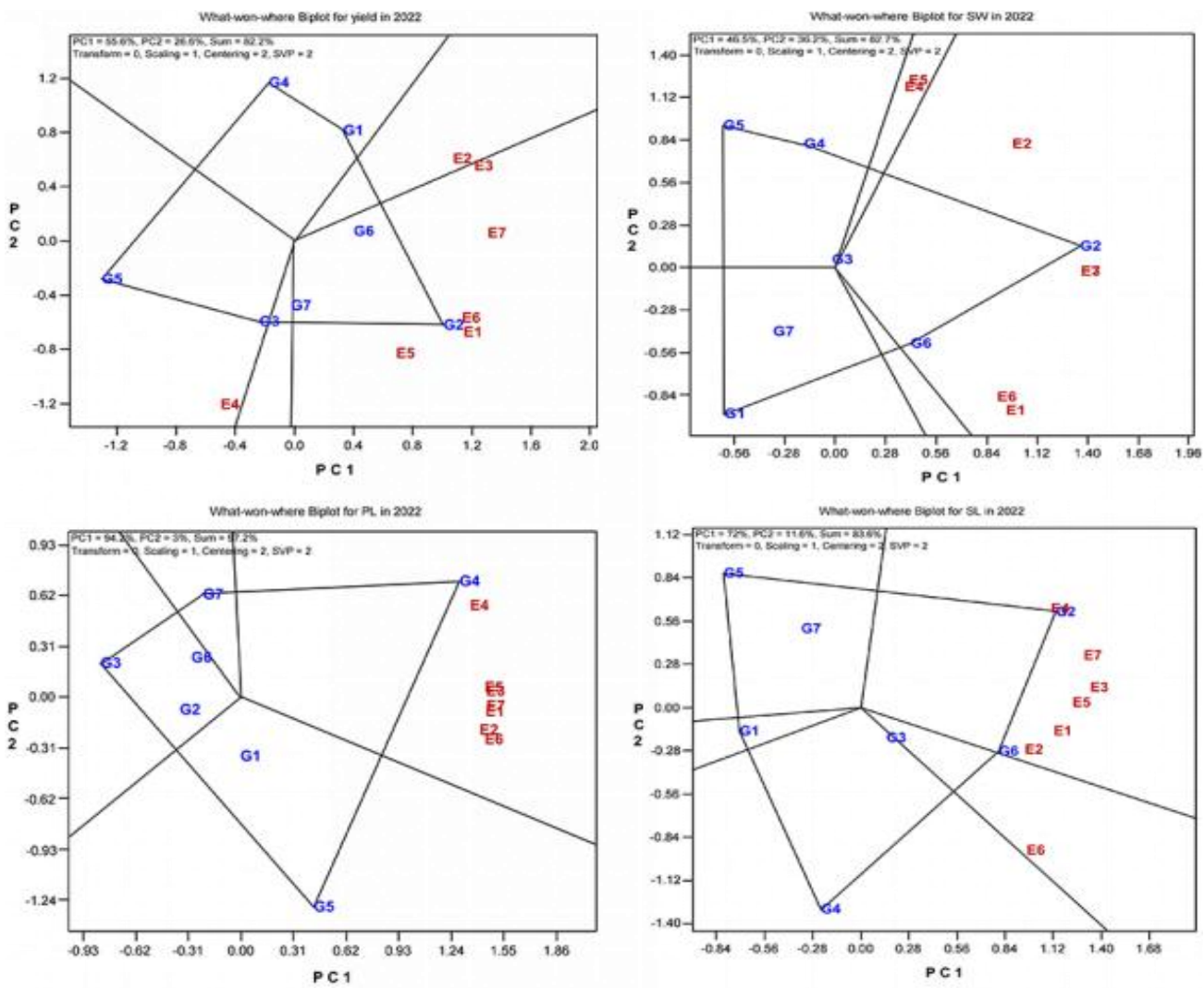


Fig. 1. "Which-won-where" biplots in 2022.
Notes: In the Figure 1 to Figure 6, PC1 and PC2 stand for the first and second principal components; blue labels for genotypes (G1-G7), red labels for test environments (E1-E7).

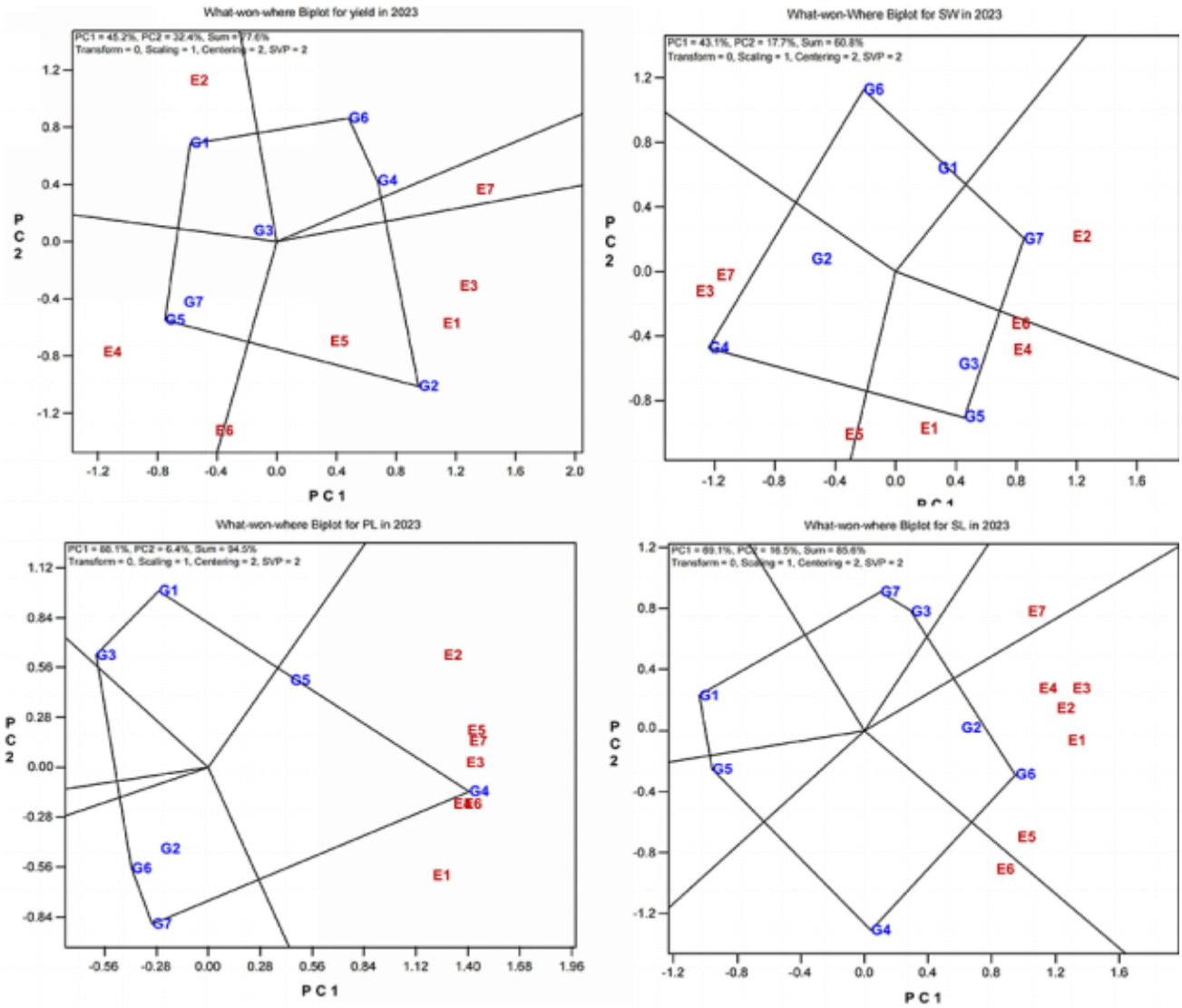


Fig. 2. “Which-won-where” biplots in 2023.

2.3 “Mean versus stability” perspective of GGE biplots.

The “mean versus stability” view of the GGE biplot was used to evaluate high yield and stability simultaneously. Genotypes are arranged in ascending order according to the ordinate line, and the two arrows on the perpendicular line represent the stability. A larger projection along the ordinate, away from the origin, indicates a stronger contribution of genotype (G) and of genotype × environment (G×E) interaction.

In 2022 (Fig. 3), traits of PH of different genotypes in the four traits collected was stable across different environments. G4 had the highest average in E1-E7 environment, followed by G5 and G1. Among yield traits, the highest average performance and the greatest stability were exhibited by G2, followed by G6 and G7. The average spike weight of G2 was the highest, stable across different environments, followed by G6. The SL was also the highest in G2 and G6.

In 2023 (Fig. 4), the most stable trait was PH, G4 was the highest and most stable, and there was no significant difference between years. Although G2 had the highest average yield, G1 had improved stability in different environments. The average SW of G5 and G3 was relatively higher, but G1 and G6 were more stable. The SL of G2 and G6 was longer and more stable. Although the stability of G1 was better, its average performance was limited.

The “Discriminativeness versus representativeness” was employed to analyze the adaptability of different genotypes in various environments (Figs. 5 and 6). The direction of the arrow on the average environment ordinate is the distinguishing force and representativeness of the test point. The projection of each environment vector on the average environment axis (AEA) indicates the discriminating ability and the representativeness of that test site. The longer the line segment, the stronger the distinguishing ability, and the smaller the angle, the stronger the representativeness. Only a distinctive and representative environment can select the best variety.

In 2022, although the yield of E4 showed strong discrimination, it lacked representativeness, while the discrimination and representativeness of E1 and E6 performed best across all environments. E3 and E7 exhibited strong representativeness in SW. Except for E4, the PH traits showed high discrimination and representativeness in other environments. E1, E2, E3, E5, and E7 had strong representativeness in SL traits.

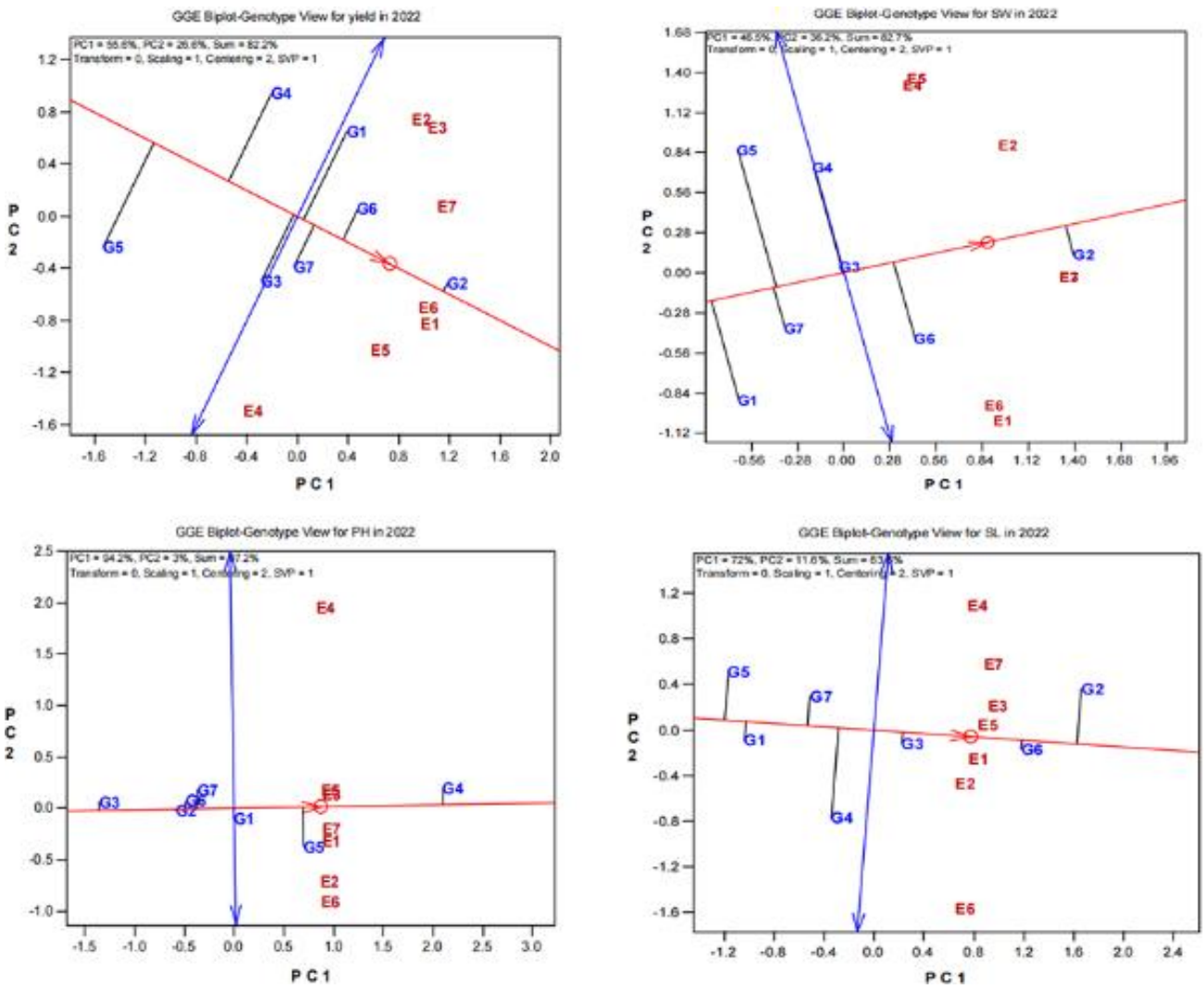


Fig. 3. "Mean versus stability" biplots in 2022.

Notes: In the Figure 3 and Figure 4, The red line represents the average environment axis (AEA). Genotypes with longer projections along the positive direction of AEA have higher mean performance across environments. The blue line, perpendicular to AEA, is the stability axis. The vertical distance from each genotype to this axis indicates the magnitude of genotype-by-environment (G×E) interaction; genotypes closer to the stability axis exhibit better stability.

In 2023, the production performance of various environments differed. Among them, E4 and E6 had the longest distance, meaning that the two environments had greater distinguishing power, while E1 and E5 had the least angle with the average environmental ordinate and the highest representativeness. Moreover, the trend of SL performance in E1 and E5 was consistent with that of yield. The PH discrimination and representativeness of E3 and E7 were optimal in all environments. E6 and E7 had strong discrimination in SL, while E1 had the strongest representativeness. Although each trait was analysed separately here, the four traits are considered together when the test sites are evaluated in disscussion.

Correlation analysis of traits: Pearson correlation coefficient analysis was conducted on the test traits, and a heatmap was drawn (Fig. 7). The yield was highly significantly positively correlated with SW and PH ($R=0.84^{**}$, $R=0.53^{**}$) and significantly positively correlated with SL ($R=0.45^{*}$). SL and SW also exhibited a significant positive correlation ($R=0.77^{**}$). There was no relationship between PH and SW.

Discussion

As a core trait of sorghum, the yield performance of the same variety varies across locations, and a high, stable yield is important (Aruna *et al*., 2016; Al-Naggar *et al*., 2018; Dariush *et al*., 2023; Bai *et al*., 2023; Wubshet *et al*., 2023). This study performed regional trials at the same test sites over two consecutive years, and significant differences in the yields of different sorghum varieties were identified across different sites, with notable differences in the discrimination and representation of each test site. This suggests significant variations in the selection and application of core germplasm among sorghum breeding units. This may stem from differences in their environmental conditions or breeding objectives. By ranking the initial yield through variance analysis and combining the "what won where" and "Mean versus stability" biplots, G2 had the highest average yield and optimal stability among the seven varieties, suggesting its potential for promotion. In practical production, yield and agronomic traits closely related to yield should be given equal attention (Hasan *et al*., 2021; Dariush *et al*., 2023;

Ishola *et al*., 2023; Xiao *et al*., 2023). Correlation analysis indicated that spike weight was positively associated with yield. In this study, G2 exhibited significant advantages in the adaptive capacity and stability of spike weight in different environments, consistent with the yield results.

Apart from spike weight, plant height and spike length are critical phenotypic traits (Hailemariam *et al*., 2017; Enyew *et al*., 2021). Plant height, as a trait susceptible to environmental influences, exhibits significant variations throughout different planting environments (Hailemariam et al., 2017). In this study, the plant heights of the seven varieties exhibited low variability across different environments and were generally consistent between years. G2 and G4 exhibited the most stable plant heights across environments, indicating that the plant height genotypes (G) of these two varieties played a crucial role and were less influenced by the environment (E). To adapt to mechanized operations, dwarfing sorghum cultivar breeding is favored. However, reduced plant height can cause decreased aboveground biomass, resulting in lower yields per plant (Aruna *et al*., 2016; Al-Naggar *et al*., 2018; Dariush *et al*., 2023; Bai *et al*., 2023; Wubshet *et al*., 2023). Therefore, in future breeding, ensuring that plant height is appropriate for biomass accumulation and dry matter translocation while limiting the risk of lodging is essential. Although the correlation analysis showed only a significant positive correlation between spike length and yield (R=0.45*), spike length still facilitates the formation of grain yield. By utilizing the "Discriminativeness versus Representativeness" biplots to identify the optimal planting regions, we identified E1 as the most discriminative and representative location for yield and related traits, followed by E6, with consistent performance across years. Although E4 showed the strongest discriminating ability for yield, it was also the site with the largest angle to the AEA, that is, the poorest representativeness. A highly discriminating but non-representative site amplifies the differences among genotypes and tends to favour genotypes that perform well only under its particular conditions; such a site is useful for exploring the full range of genotypic responses, but it should not be used alone as a core trial site, because the varieties it selects may not perform well in the wider target region. This is why E4 is not recommended as a core site, even though its discriminating power was the highest among the seven sites.

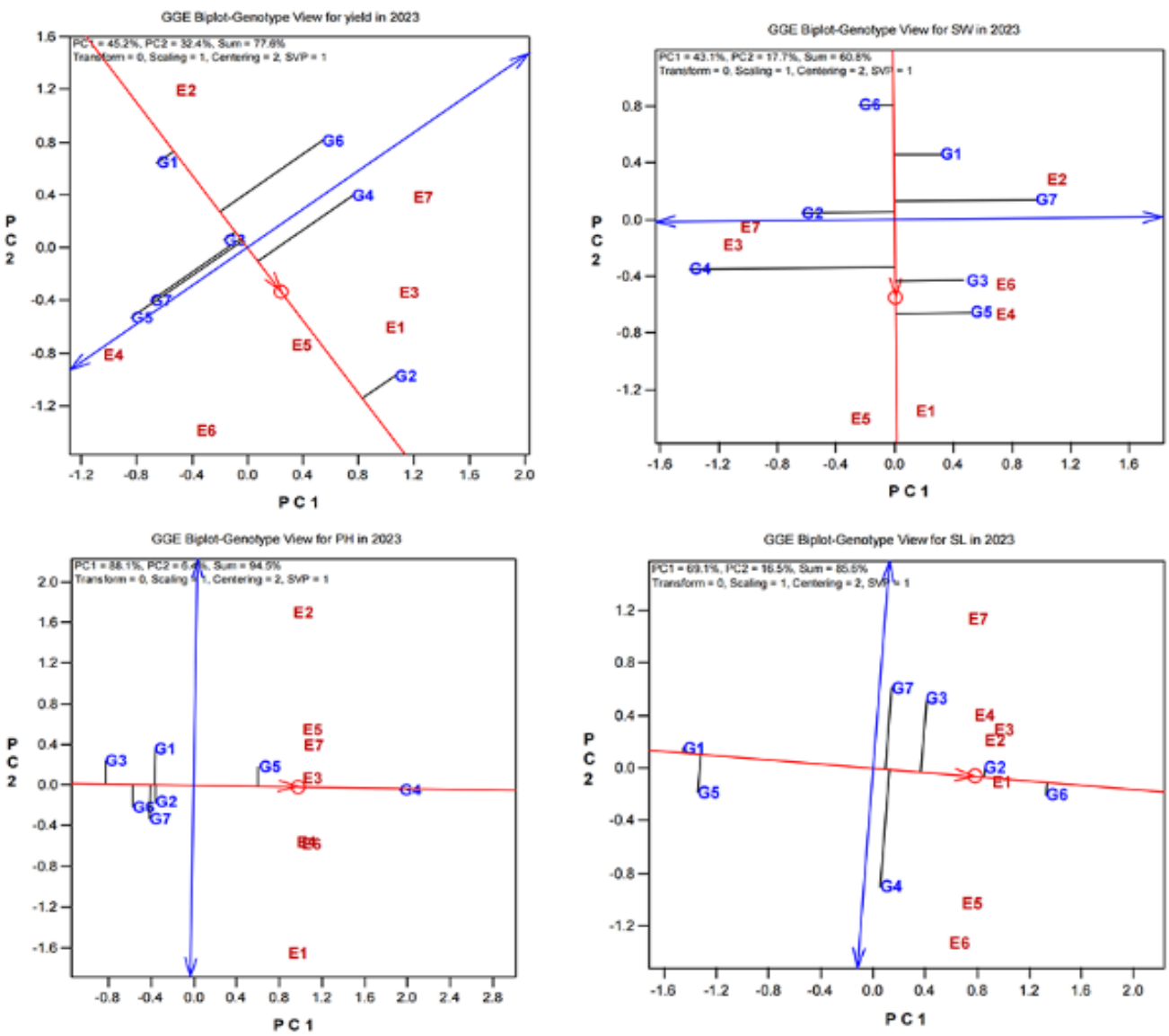


Fig. 4. “Mean versus stability” biplots in 2023.

2.4 “Discriminativeness versus Representativeness” perspective of GGE biplots

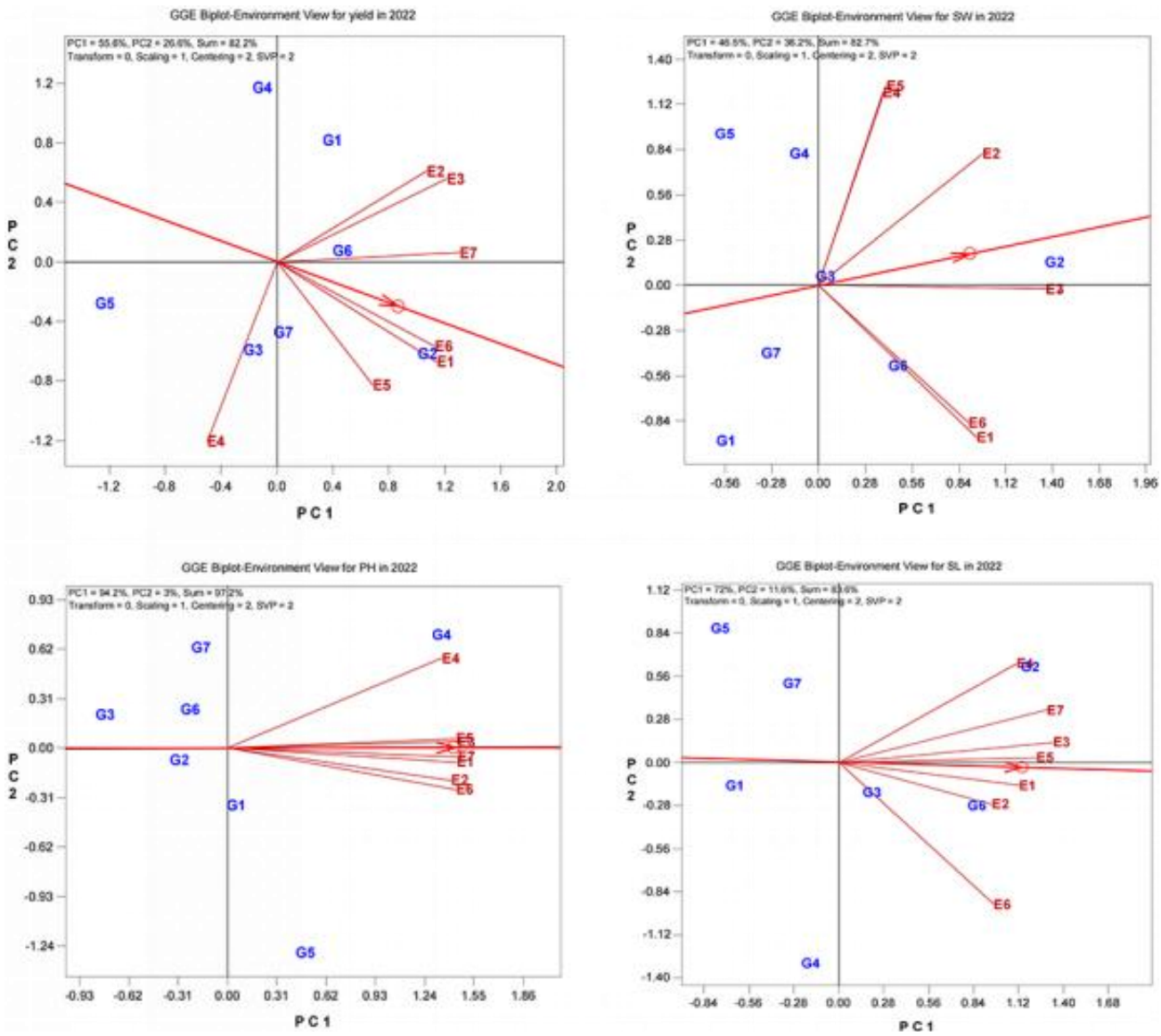


Fig. 5. "Discriminativeness versus Representativeness" biplots in 2022.
Notes: In the Figure 5 and Figure 6, the red line is the average environment axis (AEA), and the red circle denotes the virtual average environment. The black vertical line is the stability axis (AEC ordinate), perpendicular to the AEA, which indicates the degree of environmental deviation from the average environment. Each red ray is an environment vector. A smaller angle between an environment vector and the AEA indicates better representativeness of this environment; the vector length represents the discriminating ability of the environment. The angle between two environment vectors reflects the correlation between environments.

The finding that environment-related terms accounted for the largest share of the variation in yield and spike weight indicates that the performance of the tested varieties is still strongly constrained by the environment, and that the superiority of a genotype cannot be judged from a single location. The fact that G2 maintained its advantage in both years, and for both yield and spike weight, suggests that its superiority reflects a genuine genotypic adaptation rather than a favourable year effect; in contrast, the inconsistent ranking of the remaining varieties implies that their apparent stability in one year may simply reflect a favourable combination environment. It is also worth noting that the four traits did not respond to the environments in the same way: plant height was almost invariant across environments because G4 was the tallest genotype everywhere, so this trait contributed little to site discrimination, whereas yield, spike weight and spike length differed markedly among sites. Such trait-specific responses mean that conclusions about the "best" environment depend on the trait considered, and they support the view that a site should be evaluated on the basis of several traits rather than on yield alone. Finally, the relatively small differences among the varieties released by different breeding units suggest a narrow genetic base in the present germplasm, which limits the genetic gain that can be expected from further selection within this set and highlights the need to introduce new genetic variability for sorghum improvement.

The present analysis also deserves comment on how the year effect was handled. Year was treated as a component nested within environment, so no separate GGE decomposition was performed for the year-to-year variation, and part of the G × E interaction retained in the combined dataset therefore reflects climatic fluctuation between 2022 and 2023 rather than stable characteristics of the sites. The weather records show that this component was by no means

negligible. Total seasonal rainfall averaged 273 mm over the seven sites in 2022 but 471 mm in 2023, an increase of about 72%, and the increase was extremely uneven: it exceeded 600 mm at E6 and 440 mm at E1, was moderate at E3 (+234 mm) and E5 (+159 mm), and was negligible or negative at E7 (+38 mm), E4 (+1 mm) and E2 (−111 mm). The seasonal mean temperature, by contrast, changed little between the two years (18.9–24.6°C in 2022 versus 19.8–24.5°C in 2023). Because water supply is the principal factor limiting sorghum in China, the exceptionally wet season of 2023 probably removed the main yield constraint at E1 and E6 and allowed genotypic differences to be expressed more fully, whereas the much drier 2022 season at the same sites may have compressed those differences and increased the uncertainty of the estimated site vectors. The representativeness of E1 and E6 identified here should therefore be regarded as provisional, since an average environment coordinate based on only two seasons can be strongly displaced by a single anomalous year; similarly, where the yield vectors of a site pointed in different directions in the two years, this may reflect a genuine rainfall-driven change in the ranking of environments rather than instability of the genotypes themselves. Trials of at least three to five seasons, analysed with an explicit decomposition of the genotype × year effect, are needed before the final choice of core test sites is made, and the site rankings reported here should be treated as a first approximation to be refined as longer data series become available.

The discriminativeness versus representativeness analysis was carried out separately for each trait, so it does not in itself indicate whether a site that is excellent for yield is also suitable for evaluating spike weight, plant height and spike length. When the four traits are considered together, E1 combined a long environment vector with a small angle to the AEA for yield, spike weight and spike length, and was therefore the most informative site for these three traits; E6 was highly discriminative in 2023 and representative in 2022, and was the second most informative site; E5 was representative in 2023 but not in 2022, and E3 and E7 were informative mainly for plant height. Plant height behaved differently from the other traits, because G4 was the tallest genotype in every environment; this trait showed almost no G×E interaction and therefore provided little discrimination among sites. Formal integration of the four traits into a single stability index is an important direction for future research.

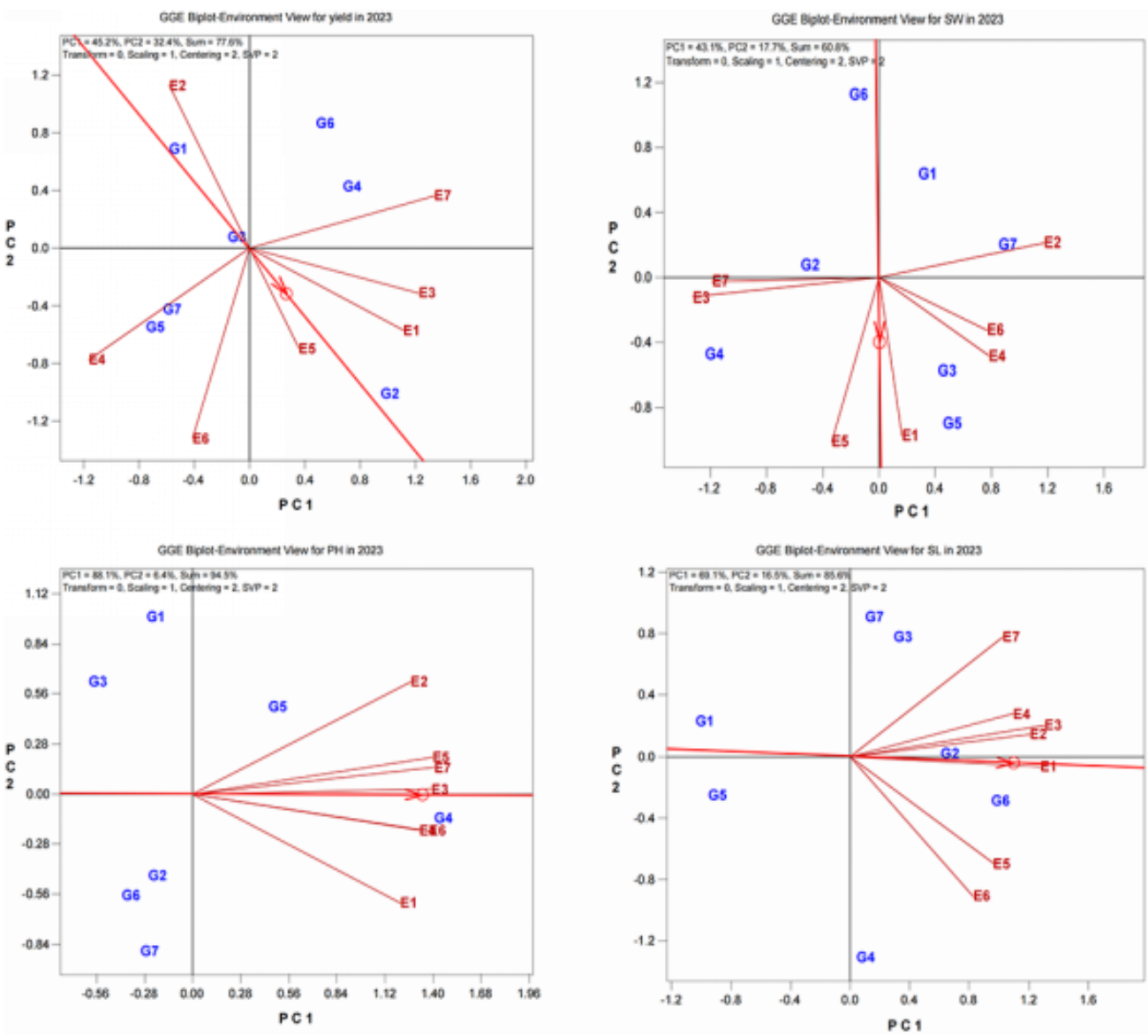


Fig. 6. “Discriminativeness versus Representativeness” biplots in 2023.

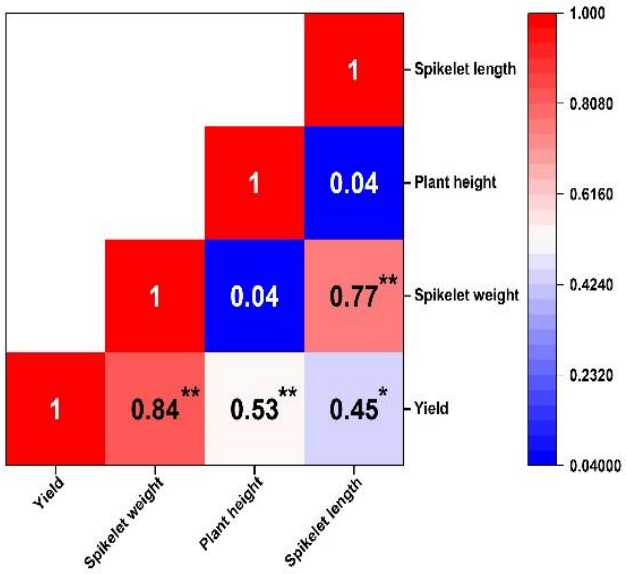


Fig. 7. Heatmap of Pearson correlation of participant traits.
Notes: The color of each block indicates the value of correlation coefficient. Red represents positive correlation and blue represents negative correlation. * indicates significant difference at $p<0.05$, ** indicates highly significant difference at $p<0.01$.

By leveraging the strengths and overcoming the limitations of GGE biplots, breeders can attain scientific and systematic guidance to screen superior varieties for specific ecological regions according to their actual needs (Fatemeh *et al*., 2023). However, the results of the GGE biplots model rely on the accuracy and completeness of the input data, and deviations or missing data may produce inaccurate results (Kempton, 1984; Joshi *et al*., 2024). With the continuous development of agricultural science and technology, future research can investigate the integration of GGE biplots with other advanced statistical approaches to improve the accuracy and reliability of analysis results, holding significant value in sorghum regional trials. While we selected four traits to focus on, our results have limitations. Future research should consider integrating additional characteristics such as growth period duration, aboveground dry matter accumulation, and grain number per panicle to better examine variety performance. After a comprehensive evaluation, G2 (Fengza 88) was found to have the optimal yield and productivity, with the widest adaptability, and its planting range could be expanded. The test environments E1 and E6 exhibited higher discrimination and representativeness, making screening high-yielding and stable sorghum varieties easier in these two locations.

Conclusions

In this study, the yield, spike weight, plant height and spike length of seven sorghum varieties were evaluated at seven sites over two years. The results showed that all four traits were significantly affected by year, environment, genotype and their interactions, and that environment-related terms accounted for the largest part of the variation in yield and spike weight. GGE biplot analysis identified G2 (Fengza 88) as the variety with the highest and most stable yield and spike weight, followed by G6 and G7; G2 is therefore recommended for wider cultivation in the target region. The discriminativeness-versus-representativeness analysis showed that E1 and E6 combined strong discriminating ability with good representativeness across years and traits, and they are recommended as core sites of the sorghum regional trial. The practical implication for breeding is that a small number of representative and discriminating sites can be used to screen varieties efficiently, and that site selection should be based on the target environment rather than on discriminating ability alone. The main limitations of the study are that only four traits and two years (2022–2023) were considered, that the year effect was not decomposed separately in the GGE analysis, and that the sites were evaluated trait by trait without a combined multi-trait index; these limitations should be taken into account when the present conclusions are extrapolated to other years or regions.

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