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Evaluation of Grain Size Stability in CIMMYT Spring Wheat Germplasm and Its Breeding Potential in the Qinghai Plateau

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Abstract: Background: Introducing CIMMYT spring wheat germplasm is crucial for improving grain yield and stability in the Qinghai Plateau. This study evaluated the performance and adaptability of exotic genotypes to provide elite genetic resources for local breeding programs. Methods: Fifteen CIMMYT spring wheat accessions and the local check variety Gaoyuan 932 were evaluated across six environments during 2023–2024. Thousand-gainl weight (TGW), Gain length (GL), width (GW), and thickness (GT) were measured. Genotype (G), environment (E), and their interaction (G×E) were analyzed using AMMI model and GGE biplot. Results: E, G, and G×E effects were highly significant ($P < 0.001$) for all traits. GW was most environment-sensitive ($F = 1707.50$), TGW showed the strongest genotypic effect ($F = 762.05$), and GL was most influenced by G×E. The first three AMMI components explained >87% of variation. E2 was the ideal environment with highest trait means and strong discrimination. G5 exhibited highest TGW (58.52 g) and GW (3.62 mm); G16 had superior GL (7.40 mm) and GT (3.42 mm); G10 showed outstanding stability. G16 adapted best to E2 and E6, while G5 performed optimally across E3–E6. Conclusion: G16 is a well-adapted genotype with comprehensive superiority. G5, G9, G10, and G2 possess complementary advantages for breeding. G16, G5, and G9 are promising parents, whereas G10 and G2 are suitable for direct promotion with environment-specific deployment.

Keywords: CIMMYT spring wheat, grain size, G×E interaction, AMMI, GGE biplot, stability, adaptability, Qinghai Plateau

1 INTRODUCTION

Wheat (Triticum aestivum L.) is one of the most important food crops globally, with grain characteristics directly determining both yield potential and processing quality (Shiferaw et al. 2013; Wang et al. 2021; El Hassouni et al. 2025). Kernel traits such as thousand-grain weight, grain length, grain width, and grain thickness are not only fundamental components of yield but also primary targets in wheat breeding programs (Gegas et al. 2010; Zombori et al. 2020; Lin et al. 2023) The expression of these traits is co-regulated by genotype (G), environmental conditions (E), and their interaction (G×E), exhibiting complex variation patterns across multi-environment trials (Maphosa et al. 2014; Fradgley et al. 2025). Therefore, accurately dissecting G×E interactions and comprehensively evaluating the yield potential, stability, and adaptability of varieties are essential for identifying elite cultivars and parental lines and for guiding regional deployment strategies.

Located in the northeastern part of the Qinghai-Tibet Plateau, Qinghai Province is characterized by a typical plateau continental climate, with high altitude, low temperatures, prolonged sunshine duration, and large diurnal temperature variations, forming a unique spring wheat ecological zone (Z. Zhang and Lu 2023). While the extended growing period in this region favors grain filling and dry matter accumulation, it also imposes higher demands on variety adaptability(Su et al. 1981; Ma et al. 2025). Introducing and evaluating exotic germplasm within the Qinghai ecosystem represents an effective approach to broadening the local wheat genetic base and overcoming breeding bottlenecks (Sharma et al. 2021; Liu et al. 2025; Y. Li et al. 2025). As a premier institution in global wheat improvement, the International Maize and Wheat Improvement Center (CIMMYT) provides spring wheat germplasm resources characterized by rich genetic diversity and broad adaptation, which have been successfully utilized across major wheat-producing regions worldwide(Y. Zhang et al. 2006; Mondaini et al. 2022). However, systematic evaluations of grain trait performance and adaptability of these germplasms in the Qinghai Plateau ecosystem remain limited.

In regional adaptability trials of crop varieties, the Additive Main Effects and Multiplicative Interaction (AMMI) model and Genotype plus Genotype-by-Environment (GGE) biplot are important tools for dissecting G×E interactions and evaluating yield stability and adaptability (Taherian et al. 2024; Al-Ghumaiz et al. 2025; Meena et al. 2025). These methods have been widely applied across various crop species, including peanut (Kona et al. 2024), sorghum (Enyew et al. 2021), and maize (Shirzad et al. 2025). For instance, through GGE biplot analysis of 35 wheat genotypes, researchers identified high-yielding and stable genotypes including G4, G10, G34, and G35, with G10 demonstrating excellent yield stability and adaptability across diverse environmental conditions(Nesa et al. 2025). Similarly, Menzir et al. evaluating 14 durum wheat varieties across six environments in Ethiopia, revealed highly significant ($p < 0.001$) effects of genotype, environment, and their interaction on yield(Menzir et al. 2025); AMMI and GGE biplot analyses identified G10 as a high-yielding and stable genotype, recommending it as a reference germplasm for breeding. Saed-Moucheshi et al. employed AMMI, GGE biplot, and heatmap clustering to comprehensively evaluate yield stability of 173 wheat lines across four environments in Iran, identifying Bamdad and lines 141 and 45 as high-yielding and stable genotypes, while proposing region-specific breeding strategies based on environmental differentiation (Saed-Moucheshi 2025). In multi-location variety trials, genotype, environment, and their interaction constitute the primary sources of phenotypic variation in yield, with effects typically reaching highly significant levels (Amini et al. 2025; Yue et al. 2025). In-depth analysis of these variance components is critically important for screening high-yielding and stable genotypes and enhancing breeding efficiency.

In this study, ten CIMMYT spring wheat accessions and the Qinghai-registered variety Gaoyuan 932 were evaluated across six environments, including Yuanmou (Yunnan Province) and Xining, Guide, and Xiangride (Qinghai Province). Four key grain traits—TGW, GL, GW, and GT—were measured. Using AMMI models and GGE biplot analysis, we systematically dissected the effects of genotype, environment, and their interaction, comprehensively evaluated the yield potential, stability, and adaptability of the tested genotypes, and assessed the discriminative ability and representativeness of the test environments. This study aims to identify elite spring wheat germplasm suitable for the Qinghai Plateau ecosystem and to provide a theoretical foundation for local wheat breeding programs and variety deployment.

2 MATERIALS AND METHODS

2.1 PLANT MATERIAL AND EXPERIMENTAL DESIGN

A total of 16 wheat genotypes were evaluated in this study (Table 1), consisting of 15 spring wheat accessions introduced from the International Maize and Wheat Improvement Center (CIMMYT) and one locally registered variety, Gaoyuan 932, which served as the local check. Field experiments were conducted across six environments during 2023–2024 (Figure 1, Table 2): Yuanmou County, Chuxiong Yi Autonomous Prefecture, Yunnan Province (E1 and E2, sown in early October as winter nurseries); Xining City, Qinghai Province (E3 and E4, sown in late March); Guide County, Hainan Tibetan Autonomous Prefecture, Qinghai Province (E5, sown in late March); and Xiangride Town, Haixi Mongolian and Tibetan Autonomous Prefecture, Qinghai Province (E6, sown in early April). A sequential arrangement design was adopted. Each genotype was planted in three rows with a row length of 1.6 m, row spacing of 20 cm, and plant spacing of 2 cm, with 80 seeds sown per row by manual dibbling. Guard rows were established around the experimental plots. Weeds were manually controlled, and all other field management practices followed local conventions.

TABLE 1 TEST MATERIAL NUMBERS AND SOURCES

Code	Variety Name	Source	Code	Variety Name	Source
G1	CIMMYT222y82	CIMMYT	G9	CIMMYT222y153	CIMMYT
G2	CIMMYT222y85	CIMMYT	G10	CIMMYT222y141	CIMMYT
G3	CIMMYT222y87	CIMMYT	G11	CIMMYT31	CIMMYT
G4	CIMMYT222y95	CIMMYT	G12	CIMMYT32	CIMMYT
G5	CIMMYT222y99	CIMMYT	G13	CIMMYT36	CIMMYT
G6	CIMMYT222y102	CIMMYT	G14	CIMMYT39	CIMMYT

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G7	CIMMYT222y118	CIMMYT	G15	CIMMYT44	CIMMYT
G8	CIMMYT222y129	CIMMYT	G16	Gaoyuan 932	Qinghai

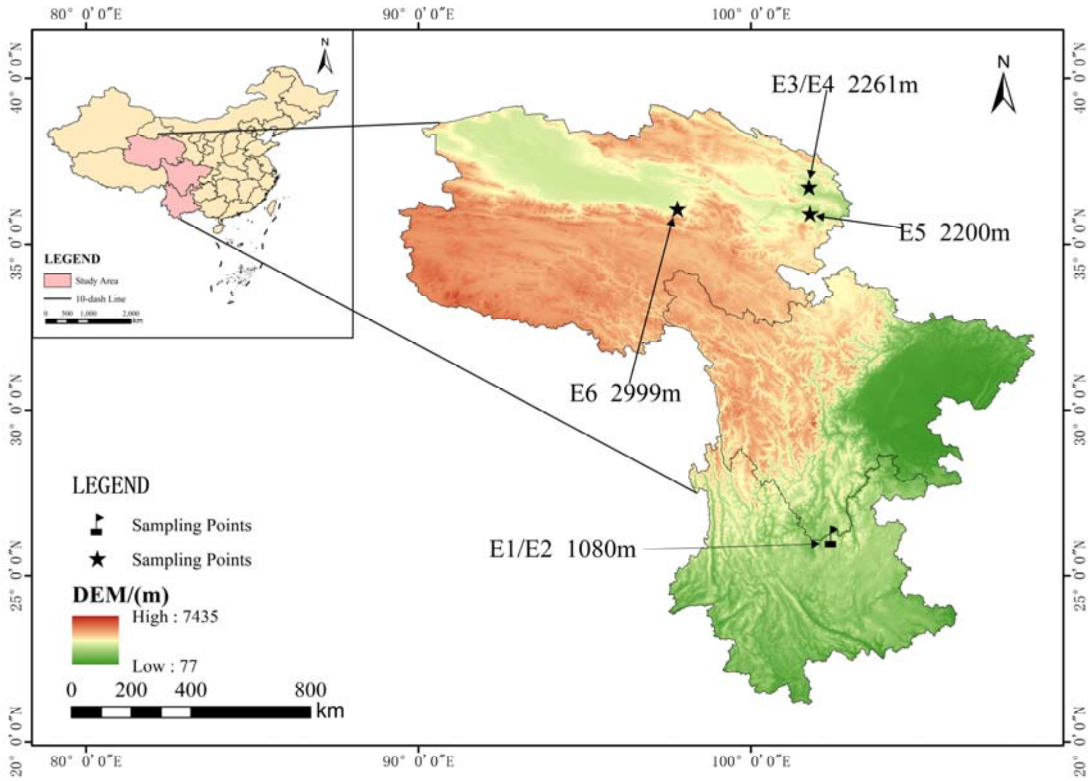

FIGURE 1 ECOLOGICAL ZONES OF WHEAT CULTIVATION IN CHINA AND THE GEOGRAPHICAL LOCATIONS OF THE SIX EXPERIMENTAL ENVIRONMENTS USED IN THIS STUDY.

TABLE 2 DESCRIPTION OF THE SIX TEST ENVIRONMENTS

Environment ID	Year	longitude	latitude	Elevation/ m	Total precipitation during the growing season/mm	Soil type
E1	2023	101° 86′ E	25° 72′ N	1080 m	32.43	Red soil
E2	2024	101° 86′ E	25° 72′ N	1080 m	33.95	Red soil
E3	2023	101°45′ E	36° 43′ N	2261 m	319.30	Chestnut soil
E4	2024	101°45′ E	36° 43′ N	2261 m	354.50	Chestnut soil
E5	2024	101°47′ E	35° 55′ N	2200 m	407.30	Irrigation-silting soil

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E6	2024	97°47′ E	36° 3′ N	2999 m	49.90	brown calcic soil

2.2 *Trait Measurement and Phenotyping*

Four grain traits—thousand-grain weight (TGW), grain length (GL), grain width (GW), and grain thickness (GT)—were evaluated across the six environments. Due to substantial variation in flowering time among the introduced germplasm, harvesting was conducted in multiple batches based on growth stage synchrony to ensure all kernels reached full maturity and met uniform measurement standards. After threshing, grains were air-dried under natural light for approximately seven days until the seed moisture content reached approximately 15%. For TGW determination, 1000 kernels were randomly selected from each genotype and weighed using a Wanshen electronic seed balance with a precision of 0.0001 g. Grain dimensions (GL, GW, and GT) were measured using a Wanshen SC-G automatic seed trait analyzer. Each measurement was repeated three times per genotype, and the mean values of the three replicates were used for subsequent statistical analyses to comprehensively assess the adaptability of grain traits among the introduced germplasm in the Qinghai Plateau ecological zone.

2.3 *Statistical Analysis*

Data were entered and organized using Microsoft Excel. Analysis of variance (ANOVA) and Additive Main Effects and Multiplicative Interaction (AMMI) model analysis were conducted using the agricolae package in R software (de Mendiburu, 2023). Genotype plus genotype-by-environment (GGE) biplot analysis was performed using the GGEBiplotGUI package in R (Frutos. et al, 2014). Correlation analysis among grain traits was carried out using Origin software. Geographic distribution maps illustrating the origins of germplasm accessions and the locations of experimental sites were generated using ArcGIS software.

3 Results

3.1 *Performance and Correlation Analysis of Grain Traits Across Multi-Environments*

Systematic analysis of the four grain traits across 16 genotypes and six environments revealed substantial variation in genotype performance under different environmental conditions (Table 3). Among all environments, E2 exhibited the most favorable conditions, with the highest mean values for all measured traits: TGW reached 54.76 g, GL 6.91 mm, GW 3.67 mm, and GT 3.32 mm, indicating that E2 represents the optimal planting environment for the evaluated germplasm. E1 ranked second, with satisfactory trait performance (TGW = 52.44 g, GL = 6.60 mm, GW = 3.58 mm, GT = 3.23 mm). E6 showed moderate performance, while E3 and E4 exhibited below-average values. E5 demonstrated the poorest performance, with TGW of only 45.70 g, representing a 16.5% reduction compared to E2, and GT of 2.70 mm, a decrease of 18.7%. These results highlight the substantial impact of environmental conditions on grain trait development.

Considerable genotypic variation was observed across all traits. TGW displayed the widest range, varying from 44.75 g to 58.52 g, with a range of 13.77 g. Genotype G5 showed the highest TGW (58.52 g), exceeding the overall mean by 8.41 g, establishing it as the highest-yielding genotype. G16 and G9 also exhibited high TGW values. For GL, G16 had the longest kernels (7.40 mm), surpassing the mean by 0.72 mm, followed by G1, G9, and G5. GW showed relatively narrow variation, with G5 exhibiting the greatest width (3.62 mm), closely followed by G16 and G9. For GT, G16 was the most prominent (3.42 mm), exceeding the mean by 0.33 mm, with G9, G5, and G15 also performing well.

Correlation analysis revealed highly significant positive associations between TGW and all three grain dimensional traits (GL, GW, and GT), with correlation coefficients ranging from 0.55 to 0.80 (Figure 2).

Table 3 Grain Trait Performance of the Varieties Tested

Environment	Grain trait	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12	G13	G14	G15	G16	Environmental mean
E1	TGW/g	54.61	53.34	51.05	53.71	62.13	52.68	49.96	51.35	59.53	54.65	46.19	45.09	43.98	46.62	47.78	66.27	52.44
	GL/mm	6.89	6.34	6.31	6.66	6.80	6.87	6.38	6.41	7.02	6.82	6.46	6.69	6.62	6.38	6.19	7.22	6.60
	GW/mm	3.52	3.68	3.63	3.53	3.87	3.56	3.59	3.73	3.86	3.63	3.46	3.41	3.39	3.43	3.48	3.82	3.58

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	GT/mm	3.27	3.23	3.27	3.22	3.54	3.09	3.29	3.18	3.36	3.36	3.14	3.09	3.05	3.16	3.18	3.60	3.23
E2	TGW/g	56.40	57.49	55.32	57.55	55.48	63.87	47.88	53.40	62.55	55.00	52.23	48.22	44.49	46.65	50.25	69.46	54.76
	GL/mm	6.98	7.21	6.50	6.86	6.83	7.02	6.36	6.71	7.21	6.61	6.97	6.86	6.95	7.00	6.70	7.67	6.91
	GW/mm	3.71	3.58	3.78	3.66	3.60	3.82	3.48	3.65	3.86	3.80	3.59	3.57	3.42	3.47	3.63	3.88	3.67
	GT/mm	3.32	3.35	3.32	3.22	3.10	3.53	3.28	3.30	3.48	3.15	3.23	3.22	3.09	3.18	3.42	3.78	3.32
E3	TGW/g	49.95	48.53	47.57	48.72	59.95	45.32	48.21	50.13	54.63	49.37	39.16	50.57	47.57	47.90	48.35	42.37	47.52
	GL/mm	7.22	6.65	6.67	6.91	7.43	6.99	6.70	6.72	7.17	7.05	6.42	6.82	6.71	6.58	6.44	7.25	6.86
	GW/mm	3.42	3.50	3.45	3.48	3.92	3.35	3.48	3.65	3.65	3.67	3.13	3.57	3.49	3.36	3.48	3.23	3.47
	GT/mm	3.13	3.11	3.09	3.01	3.62	2.92	3.11	3.11	3.23	3.18	3.09	3.10	3.19	3.16	3.23	3.13	3.12
E4	TGW/g	49.02	48.46	48.28	46.63	52.83	42.38	45.05	47.71	48.48	48.97	43.07	45.64	44.05	48.86	47.55	53.36	47.69
	GL/mm	7.25	6.68	6.60	7.08	7.20	6.94	6.58	6.61	7.06	7.23	6.51	6.70	6.58	6.71	6.44	7.68	6.87
	GW/mm	3.39	3.51	3.47	3.48	3.62	3.25	3.43	3.59	3.50	3.51	3.36	3.48	3.37	3.53	3.49	3.66	3.47
	GT/mm	3.16	3.14	3.15	3.07	3.49	2.94	3.16	3.10	3.15	3.26	3.16	3.18	3.04	3.25	3.25	3.40	3.16
E5	TGW/g	50.53	48.89	43.67	41.41	56.64	47.89	44.90	45.44	46.28	48.14	42.97	42.23	41.73	39.29	42.28	48.86	45.70
	GL/mm	6.08	6.72	5.82	6.67	6.37	5.55	6.02	6.00	6.35	5.97	6.25	6.43	6.43	5.93	6.02	7.07	6.17
	GW/mm	3.25	3.16	2.79	2.96	3.37	2.73	3.03	2.56	3.06	3.09	3.30	3.23	3.22	2.89	3.25	3.40	3.05
	GT/mm	2.79	2.85	2.69	2.69	2.19	2.48	2.61	2.49	2.76	2.71	3.00	2.82	2.81	2.60	2.75	3.39	2.70
E6	TGW/g	46.67	54.51	48.03	53.66	64.06	49.38	52.82	53.01	59.43	54.72	46.60	46.39	46.66	49.26	49.36	51.37	51.62
	GL/mm	7.08	6.36	6.63	6.13	6.44	7.05	6.09	6.46	6.44	6.57	6.72	6.65	6.84	6.80	6.37	7.52	6.68

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	GW/mm	3.36	3.20	3.54	3.10	3.35	3.43	3.22	3.51	3.35	3.39	3.48	3.41	3.51	3.55	3.45	3.41	3.39
	GT/mm	2.96	2.98	3.06	3.03	3.03	3.03	2.91	2.91	3.03	3.00	2.90	3.05	2.93	2.91	3.06	3.24	3.00
Genotypic mean	TGW/g	51.20	51.87	48.99	50.28	58.52	50.25	48.14	50.18	55.15	51.81	45.04	46.36	44.75	46.43	47.60	55.28	50.11
	GL/mm	6.92	6.66	6.42	6.72	6.84	6.74	6.36	6.48	6.88	6.71	6.56	6.69	6.69	6.57	6.36	7.40	6.68
	GW/mm	3.44	3.44	3.44	3.37	3.62	3.36	3.37	3.45	3.55	3.52	3.39	3.45	3.40	3.37	3.46	3.57	3.44
	GT/mm	3.10	3.11	3.10	3.04	3.16	3.00	3.06	3.02	3.17	3.11	3.09	3.08	3.02	3.04	3.15	3.42	3.09

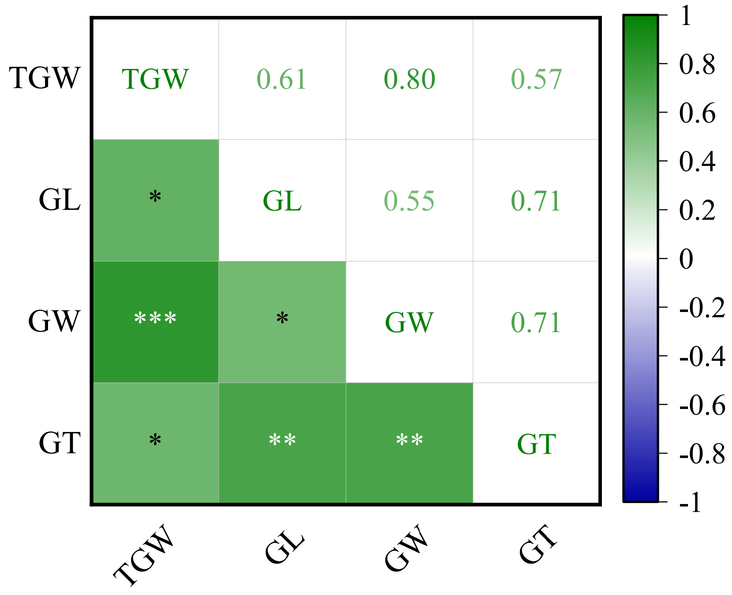

FIGURE 2 CORRELATION PLOT OF GRAIN TRAITS

3.2 *AMMI ANALYSIS OF VARIANCE FOR GRAIN TRAITS*

Analysis of variance for the four grain traits—TGW, GL, GW, and GT—revealed that the effects of environment (E), genotype (G), and their interaction (G×E) were highly significant ($P < 0.001$) for all traits (Table 4). Based on F-values, environmental effects were most pronounced for GW (F = 1707.50), followed by GL (F = 1540.39) and GT (F = 1340.36), while TGW exhibited a relatively lower environmental effect (F = 520.61), indicating that GW was the most sensitive to environmental variation. For genotypic effects, TGW showed the strongest genetic differentiation (F = 762.05), followed by GL (F = 1,196.52), with comparatively lower F-values for GW and GT, suggesting that TGW is under stronger genetic control. The G×E interaction effects were also highly significant, with GL exhibiting the highest F-value (F = 169.46), followed by TGW (F = 115.36), while GW and GT showed relatively lower interaction effects, indicating that GL is more susceptible to genotype-by-environment interactions.

Decomposition of the interaction sum of squares using principal component analysis revealed that the first three interaction principal components (IPC1, IPC2, and IPC3) cumulatively explained over 87% of the total G×E variation for all traits: 87.9% for TGW, 92.5% for GL, 90.3% for GW, and 95.3% for GT. All principal components were highly significant based on F-tests, confirming their effectiveness in capturing the underlying G×E interaction patterns. Examination of individual IPC

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contributions showed that TGW and GT were predominantly influenced by IPC1, which accounted for 64.5% and 68.4% of the variation, respectively. In contrast, GL and GW exhibited more complex interaction structures, with substantial contributions from multiple principal components. The residual mean squares were consistently small across all traits, indicating well-controlled experimental error and ensuring the reliability of the analysis.

Table 4 Analysis of Variance (ANOVA) for Grain Traits Using AMMI

Source	df	TGW				GL				GW				GT			
		SS	MS	F值	Cumulative (%)	SS	MS	F值	Cumulative (%)	SS	MS	F值	Cumulative (%)	SS	MS	F值	Cumulative (%)
ENV	5	2768.6	553.72	520.61***		15.5581	3.1116	1540.39***		9.9832	1.9966	1707.50***		10.863	2.1726	1340.36***	
GEN	15	4025.9	268.39	762.05***		17.7972	1.1865	1196.52***		1.6272	0.1085	188.87***		2.6808	0.1787	64.35***	
E×G	75	3047.2	40.63	115.36***		12.6031	0.168	169.46***		5.7256	0.0763	132.91***		4.9039	0.0654	23.54***	
PC1	19	1964.07	103.37	293.51***	64.50%	6.0829	0.3202	322.86***	48.30%	2.5872	0.1362	237.06***	45.20%	3.3545	0.1766	63.57***	68.40%
PC2	17	406.07	23.89	67.82***	77.80%	4.7826	0.2813	283.71***	86.20%	1.4907	0.0877	152.66***	71.20%	0.9754	0.0574	20.66***	88.30%
PC3	15	308.68	20.58	58.43***	87.90%	0.7935	0.0529	53.35***	92.50%	1.0926	0.0728	126.81***	90.30%	0.341	0.0227	8.19***	95.30%
PC4	13	247.3	19.02	54.01***	96.00%	0.5928	0.0456	45.99***	97.20%	0.3873	0.0298	51.86***	97.10%	0.1386	0.0107	3.84***	98.10%
PC5	11	121.06	11.01	31.25***	100%	0.3513	0.0319	32.20***	100%	0.1679	0.0153	26.58***	100%	0.0944	0.0086	3.09***	100%
Residuals	180	63.4	0.35			0.1785	0.001			0.1034	0.0006			0.4999	0.0028		
Total	287	9928.5				46.1611											

Note: *, **, and *** indicate significance at $P < 0.05$, $P<0.01$, and $P<0.001$, respectively.

4 GGE BIPLOT ANALYSIS

4.1 *HIGH-YIELDING POTENTIAL AND STABILITY OF GENOTYPES*

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The yield potential and stability of different genotypes were visualized using GGE biplots (Figure 3). In these biplots, the abscissa (x-axis) points toward higher trait values, with genotypes projecting further to the left exhibiting higher trait performance; the ordinate (y-axis) represents stability, where genotypes positioned closer to the horizontal axis demonstrate greater stability across environments.

For thousand-grain weight (TGW), genotypes G16, G9, and G5 were located on the left side of the biplot, indicating high TGW performance, with G16 and G5 exhibiting the most prominent values. However, G5 and G16 showed substantial deviation from the horizontal axis, suggesting that their TGW performance was highly susceptible to environmental variation. In contrast, G10, G2, and G8 were positioned closer to the horizontal axis with minimal vertical displacement, indicating superior stability. Notably, G10 achieved moderately high TGW while maintaining good stability, representing a favorable balance between high yield potential and stable performance.For grain length (GL), G16 demonstrated the most superior performance with a clear advantage in kernel length, while also exhibiting relatively good stability. G1 and G9 followed in GL performance. Regarding stability, G5, G8, and G12 were positioned closest to the horizontal axis, indicating more consistent GL expression across environments.For grain width (GW), genotypes G11, G13, G15, and G16 displayed larger kernel widths, with G15 showing the highest stability among this group.For grain thickness (GT), G16 exhibited the greatest thickness coupled with good stability, followed by G9, G5, and G15. However, G5 showed poor stability despite its high GT value. Genotypes G4, G3, and G1 demonstrated moderate GT values but exhibited favorable stability characteristics.

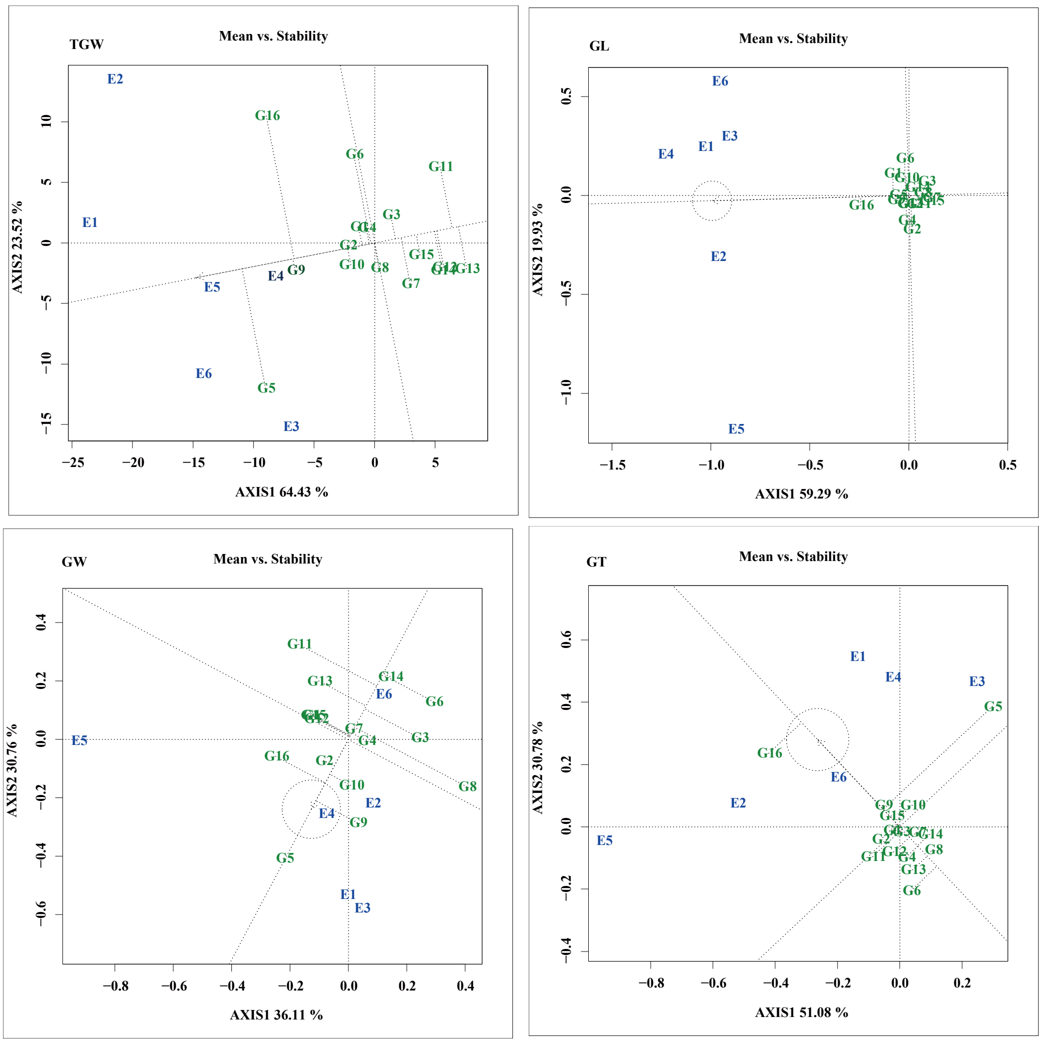

FIGURE 3: ANALYSIS OF HIGH-YIELD POTENTIAL AND YIELD STABILITY BASED ON GRAIN TRAITS OF DIFFERENT VARIETIES

4.2 *ADAPTABILITY ANALYSIS OF GENOTYPES*

The optimal genotypes for each environment and their adaptation patterns were visualized using polygon views of the GGE biplots (Figure 4). In these biplots, rays drawn from the biplot origin to the environmental vectors partition the plot into several sectors, with the genotype located at the vertex of each sector representing the best-performing genotype for environments falling within that sector.

For thousand-grain weight (TGW), the biplot was divided into four sectors. Environments E1 and E2 fell within the same sector, with G16 identified as the vertex genotype, indicating its superior performance in these two environments. Environments E3, E4, E5, and E6 were grouped into another sector, where G5 emerged as the best-performing genotype. The sectors containing G11 and G13 at their vertices contained no test environments, suggesting these genotypes did not exhibit specific adaptation advantages in the evaluated locations. The remaining genotypes showed no clear adaptive superiority. For grain length (GL), the biplot was partitioned into five sectors. Notably, all six environments (E1–E6) were located within a single sector, with G16 at the vertex, demonstrating its consistent superior performance across all environments for this trait. The sectors containing G6, G2, and G7 at their vertices contained no corresponding environments. For grain width (GW), the biplot revealed six sectors. Environments E1, E2, E3, and E4 were grouped together, with G16 as the vertex genotype, indicating its optimal performance across these locations. G6 and G14 showed outstanding performance specifically in E6. Environment E5 formed an isolated sector without a clearly associated vertex genotype, suggesting no single genotype was optimally adapted to this specific environment. For grain thickness (GT), the biplot displayed five sectors. Environments E1, E2, E5, and E6 were clustered in one sector with G5 as the vertex genotype. G5 also demonstrated superior performance in E3 and E4, which fell within another sector, further confirming its broad adaptation for this trait. Collectively, these results indicate that G16 and G5 exhibited wide adaptability across multiple environments for TGW and GW traits, demonstrating their potential as broadly adapted genotypes suitable for diverse ecological conditions in the Qinghai Plateau.

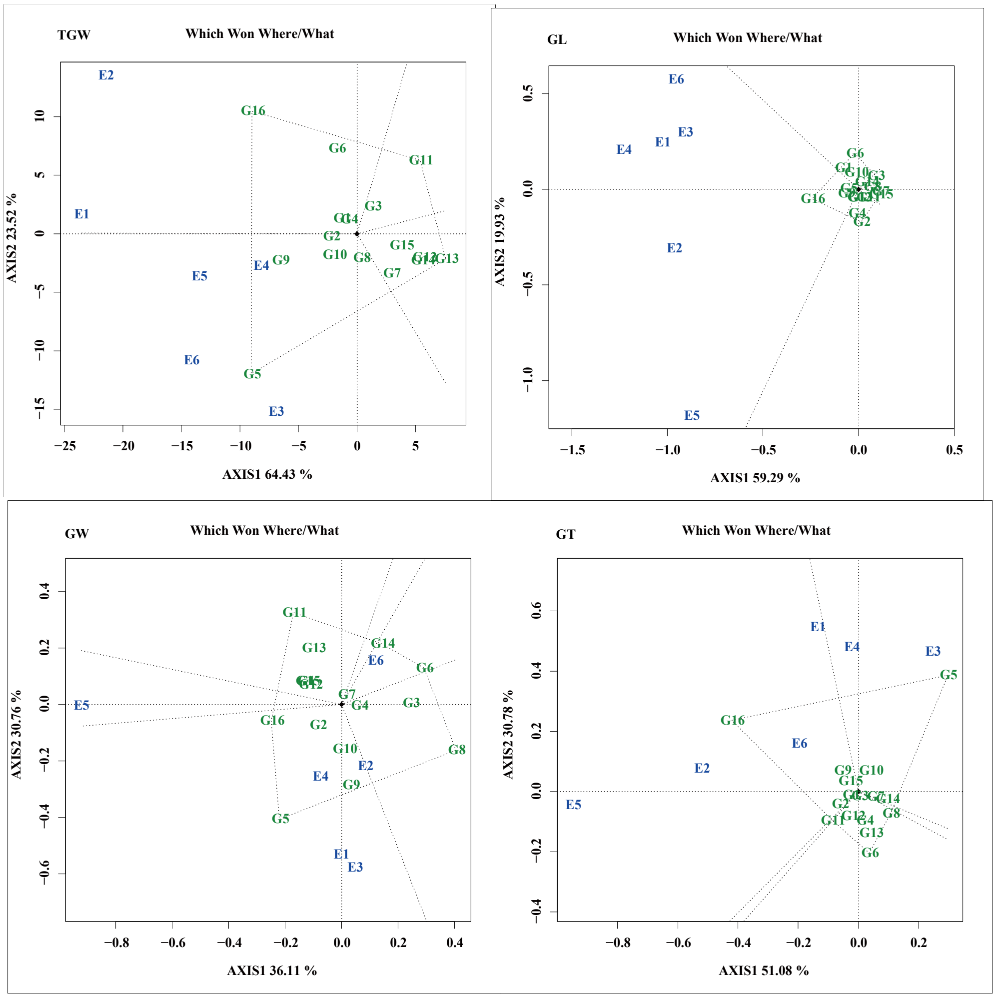

FIGURE 4 ADAPTABILITY ANALYSIS OF GRAIN TRAITS ACROSS DIFFERENT VARIETIES

4.3 DISCRIMINATING ABILITY AND REPRESENTATIVENESS OF TEST ENVIRONMENTS

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The discriminating ability and representativeness of the six test environments were evaluated using GGE biplots (Figure 5). In these biplots, the arrow indicates the average environment, whose coordinates are calculated as the mean of all environment coordinates, serving as a representative of the target ecological region. The line passing through the origin and the average environment is designated as the average environment axis (AEA). The vector length of each test environment measures its discriminating ability, with longer vectors indicating stronger capacity to differentiate among genotypes. The angle between an environment vector and the AEA reflects its representativeness of the target environment: smaller angles indicate greater representativeness, while obtuse angles suggest the environment is unsuitable as a test location.

For thousand-grain weight (TGW), environments E1 and E2 exhibited relatively long vectors, indicating strong discriminating ability. E4 and E5 showed small angles with the AEA, demonstrating good representativeness. E6 displayed moderate vector length and angle. E3 had a short vector, indicating weak discriminating ability, coupled with a large angle relative to the AEA, suggesting poor representativeness. For grain length (GL), E4 demonstrated both strong discriminating ability and good representativeness. E1 and E2 showed moderate discriminating ability with favorable representativeness. E6 exhibited weak discriminating ability and poor representativeness. For grain width (GW), E5 had the longest vector, indicating the strongest discriminating ability; however, its large angle with the AEA suggested poor representativeness. E1 and E3 displayed strong discriminating ability coupled with good representativeness. E4 and E2 had relatively short vectors, indicating weak discriminating ability. For grain thickness (GT), E5 again showed strong discriminating ability but poor representativeness. E1 and E2 exhibited both good discriminating ability and representativeness. E3 and E4 demonstrated weak discriminating ability and poor representativeness. E6 showed good representativeness but weak discriminating ability. These results indicate that no single environment simultaneously exhibited optimal discriminating ability and representativeness across all traits. E1 and E2 consistently demonstrated relatively good performance in both aspects for multiple traits, suggesting their suitability as primary test locations. In contrast, environments such as E3 and E6 showed limitations in either discriminating ability or representativeness depending on the trait evaluated, highlighting the importance of multi-environment trials for comprehensive germplasm evaluation.

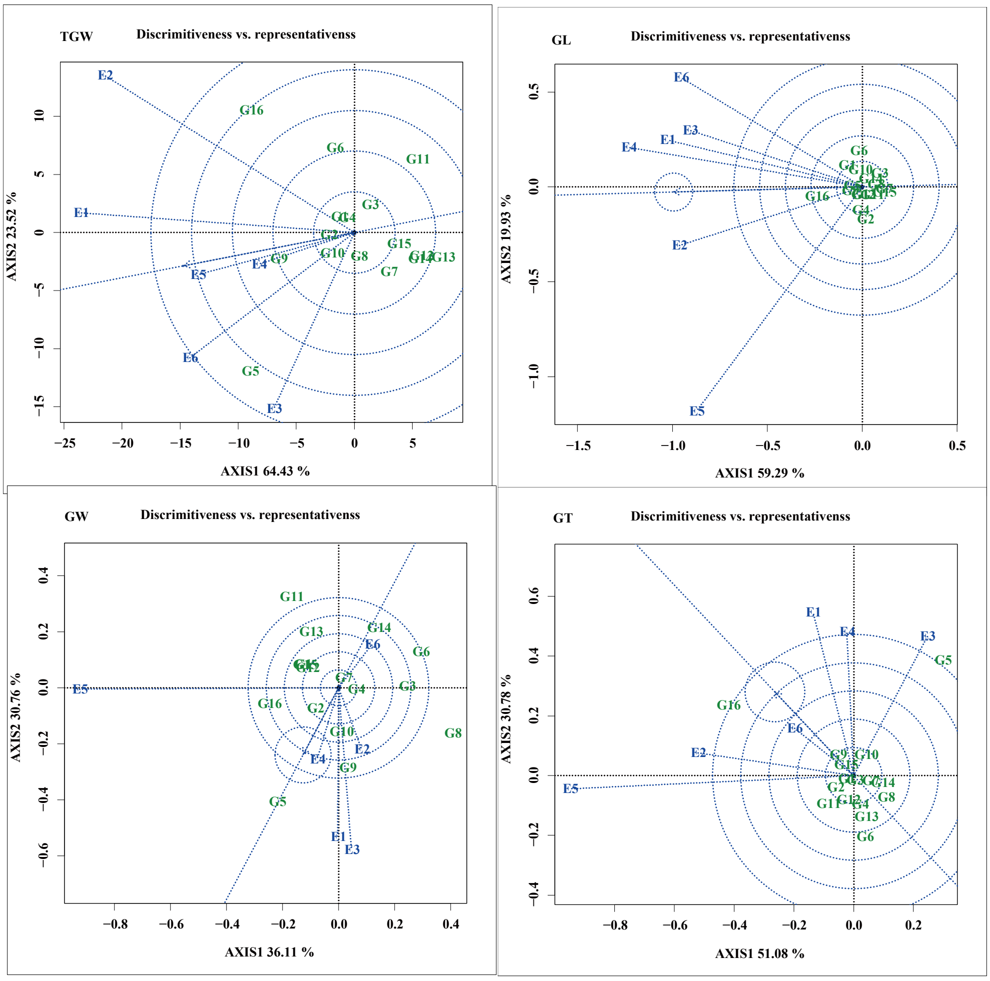

FIGURE 5: ANALYSIS OF THE DISCRIMINATORY POWER AND REPRESENTATIVENESS OF THE TEST ENVIRONMENT

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4.4 *IDEAL GENOTYPE ANALYSIS*

The identification of ideal genotypes was visualized using GGE biplots with concentric circles centered on the "ideal genotype" (Figure 6). The ideal genotype is defined as the point located at the farthest distance from the biplot origin along the positive direction of the average environment axis (AEA), representing a theoretical reference with both maximum trait performance and perfect stability. Genotypes positioned closer to this ideal point exhibit superior comprehensive performance.

For thousand-grain weight (TGW), G9 was located closest to the ideal genotype, demonstrating the most favorable comprehensive performance with both high trait values and relatively good stability. G2 and G10 ranked next in comprehensive performance, followed by G5. G16, G3, and G8 were positioned in outer concentric circles, indicating moderate performance. G7, G11, G12, G13, and G14 were situated farthest from the ideal point, exhibiting the poorest comprehensive performance. For grain length (GL), G16 was positioned closest to the ideal genotype, showing superior comprehensive performance. All remaining genotypes were located between the first and second concentric circles, indicating relatively similar performance levels. For grain width (GW), G5 fell within the innermost concentric circle, demonstrating the most favorable comprehensive performance, followed by G9. G10, G16, and G12 showed moderate performance, while the remaining genotypes exhibited inferior performance. For grain thickness (GT), G16 was located closest to the ideal genotype, displaying superior comprehensive performance. All other genotypes were positioned outside the concentric circles, indicating comparatively poorer performance for this trait. These results collectively highlight G9 and G16 as genotypes with superior comprehensive performance across multiple traits, making them valuable genetic resources for wheat breeding programs in the Qinghai Plateau.

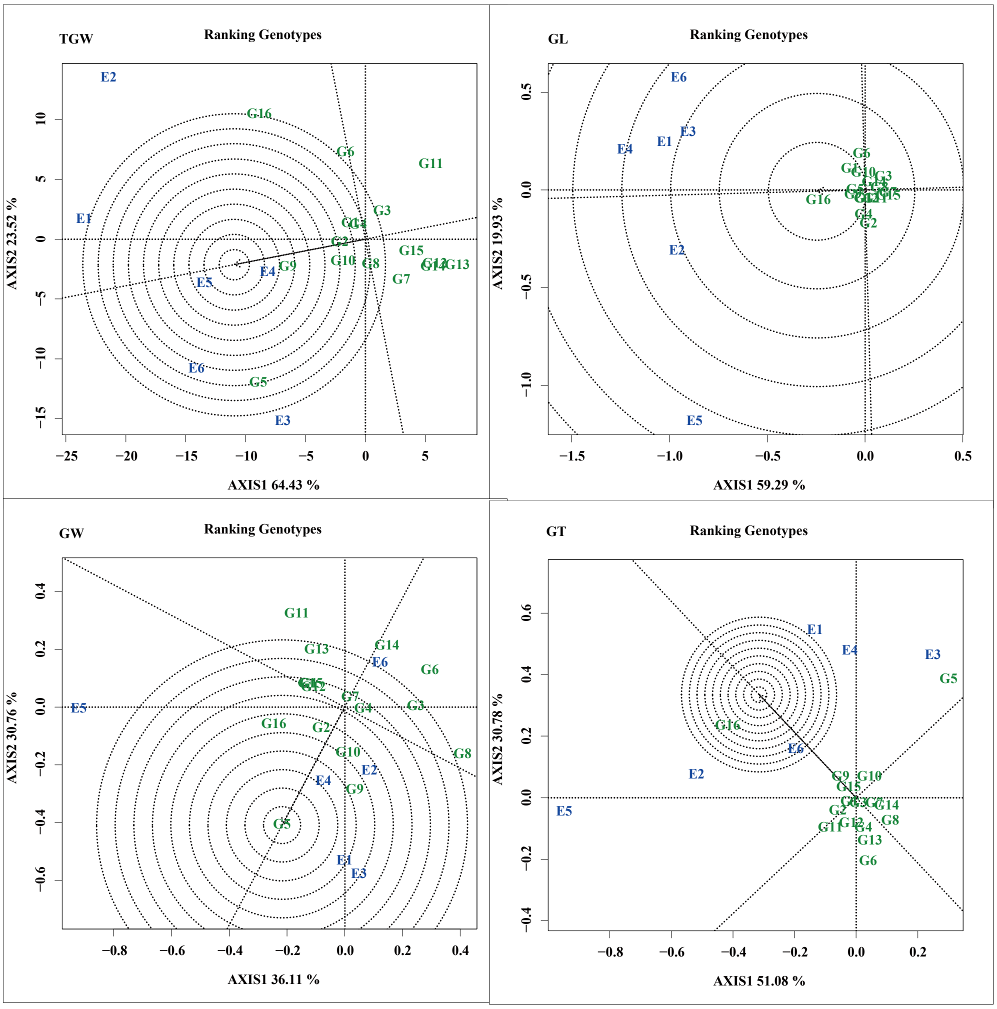

FIGURE 6: ANALYSIS OF IDEAL VARIETIES

4.5 *IDEAL ENVIRONMENT ANALYSIS*

The comprehensive performance of the six test environments was evaluated using GGE biplots with concentric circles centered on the "ideal environment" (Figure 7). The ideal environment represents a theoretical reference point that combines both strong discriminating ability and high representativeness. Environments positioned closer to this ideal point exhibit superior comprehensive performance, while those farther away demonstrate progressively poorer performance.

For thousand-grain weight (TGW), E1 was located within the innermost concentric circle, exhibiting the most favorable comprehensive performance and thus representing the most ideal test environment. E5 and E6 ranked next in comprehensive performance, followed by E4 and E2 with moderate performance. E3 was positioned farthest from the ideal point, demonstrating the poorest comprehensive performance. For grain length (GL), E4 fell within the innermost concentric circle, showing superior comprehensive performance. E1 and E2 ranked second, followed by E3 with moderate performance. E5 was located farthest from the ideal point, exhibiting the poorest performance. For grain width (GW), E1 and E3 were positioned within the innermost concentric circle, demonstrating the most favorable comprehensive performance. E4 ranked next, followed by E2 and E5 with moderate performance. E6 was situated farthest from the ideal point, showing the poorest performance. For grain thickness (GT), E1, E2, and E6 fell within the innermost concentric circle, exhibiting superior comprehensive performance. E4 and E5 ranked second, while E3 was positioned farthest from the ideal point, demonstrating the poorest performance. These results reveal that no single environment consistently performed as the ideal test location across all traits. E1 demonstrated superior comprehensive performance for multiple traits (TGW, GW, and GT), suggesting its suitability as a primary test environment. In contrast, environments such as E3 and E6 showed trait-dependent performance, with E3 performing poorly for TGW and GT but optimally for GW, and E6 performing optimally for GT but poorly for GW. These findings underscore the importance of multi-environment trials to capture trait-specific environmental responses and ensure comprehensive germplasm evaluation.

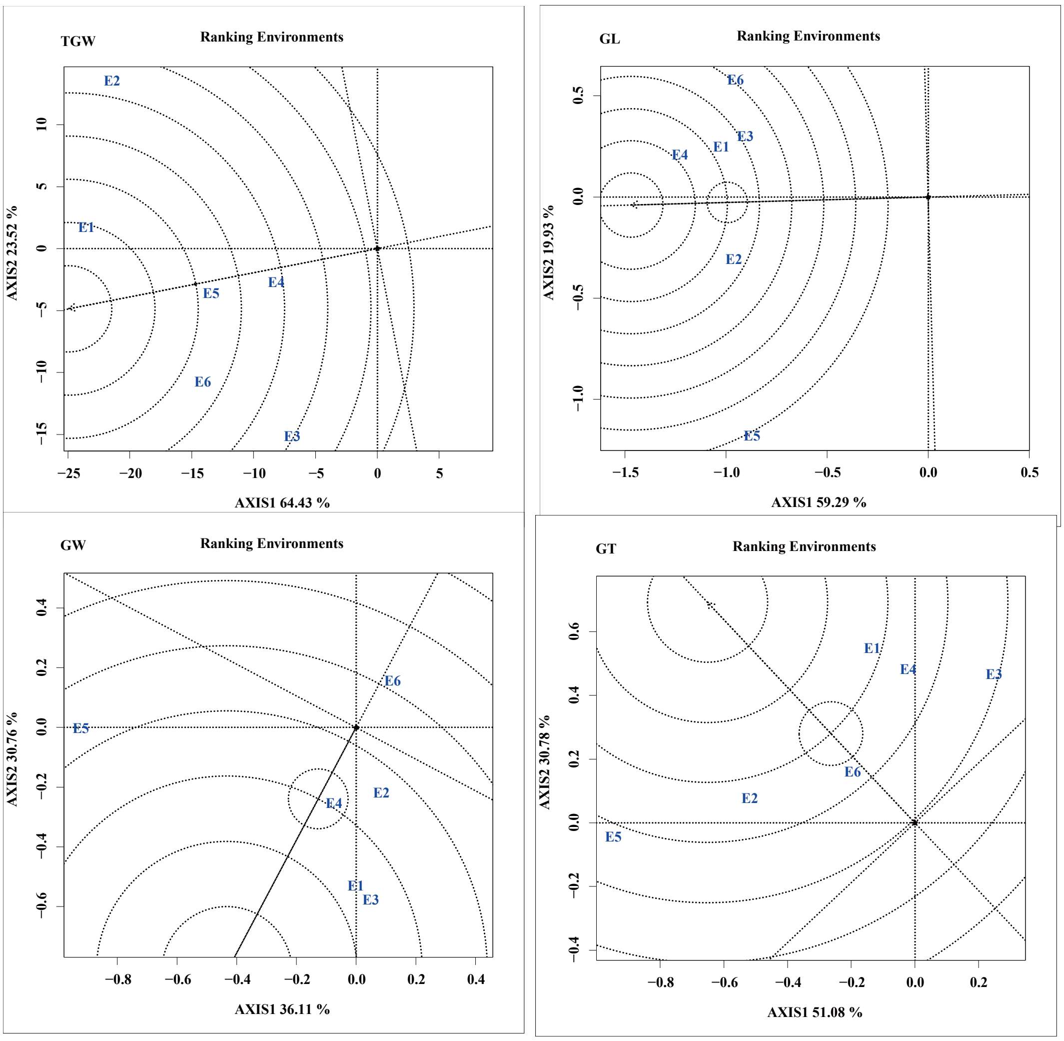

FIGURE 7: ANALYSIS OF THE IDEAL ENVIRONMENT

5 DISCUSSION

5.1 EFFECTS OF ENVIRONMENT, GENOTYPE, AND THEIR INTERACTION ON GRAIN TRAITS

The AMMI model and GGE biplot are effective tools for analyzing multi-environment trial data and dissecting complex genotype-by-environment interactions (Pour-Aboughadareh et al. 2022; Sattar et al. 2023; Singh et al. 2026). In this study, AMMI analysis of variance revealed highly significant effects of environment (E), genotype (G), and their interaction (G×E) on all grain traits, which is consistent with previous findings. For instance, Hnizil et al. observed in wheat that genotype-by-environment interactions significantly influenced key agronomic traits including yield, thousand-grain weight, and spikes per square meter(Hnizil et al. 2024). Similarly, Roostaei et al. through AMMI analysis of multi-year multi-location trials involving 24 winter wheat genotypes, further demonstrated that the effects of genotype, environment, and their interaction on yield were all highly significant ($p < 0.01$)(Roostaei et al. 2022). Regarding trait-specific sensitivity to environmental variation, grain width exhibited the largest environmental effect ($F = 1707.50$), indicating that it was most significantly influenced by environmental conditions. This may be attributed to the greater sensitivity of grain width to fluctuations in water availability and temperature(Maphosa et al. 2014). In contrast, while thousand-grain weight was also affected by environmental factors, its expression was more strongly regulated by genetic factors. Studies have shown that thousand-grain weight in wheat possesses relatively high heritability, with phenotypic variation resulting from the combined effects of genotype, environment, and their interaction (P. Zhang et al. 2026). Under the specific conditions of this study, genotypic effects predominated for TGW ($F = 762.05$).

Decomposition of the G×E interaction using the AMMI model revealed that the first three interaction principal components cumulatively explained over 87% of the total interaction variation across all four traits, effectively capturing the underlying interaction patterns. Notably, TGW and GT were predominantly influenced by the first principal component, which accounted for 64.5% and 68.4% of the interaction variation, respectively, suggesting relatively simple interaction structures for these two traits. This finding aligns with Muhammad (2018), who reported that IPCA1 explained 64.0% of the interaction sum of squares in wheat, followed by IPCA2 with 25.8%. In contrast, grain length and grain width exhibited more complex interaction patterns with substantial contributions from multiple principal components, indicating that their G×E mechanisms may involve differentiated responses to a broader range of environmental factors.

The six test environments in this study represented distinct wheat-growing regions with pronounced climatic differences. Regarding crop duration, Yuanmou County in Yunnan Province (E1, E2) is located in the low-latitude Jinsha River dry-hot valley, characterized by favorable thermal conditions (Yao et al. 2012), resulting in relatively short wheat growth periods. For the high-altitude locations—Xining (E3, E4), Guide (E5), and Xiangride (E6) in Qinghai Province—spring wheat growth duration was more sensitive to temperature variations, with each 1°C increase in mean daily temperature shortening the growth period by approximately 11.7 days (Wang Li et al. 2011). The Qaidam Basin (E6) possesses unique plateau climatic advantages for wheat production, including extended sunshine duration and prolonged functional leaf longevity during grain filling, which favor kernel filling and dry matter accumulation (Su Tizhi,Pan Zingshan 1981).In the present study, substantial variation was observed in genotype performance across environments. Certain genotypes that exhibited outstanding performance in Yuanmou (E1, E2) showed only moderate performance across the Qinghai locations, underscoring the significant impact of G×E interactions. These findings highlight the necessity of conducting site-specific variety screening and adaptation evaluations tailored to particular ecological regions, rather than relying on performance data from a single environment.

5.2 EVALUATION OF GENOTYPIC YIELD STABILITY AND TEST ENVIRONMENTS

GGE biplot is an effective tool for visualizing genotype performance and stability, and for dissecting genotype-by-environment interactions to identify ideal genotypes (Saeidnia et al. 2023; Aboye and Edo 2024; Gupta et al. 2025). A key advantage of the GGE biplot is its "which-won-where" pattern analysis, which graphically displays the types of crossover interactions between genotypes and environments, mega-environment differentiation patterns, and the adaptive characteristics of specific genotypes(Yan and Hunt 2001; Alemu et al. 2024; Mohammadi et al. 2025). In the polygon view, the genotype at the vertex of each sector represents the best-performing genotype for environments falling within that sector (Yan et al. 2000; Lin et al. 2023; Mullualem et al. 2024). Environments within the same sector are highly correlated; however, a genotype that performs stably in one environment may not maintain the same yield level in other environments(Stansluos et al. 2025). In the present study, G16 exhibited optimal performance in environments E2 and E6, while G5 performed best in E3, E4, E5, and E6. Both G16 and G5 demonstrated broad adaptability across multiple environments for thousand-grain weight and grain width. G9 ranked among the top performers across all four traits, representing the most balanced genotype with superior comprehensive traits. This environment-specific adaptation pattern may be attributed to variations in climatic conditions and physiological characteristics across the test sites.

In GGE biplot analysis, an ideal genotype should possess both high yield potential and stable performance. Generally, genotypes with high PC1 scores exhibit higher mean yields, while those with low absolute PC2 scores demonstrate greater stability across environments (Yan and Tinker 2006; Irfan et al. 2025). In this study, G10 was identified as a high-yielding and stable genotype, exhibiting excellent stability across all traits and achieving a favorable balance between high yield potential and stable performance. Its proximity to the average environment axis coupled with high PC1 scores indicated insensitivity to environmental variation and outstanding yield potential.

The GGE biplot is also applicable for evaluating test environments, with its discriminating ability and representativeness assessment based on the GGE perspective outperforming the AMMI model (Yan et al. 2007; Yan and Holland 2010; Aktaş 2016). Longer environment vectors indicate stronger discriminating ability, whereas shorter vectors suggest weaker discriminatory power. The angle between an environment vector and the average environment axis (AEA) reflects its representativeness: smaller angles indicate stronger representativeness of the average test environment (Luo et al. 2015; M. Li et al. 2019). In this study, E2 exhibited relatively long environment vectors and small AEA angles across all four traits, demonstrating both strong discriminating ability and good representativeness, making it the most ideal test environment. E1 and E6 showed moderate performance and could serve as supplementary test locations. In contrast, E5 displayed short environment vectors and large deviations from the AEA for most traits, indicating weak discriminating ability and poor representativeness; therefore, it is unsuitable as a standard test environment for evaluating general genotypic adaptability. Regarding environmental performance, E2 exhibited the highest mean values across all traits (TGW = 54.76 g, GL = 6.91 mm, GW = 3.67 mm, GT = 3.32 mm), representing the most favorable planting environment for the evaluated germplasm. Conversely, E5 showed the poorest performance, with TGW reduced by 16.5% and GT reduced by 18.7% compared to E2. These results underscore the necessity of selecting stable germplasm: genotypes performing well in E3 may not maintain the same yield potential in E5, as each test genotype is differentially influenced by environmental conditions.

In conclusion, G16, as a Qinghai-registered variety, exhibited superior grain morphology and broad adaptability, representing a locally adapted genotype with excellent comprehensive traits. The introduced genotypes G5, G9, G10, and G2 each possess distinct advantages and can serve as valuable genetic resources. G16, G5, and G9 are recommended as parental lines for breeding programs, while G10 and G2 show potential for direct production deployment. Variety deployment should be strategically arranged according to adaptation zones to maximize the production potential of each genotype.

6 CONCLUSIONS

In this study, four grain traits of 16 wheat genotypes evaluated across six environments were comprehensively analyzed using analysis of variance, AMMI model, and GGE biplot to assess yield potential, stability, and adaptability of genotypes, as well as the discriminating ability and representativeness of test environments. Analysis of variance revealed highly significant effects of environment, genotype, and their interaction on all traits. Grain width was most sensitive to environmental variation, thousand-grain weight exhibited the strongest genotypic effect, and grain length was most influenced by genotype-by-environment interaction. Among environments, E2 exhibited the highest mean values across all traits (TGW = 54.76 g, GL = 6.91 mm, GW = 3.67 mm, GT = 3.32 mm), identifying it as the most favorable planting environment, followed by E1. E5 showed the poorest performance, with TGW and GT reduced by 16.5% and 18.7%, respectively, compared to E2. Environment evaluation further demonstrated that E2 possessed both strong discriminating ability and good representativeness across all traits, making it the most ideal test location. E1 and E6 showed moderate performance, while E5 exhibited weak discriminating ability and poor representativeness for most traits, rendering it unsuitable as a standard test environment.

Regarding genotypic performance, G5 exhibited the highest TGW (58.52 g) and GW (3.62 mm), characterizing it as a high-yielding bold-kernel type. G16 displayed the longest GL (7.40 mm) and greatest GT (3.42 mm), indicating superior grain morphology. G9 ranked among the top performers across all four traits, demonstrating balanced and excellent comprehensive traits. G10, despite showing moderately high yield, exhibited outstanding stability, achieving a favorable balance between high yield potential and stable performance. Comprehensive genotype ranking revealed that G9 performed best for TGW, G16 excelled in GL and GT, and G5 was optimal for GW. G10 and G2 showed favorable performance across most traits and possess potential for direct promotion.

In conclusion, G16, as a Qinghai-registered variety, exhibited superior grain morphology and broad adaptability, representing a locally adapted genotype with excellent comprehensive traits. The introduced genotypes G5, G9, G10, and G2 each possess distinct advantages and can serve as valuable genetic resources. It is recommended that G16, G5, and G9 be utilized as parental lines in breeding programs, while G10 and G2 are suitable for direct production deployment. Variety deployment should be strategically arranged according to adaptation zones: G16 and G5 are prioritized for E2 and E6; G2, G3, and G8 for E1 and E4; G9 for E3; and G1 for E5, to maximize the production potential of each genotype.

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