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Integrated Multi-Trait Selection of Bread Wheat Genotypes Using GYT Biplot Analysis under Contrasting Moisture Regimes

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ABSTRACT

Improving wheat yield and stability under variable water availability a major challenge in semi-arid agroecosystems. Conventional selection strategies often emphasize yield alone, overlooking its interaction with key agronomic traits. study sought to identify high-performing and stable bread wheat genotypes using the Genotype by Yield × Trait (GYT) biplot approach as traditional selection indices. Twelve genotypes were evaluated over four growing seasons (2019–2023) under rainfed and supplementary irrigation conditions in Kurdistan Province, Iran. The GYT biplot integrated grain yield with twelve agronomic traits, allowing genotype performance to be assessed based on yield–trait combinations rather than yield alone. Principal component analysis explained 79.43% and 85.04% of the total variation under rainfed and irrigated conditions, respectively. Genotype G5 consistently achieved the highest Superiority Index (SI) in both environments (SI = 2.08 under irrigation and 1.44 under rainfed conditions). Its superior ranking was primarily associated with favorable yield combinations for spike weight, thousand grain weight (TGW), and harvest index (HI). These results suggest that G5 combined favorable yield-related traits under the evaluated moisture regimes; however, the physiological mechanisms underlying this superiority require further investigation. A moderate to strong positive correlation ($r = 0.59$ to 0.60, $P < 0.05$) between the GYT-based Superiority Index (SI) under rainfed conditions and conventional drought tolerance indices, including Geometric Mean Productivity (GMP) and Stress Tolerance Index (STI), further supports the applicability of this multi-trait framework. These findings highlight the value of GYT analysis in enhancing selection efficiency and identify G5 as a promising genotype for breeding programs aimed at improving yield resilience under variable moisture conditions.

Keywords: Drought tolerance indices, Phenotypic, Selection index, Wheat, Yield components synergy.

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INTRODUCTION

Wheat (*Triticum* spp.), widely known as the "golden grain," plays a central role in global food security and human nutrition, supplying nearly 20% of the calories and protein consumed worldwide and ranking among the most strategically important cereal crops (Sharma and Sharma, 2025). As global population growth continues alongside increasing climatic variability, maintaining stable wheat production has become progressively more challenging. Recent projections of future wheat productivity have often assumed that the geographical distribution of cultivation will remain unchanged, thereby estimating yield reductions without fully considering potential shifts in cropping zones under changing climate scenarios (Cong *et al*., 2026). Such assumptions may oversimplify the dynamic nature of agricultural systems, particularly in regions highly vulnerable to water scarcity.

Grain yield remains the primary target trait in wheat breeding programs; however, it is a complex quantitative character controlled by numerous morphological, physiological, and environmental factors. Its expression depends on the coordinated interaction of yield components and adaptive traits that collectively determine productivity across diverse growing conditions. Consequently, modern breeding strategies increasingly emphasize comprehensive evaluation of genetic resources to identify optimal combinations of yield-related traits rather than relying solely on yield performance (Faheem *et al*., 2023). Selection based on highly heritable morphological traits and yield components continues to provide a dependable pathway for identifying superior genotypes (Gholizadeh and Dehghani, 2016). In this context, understanding the magnitude and direction of relationships among traits is critical, since grain yield is closely associated with agronomic variables influencing plant architecture, biomass accumulation, and assimilate partitioning (Torres *et al*., 2004).

Correlation analysis has traditionally been used to quantify phenotypic associations resulting from both genetic and environmental effects (Malik *et al*., 2010). Although this approach offers valuable insights into trait interrelationships, breeding decisions are frequently complicated by unfavorable correlations and genotype-by-environment interactions (GEI). When desirable traits are negatively associated, simultaneous improvement becomes difficult, thereby limiting the efficiency of conventional selection strategies (Bernardo, 2010). To address multi-trait improvement, breeders have historically applied methods such as tandem selection, independent culling levels, and index selection (Bourima and Abdoua, 2019). While these methods have

facilitated genetic gain, they often rely on subjective weighting of traits and predefined thresholds, which may introduce bias and reduce selection consistency, as noted by Yan and Fregeau-Reid. (2018).

To overcome these limitations (Yan and Fregeau-Reid, 2018) proposed the Genotype-by-Yield × Trait (GYT) biplot methodology, which integrates grain yield with secondary traits through multiplicative or divisive transformations. This approach ensures that trait performance is interpreted directly in relation to yield, thereby aligning selection decisions with breeding objectives. By generating a Superiority Index (SI), the GYT framework provides a comprehensive and visually intuitive means of ranking genotypes based on their overall multi-trait performance (Merrick *et al*., 2020). The effectiveness of GYT analysis has been demonstrated in several crops, including durum wheat (Kendal, 2019; Mohammadi, 2019), spring wheat (Merrick *et al*., 2020), barley (Karahan and Akgün, 2020; Yan and Fregeau-Reid, 2021), rapeseed (Zeinalzadeh Tabrizi *et al*., 2021), and sesame (Bourima and Abdoua, 2019). In addition to improving selection precision, this method has been shown to enhance breeding efficiency by reducing time and resource demands associated with extensive trait measurements (Mohammadi, 2019; Purwati *et al*., 2022).

Given the increasing frequency of drought events and the growing importance of efficient water management in wheat production systems, evaluating genotypes under both rainfed and supplementary irrigation conditions is essential for identifying broadly adapted and drought-resilient materials. Multi-year assessments further strengthen the reliability of genotype evaluation by capturing environmental variability and GEI effects. Therefore, the present study aimed to apply the GYT biplot methodology to twelve bread wheat genotypes grown under contrasting moisture regimes in a semi-arid environment. The specific objectives were to: (i) implement GYT analysis for comprehensive evaluation of genotype performance across yield–trait combinations; (ii) identify genotypes exhibiting superior and stable performance under both rainfed and supplementary irrigation conditions; and (iii) assess the usefulness of the GYT framework as a robust tool for multi-trait selection in drought-oriented wheat breeding programs.

MATERIALS AND METHODS

Plant Materials

The plant material consisted of twelve bread wheat genotypes (*Triticum aestivum* L.) obtained from the Kurdistan Agricultural and Natural Resources Research Center, Kurdistan Province, Iran. The evaluated materials included both released cultivars and advanced breeding lines selected for their agronomic relevance and adaptation to semi-arid conditions. Each genotype was assigned a specific code (G1–G12), and their names and pedigree/origin information are presented in Table 1. The inclusion of genetically diverse materials with contrasting agronomic backgrounds enabled a comprehensive evaluation of yield potential and associated agronomic traits under different moisture regimes. A schematic representation of the experimental workflow, from genotype selection to multivariate statistical evaluations, is illustrated in Figure 1.

Table 1. Description of the 12-bread wheat (*Triticum aestivum* L.) genotypes evaluated, including genotype codes, pedigree information, and breeding origin.

Genotypes code	Genotype Name	Pedigree/Origin
G1	Zargana 21	Heidari / Synthetic Hexaploid Wheat (SHW)
G2	Zargana 22	Advanced Breeding Lines (from ICARDA/CIMMYT)
G3	Waran	Modern Improved Cultivars
G4	Uok	Local Ecotypes / Selection Lines
G5	Aohadi	Old Improved Cultivars
G6	Hashtrood	Modern Improved Cultivars
G7	Baran	Modern Improved Cultivars
G8	MV17	Advanced Breeding Lines (from ICARDA/CIMMYT)
G9	MV18	Advanced Breeding Lines (from ICARDA/CIMMYT)
G10	Azar2	Old Improved Cultivars
G11	Sardari	Local Landrace (Traditional Check)
G12	Gawdareh	Local Landrace

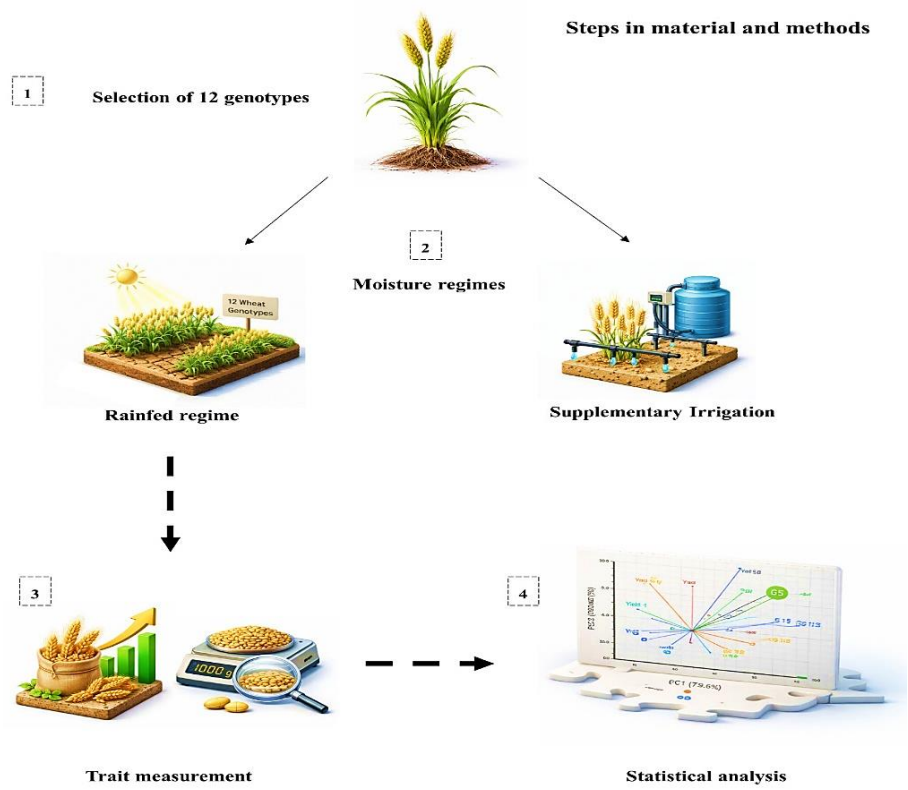


Figure 1. Experimental workflow and analytical framework. Schematic representation of the study design: (1) selection of 12 bread wheat genotypes; (2) evaluation under two moisture regimes (rainfed and supplementary irrigation) over four seasons; (3) measurement of grain yield and associated agronomic traits; and (4) statistical analysis using GT and GYT biplot methods to rank genotypes based on integrated yield–trait performance.

Experimental Site and Design

Field experiments were conducted at the Dehgolan Research Farm, University of Kurdistan, Iran, over four consecutive growing seasons (2019–2023). The experimental site is characterized by a semi-arid climate with variable annual precipitation and marked inter-annual fluctuations in rainfall distribution. Climatic data, including total seasonal rainfall and temperature patterns during each cropping season, are in Figure 2. The experiment was arranged in a split-plot design based on a randomized complete block design (RCBD) with three replications. The Water regime was assigned to the main plots, comprising two treatments: (i) rainfed conditions and (ii) supplementary irrigation applied at critical growth stages to prevent severe moisture stress. The twelve wheat genotypes were allocated to sub-plots within each main plot.

Seasonal rainfall, irrigation schedules, application volumes, and total water applied across four growing seasons are summarized in Table 2. Each experimental unit measured 8.4 m² and consisted of eight rows, each 8 m in length, with 15 cm spacing between rows. Seeds were sown at a rate of 170 kg ha^{-1}. Fertilization was applied at planting according to regional agronomic recommendations, including 60 kg N ha^{-1} and 60 kg P_2O_5 ha^{-1}.

Supplementary irrigation was applied using a surface drip irrigation system equipped with volumetric flow meters. Irrigation scheduling was strictly based on fixed phenological stages (Zadoks scale). In the first growing season (2019–2020), four irrigation events were applied: 20 mm at booting (Z41–Z45), followed by 35mm each at heading (Z49–Z59), flowering (Z60–Z69), and grain-filling (Z71–Z75) stages. In the second and third seasons (2020–2022), three irrigation events of 35mm each were applied at heading, flowering, and grain filling. In the fourth season (2022–2023), two irrigation events were applied: 25 mm immediately after sowing, owing to low autumn precipitation deficit, to ensure uniform seedling emergence, and 35 mm at the grain-filling stage. rainfed plots received natural precipitation only.

The inter-annual variation in supplementary irrigation amounts was necessitated by seasonal fluctuations in potential evapotranspiration (ET_0) and rainfall distribution. Specifically, low early-spring temperatures in the first season delayed crop growth into higher temperatures, which, coupled with a spring rainfall deficit and the resulting mismatch between the crop growth period and rainfall occurrence, required higher irrigation volumes. In contrast, better precipitation alignment with critical growth stages in the second and third seasons reduced irrigation requirements, while sufficient overall rainfall in the fourth season limited supplementary irrigation strictly to crop establishment and grain filling.

Drought intensity (DI) for each growing season was calculated as $DI = 1 - (\bar{Y}_S / \bar{Y}_P)$, where $\bar{Y}_S$ and $\bar{Y}_P$ represent the overall mean grain yield across all genotypes under rainfed and supplementary irrigation conditions, respectively. To prevent any ambiguity with the GYT-derived Superiority Index (SI), the abbreviation DI is used strictly for drought intensity throughout the manuscript, whereas SI refers exclusively to the GYT Superiority Index.

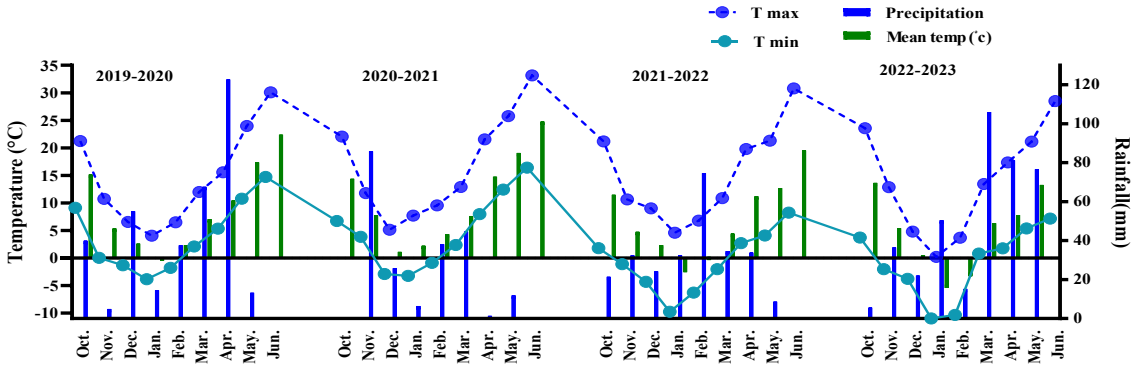


Figure 2. Monthly total precipitation (mm) and maximum (T_{max}), minimum (T_{min}), and mean (T_{mean}) temperatures during four growing seasons (2019–2023) at the experimental site.

Table 2. Seasonal rainfall, irrigation schedules, application volumes, and total water applied across four growing seasons (2019–2023).

Growing season	Seasonal Rainfall (mm)	Irrigation Regime	Number of Irrigations	Irrigation Stage & Date	Volume per Irrigation (mm)	Total Irrigation (mm)	Total Water Received (mm)
2019-2020	355.9	Rainfed	0		0	0	355.9
		Supplementary Irrigation	4	Booting (19 May)	20	125	480.9
				Heading (27May)	35		
				Flowering (4 June)	35		
				Grain felling (12 June)	35		
2020-2021	214.1	Rainfed	0		0	0	214.11
		Supplementary Irrigation	3	Heading (19 May)	35	105	319.1
				Flowering (27 May)	35		
				Grain filling (4 June)	35		
2021-2022	262.4	Rainfed	0		0	0	262.4
		Supplementary Irrigation	3	Heading (19 May)	35	105	367.4
				Flowering (27 May)	35		
				Grain filling (4 June)	35		
2022-2023	398.6	Rainfed	0		0	0	398.6
		Supplementary Irrigation	2	Sowing (7 October)	25	55	458.6
				Grain filling (12 June)	35		

Agronomic Management

Sowing and harvesting were conducted on specific dates across the four growing seasons. In the first season (2019–2020), sowing was conducted on October 25 and harvesting on August 1; in the second season (2020–2021), sowing was conducted on October 20 and harvesting on July 10; in the third season (2021–2022), sowing was conducted on October 23 and harvesting on July 18; and in the fourth season (2022–2023), sowing was conducted on October 22 and harvesting on July 27.

Weed control was carried out entirely by manual weeding at multiple growth stages (including early tillering, stem elongation, and heading) to maintain weed-free plots throughout the growing periods without the application of chemical herbicides. Disease and pest incidence were monitored

weekly throughout the growing seasons from jointing to grain filling, using standardized field sampling protocols (10 random 1m² quadrats per replication). Pest infestation and disease severity were evaluated against the official national Economic Injury Levels (EIL) defined by the Plant Protection Organization. Across all four experimental years, Sunn pest nymph densities remained strictly below the action threshold of 1–2 nymphs/m², and yellow rust severity did not exceed 5% on flag leaves. Consequently, no chemical insecticides or fungicides were applied.

Trait Measurements

Morphological, and yield-related traits were recorded for each genotype under both moisture regimes at physiological maturity (Zadoks scale GS 92). To minimize border effects, five representative plants were randomly sampled from the four central rows of each plot to determine the key agronomic traits. The recorded traits included plant height (PH, cm), spike length (SL, cm), number of spikelet per spike (SSP), peduncle length (Pe, cm), penultimate internode length (Pen, cm), and extrusion length (Ex, cm), defined as the portion of the peduncle extending above the flag leaf. At physiological maturity, a one-square-meter area was harvested from each plot to determine grain yield and its components. Grain yield was measured and converted to kg ha^{-1}. Yield components included spike number per square meter (SN), grain number per square meter (GNM^2), total spike biomass per square meter (spike weight; SW), measured by weighing all harvested spikes from the 1 m^2 area before threshing), and thousand-grain weight (TGW). TGW was determined by randomly counting two samples of 100 sound grains per plot, weighing them using a precision digital balance (0.001 g), and multiplying the mean weight by 10.

The harvest index (HI) was calculated as the ratio of grain yield to total above-ground biomass (the combined dry weight of grain and straw harvested from $1m^2$, measured after air-drying and prior to threshing) and expressed as a percentage.

Genotype × Yield × Trait (GYT) Biplot Analysis

To evaluate genotypes based on their ability to combine grain yield with desirable agronomic and physiological traits, the Genotype-by-Yield × Trait (GYT) biplot methodology proposed by Yan and Frégeau-Reid (2018) was applied using the metan package in R. For each irrigation regime, trait data were averaged across the four experimental years (2019–2023) to construct the mean yield–trait data matrix.

Yield–trait combinations were determined based on the breeding target for each trait. For traits where an increase in value is desirable, combinations were calculated by multiplying grain yield by the trait value (GY×T), whereas to select for shorter stature and reduce lodging susceptibility, plant height was combined as a ratio (GY/PH).

To ensure comparability among indices measured on different scales, all yield–trait combinations were standardized to a mean of zero and unit variance (mean = 0, SD = 1) within each irrigation regime using Z-score transformation according to the following equation:

$$Z=\frac{Xi-\mu}{\sigma}$$

where Z represents the standardized value, X_i is the observed yield–trait combinationtrait value, μ is the overall mean of the trait, and σ is the standard deviation.

A total of twelve evaluated traits were consistently included in the GYT biplot analyses: plant height (PH), peduncle length (pe), Extrusion (Ex), penultimate internode length (pen), spike length (SL), thousand grain weight (TGW), grains per spike (GNS), spikelet per spike (SSP), harvest index (HI), grains per square meter (GNM^2), spike weight (SW), grain yield (GY), and spike number per square meter (SN).

Polygon ("which-won-where") views were used to identify genotypes with superiority in specific trait sectors, while the Average Tester Coordination (ATC) view facilitated ranking of genotypes relative to an "ideal" genotype defined by maximum values across all combinations. A Mean Superiority Index (SI) was calculated for each genotype as the average of its standardized yield–trait values, providing an overall measure of multi-trait performance. This multivariate framework enabled comprehensive assessment of genotype strengths and weaknesses and facilitated identification of materials combining high yield potential with favorable agronomic traits under contrasting moisture conditions.

Table 3. Description and codes of the yield–trait combinations used in the GYT biplot analysis.

Trait	Trait Code	Yield–Trait Combination **Code**	Yield–Trait Combination Description
Harvest Index	HI	GY × HI	Grain yield × Harvest Index
Spike Weight	SW	GY × SW	Grain yield × Spike Weight per square meter
Spike number	SN	GY × SN	Grain yield × Spike number per square meter
Grain Number per m²	GNM^2	GY × GNM2	Grain yield × Number of grains per square meter
Grains per Spike	GNS	GY × GNS	Grain yield × Number of grains per spike
Thousand Grain Weight	TGW	GY × TGW	Grain yield × Thousand grain weight
Plant Height	PH	GY / PH	Grain yield / Plant height
Extrusion Length	Ex	GY × Ex	Grain yield × Extrusion length
Peduncle length	Pe	GY × Pe	Grain yield × Peduncle length
Penultimate length	Pen	GY × Pen	Grain yield × Penultimate length
Spikelet per Spike	SSP	GY × SSP	Grain yield × Number of spikelet per spike
Spike Length	SL	GY × SL	Grain yield × Spike length

Drought Tolerance Indices

To evaluate genotypic responses to moisture deficit, eight stress tolerance and susceptibility indices were calculated based on mean grain yield under supplementary irrigation (Y_p) and rainfed conditions (Y_s) across environments. The mathematical formulations and reference sources for each index are summarized in Table 4.

Table 4. Mathematical equations and formulations of drought tolerance and susceptibility indices.

Index	Equation / Formula	Reference
Tolerance Index (TOL)	(Y_P-Y_S)	Rosielle and Hamblin (1981)
Mean Productivity (MP)	$[(Y_P+Y_S)/2]$	Rosielle and Hamblin (1981)
Geometric Mean Productivity (GMP)	$(\sqrt{Y_P}\times\sqrt{Y_S})$	Fernandez (1992)
Harmonic Mean (HAM)	$(2 \times Y_P \times Y_S/Y_P + Y_S)$	Bouslama and Schapaugh (1984)
Yield Stability Index (YSI)	(Y_S/Y_P)	Bouslama and Schapaugh (1984)
Yield Index (YI)	$(Y_S/\bar{Y}_S)$	Gavuzzi et al. (1997)
Stress Tolerance Index (STI)	$(Y_P \times Y_S/Y_P^2)$	Fernandez (1992)
Stress Susceptibility Index (SSI)	$([1-(Y_S/Y_P)]/[1-(\bar{Y}_S/\bar{Y}_P)])$	Fischer and Maurer (1978)

Y_s and Y_p denote the mean grain yield of a given genotype under rainfed and supplementary irrigation conditions, respectively. $\bar{Y}_S$ and $\bar{Y}_P$ represent the grand mean grain yield across all evaluated genotypes under rainfed and supplementary irrigation conditions, respectively.

Statistical Analysis

Combined analysis of variance across four growing seasons was performed using a linear mixed-model framework to account for the split-plot structure in time. The statistical model was specified as follows:

$$Y_{ijkln} = u + Y_i + R_m(Y)_i + S_j + (Y \times S)_{ij} + Ea_{ijm} + G_k + (Y \times G)_{ik} + (S \times G)_{jk} + (Y \times S \times G)_{ijk} + e_{ijkln}$$

where Y_{ijkln} is the observed trait value; u is the overall mean; Y_i is the fixed effect of the i-th year; $R_m(Y)_i$ is the random effect of the m-th replication nested within the i-th year; S_j is the fixed effect of the j-th water regime; $(Y \times S)_{ij}$ is the interaction between year and water regime; E_a, ijm is the main-plot random error term representing the variation among main plots within reps and years; G_k is the fixed effect of the k-th genotype; $(Y \times G)_{ik}$, $(S \times G)_{jk}$, and $(Y \times S \times G)_{ijk}$ are the corresponding interaction terms; and e_{ijkln} is the residual random error associated with sub-plots (sub-plot error).

All statistical tests were evaluated at the $\alpha = 0.05$ significance level. Homogeneity of residual variances across environments was examined using Levene's test and visually verified via fitted value versus residual diagnostic plots. To model variance heterogeneity when present, the varident variance structure function was incorporated into the mixed-model fitting (lme function in the nlme package in R). Traditional pairwise mean comparison tests (e.g., Tukey's HSD or LSD) were

not performed because the primary objective of this study was the simultaneous evaluation of genotype performance for grain yield and multiple agronomic traits within the GYT multivariate framework, rather than univariate pairwise comparisons of individual traits. The GYT approach integrates grain yield with multiple traits into composite yield–trait combinations and enables simultaneous assessment of genotype performance across contrasting moisture regimes. In the present study, significant Y × S × G interactions were detected for seven traits, further supporting the importance of considering genotype responses across experimental conditions.

GYT Biplot Analysis

Genotype-by-Yield × Trait (GYT) biplot analysis was performed using the gtb() function within the metan package in R (version 4.3.3). Prior to Singular Value Decomposition (SVD), the yield-trait matrix was standardized using column-centering (centering= "column") and column-standardization (scaling= "column") to transform combinations into unit variance (mean= 0, SD = 1). Singular value partitioning was configured with tester-focused scaling (SVP= "tester" or SVP= 2) to optimize the visualization of trait relationships and genotype rankings relative to yield-trait combinations.

RESULTS

A combined analysis of variance was performed to assess the main effects of genotype (Gen), growing season (Year), moisture regime (Stress), and their two-way interactions across the four experimental seasons (2019–2023). The results revealed significant main effects of Year, Stress, and Gen, as well as significant interaction effects (Year × Stress, Year × Gen, and Stress × Gen) for grain yield and most evaluated traits (Table 5).

Table 5. Type III Wald Chi-square (χ^2) test values and grand means for combined mixed-model analysis of 13 evaluated traits across four years and two moisture regimes.

Source of variation	Df	(χ^2) GY	(χ^2) HI	(χ^2) SW	(χ^2) SN	(χ^2) GNM^2	(χ^2) GNS	(χ^2) TGW	(χ^2) PH	(χ^2) Ex	(χ^2) Pe	(χ^2) Pen	(χ^2) SSP	(χ^2) SL
Year	3	0.19ns	7.1961ns	5.70ns	1.94ns	11.52**	14.60**	26.82**	73.37**	5.70ns	9.25*	15.56**	4.47ns	34.95***
Stress	1	19.24***	0.0006ns	10.90***	0.27ns	6.11*	4.90*	4.51*	19.49**	24.73***	27.03***	14.58***	2.91ns	9.61**
Gen	11	48.15***	24.6510*	35.33***	68.39**	22.14*	121.47***	82.66**	155.55***	112.97***	56.16***	16.38ns	110.62***	42.89**
Year:Stress	3	10.90*	8.30*	4.48ns	1.50ns	4.93ns	8.69*	33.50**	10.15*	13.25**	15.31**	4.75ns	0.34ns	3.84ns
Year:Gen	33	109.60***	84.84***	113.23***	196.99***	86.49**	159.81***	135.23**	176.49***	115.66***	57.12**	91.65***	87.07**	74.93**
Stress:Gen	11	22.40*	19.25ns	27.41**	12.26ns	8.39ns	13.22ns	10.09ns	34.70**	46.78***	24.55*	24.48*	7.30ns	9.43ns
Year:Stress:Gen	33	53.57*	61.83**	49.45*	31.21ns	19.91ns	32.32ns	38.10ns	96.88**	63.73**	60.31**	55.54**	40.08ns	27.87ns
Grand Mean		3410.94	35.93	502.92	446.64	8401.17	19.49	40.71	76.68	15.26	32.18	18	15.70	9.71
CV (%)		9.64	7.01	9.45	7.97	13.12	14.32	9.80	6.80	15.60	7.37	9.39	8.89	5.15

$P < 0.001^{***}$; $P < 0.01^{**}$; $P < 0.05^{*}$; $P > 0.05^{ns}$: non-significant.

Genotype–Trait (GT) Biplot Analysis under Contrasting Moisture Regimes

The genotype-by-trait (GT) biplot analysis was conducted separately for rainfed and supplementary irrigation environments using four-year mean data (2019–2023) to visualize trait interrelationships and genotype-specific performance profiles (Figure 3a, b). In the GT biplot, the cosine of the angle between trait vectors approximates the Pearson correlation coefficient, whereas vector length reflects the magnitude of trait contribution to the total explained variation. This graphical representation enabled simultaneous interpretation of trait associations and genotype behavior under contrasting moisture conditions.

Under rainfed conditions (Figure 3a), several traits exhibited relatively short vector lengths, including penultimate internode length (Pen), spike length (SL), and harvest index (HI), indicating limited genotypic variability under drought stress. This indicates their limited discriminatory power and lower contribution to the total explained phenotypic variation, under drought stress. A similar pattern was observed for the GY × GNS combination in the GYT biplot (Figure 8a), where the short vector further confirmed weak differentiation among genotypes under stress conditions. Collectively, these results demonstrate that while drought stress suppressed genotypic differentiation in certain vegetative and spike-related traits, harvest index (HI) maintained remarkable stability across water regimes (χ^2= 0.0006, $P > 0.05$), reflecting a highly conserved biomass partitioning efficiency among the evaluated genotypes under moisture deficit.

In contrast, under supplementary irrigation (Figure 3b), most traits displayed longer vectors, reflecting enhanced genotypic variability when water limitations were alleviated. Grain yield (GY), spike number per square meter (SN), spike weight per square meter (SW), and grain number per square meter (GNM^2) showed substantial vector lengths, indicating strong discriminatory capacity and high genetic variation under favorable moisture conditions. Notably, spike length (SL) remained relatively short even under irrigation, suggesting that this trait is more genetically controlled and less influenced by environmental variation. Overall, irrigation promoted trait expression and amplified genetic differences, thereby facilitating clearer identification of superior ideotypes.

Genotype distribution within the GT biplot further illustrated differences in stability and adaptability. In the rainfed environment (Figure 3a), genotype G1 was positioned far from the origin, indicating high phenotypic responsiveness and potential instability under moisture stress. In contrast, G11 and G12 were located close to the origin, indicating lower responsiveness to specific traits and near-average expression across evaluated characters, rather than true biological stability, characteristics desirable for marginal environments. Under supplementary irrigation (Figure 3b), G1, G5, and G9 occupied peripheral positions, demonstrating distinctive trait profiles but potentially greater sensitivity to environmental fluctuations. Conversely, G4, G12, G11, G2, and G7 clustered nearer the origin, suggesting balanced trait expression and improved stability under well-managed conditions.

Trait Interrelationships and Genotype Profiles

The GT biplots revealed strong positive associations between grain yield (GY) and major yield components, particularly SN, SW, and GNM^2 (Figure 3a, b). The acute angles among these vectors confirmed synergistic relationships, underscoring the importance of spike density and grain number in determining final productivity. The near-orthogonal orientation of SL relative to yield components suggested relative independence, indicating that spike length may contribute less directly to yield variation compared to spike density and grain weight. Importantly, the absence of obtuse angles among major yield components indicated minimal antagonistic relationships, supporting the feasibility of simultaneous improvement.

Genotype distribution patterns further clarified performance profiles. Genotype G5 consistently aligned with the grain yield cluster across both environments, demonstrating strong association

with yield-related traits and indicating superior stability. In contrast, G1 displayed environment-dependent shifts; under rainfed conditions it aligned more closely with SSP, whereas under irrigation it showed stronger association with HI. This shifting alignment explains its inconsistent ranking across moisture regimes. Irrigation conditions increased overall dispersion of genotypes within the biplot space, highlighting environment-specific advantages for G1, G5, and G9. Meanwhile, G11 and G12 maintained relatively central positions under stress, reinforcing their stability. Although the GT biplot effectively illustrated trait relationships and genotype profiles, it did not provide a direct ranking framework; therefore, the GYT approach was employed for integrated multi-trait selection.

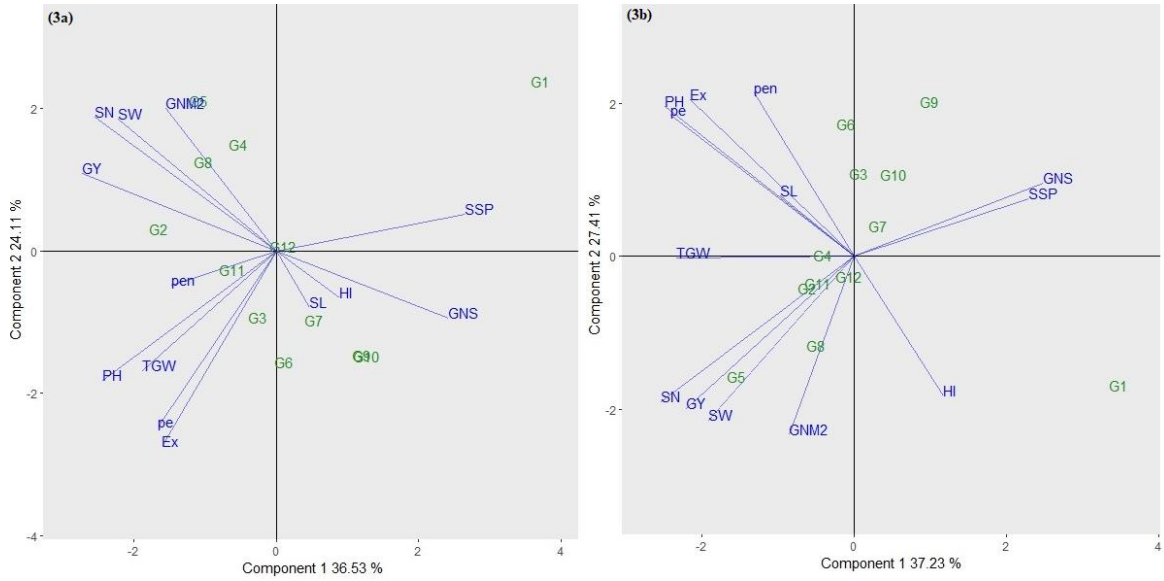


Figure 3. Genotype-by-trait (GT) biplots under (a) rainfed and (b) Supplementary irrigation conditions. Vector length indicates the discriminating ability of traits, and the angle between vectors approximates their correlation. Genotype positions reflect relative trait profiles within each moisture regime. Trait abbreviations: GY, SN, SW, GNM^2, SL, SSP, GNS, HI, PH, TGW, Pen, Pe, and Ex.

Evaluation of Genotypes Based on GYT Biplot Analysis

The Genotype-by-Yield × Trait (GYT) biplot provided an integrated assessment of yield–trait combinations under both moisture regimes (Figure 4a, b). Under rainfed conditions, the first two principal components explained 79.43% of the total variation, exceeding the 60% reliability threshold and ensuring a highly reliable graphical interpretation. The polygon ("which-won-where") view formed five distinct sectors (Figure 4a), with G1, G9, G6, G2, and G5 occupying the vertex positions as the top-performing materials for the yield–trait combinations within their

respective sectors. Specifically, G5 dominated the major sector containing efficiency- and yield-component combinations, demonstrating its overall multi-trait superiority under moisture stress, while G2 and G6 headed sectors associated with specific adaptive and architectural traits.

Under supplementary irrigation, the total explained variation increased to 85.04%, reflecting stronger differentiation among genotypes (Figure 4b). The polygon view for this environment revealed four distinct sectors, with G1, G5, G9, and G6 positioned as the vertex genotypes. Notably, G5 consistently appeared as a key vertex genotype across both moisture regimes, highlighting its broad adaptability and superior capacity to integrate high grain yield with multiple agronomic traits.

The tester-vector view revealed strong synergistic interactions between GY × GNM^2 and GY × SW, as indicated by their long vectors and acute angles (Figure 5a, b). These combinations showed high discriminatory power and contributed substantially to genotype differentiation. In contrast, GY × GNS exhibited shorter vectors in both environments (Figure 8a, b), indicating lower discriminating ability across moisture regimes. Furthermore, GY × SN demonstrated stronger discriminatory capacity under irrigation compared to drought conditions, indicating that spike number was a more decisive factor under favorable moisture.

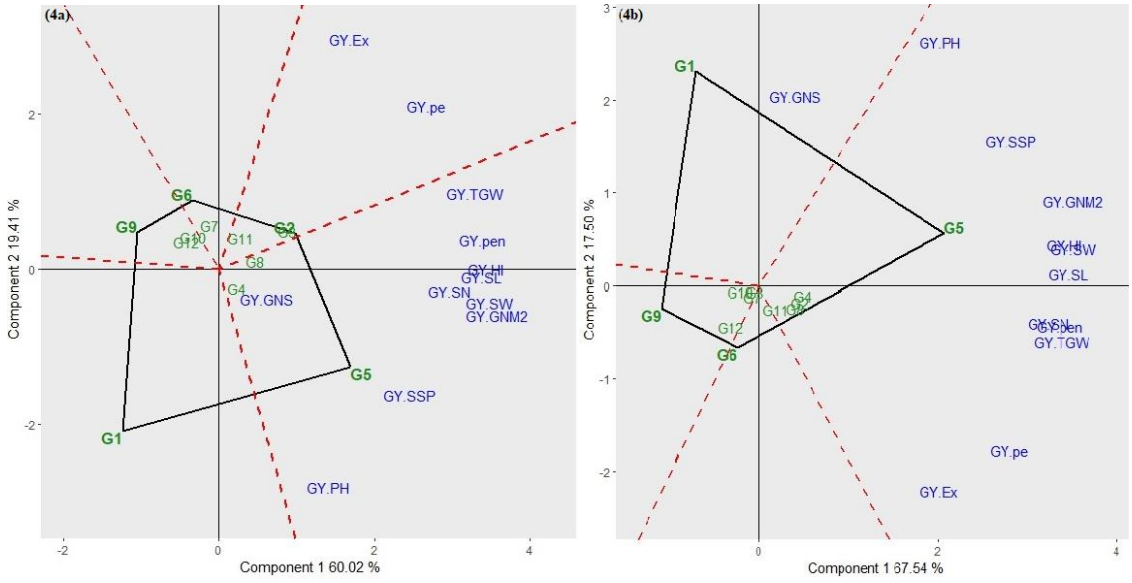


Figure 4. "Which-won-where" view of the genotype – by – yield × trait (GYT) biplots under (a) rainfed and (b) Supplementary irrigation. Polygon sectors identify vertex genotypes with superiority in specific yield–trait combinations. Trait codes are consistent across both environments. Note: GY.PH represents the grain yield / plant height ratio (GY/PH).

Relationship among Yield–Trait Combinations

Acute angles between the GY vector and secondary-trait vectors indicated positive associations between these traits and grain yield (Figure 3). In the GYT biplots, acute angles among yield–trait combination vectors indicated positive associations among the corresponding combinations (Figure 8).

Under rainfed condition, five distinct sectors were identified in the polygon view (Figure 4a), with G1, G9, G6, G2, and G5 emerging as vertex genotypes. Under supplementary irrigation conditions, four sectors were observed (Figure 4b), with G1, G5, G9, and G6 occupying vertex positions. Notably, G5 consistently appeared as a vertex genotype across both moisture regimes, indicating favorable performance for multiple yield–trait combinations. The GYT Superiority Index (SI) provided an integrated measure of yield and associated traits and facilitated the ranking of genotypes across the two moisture regimes.

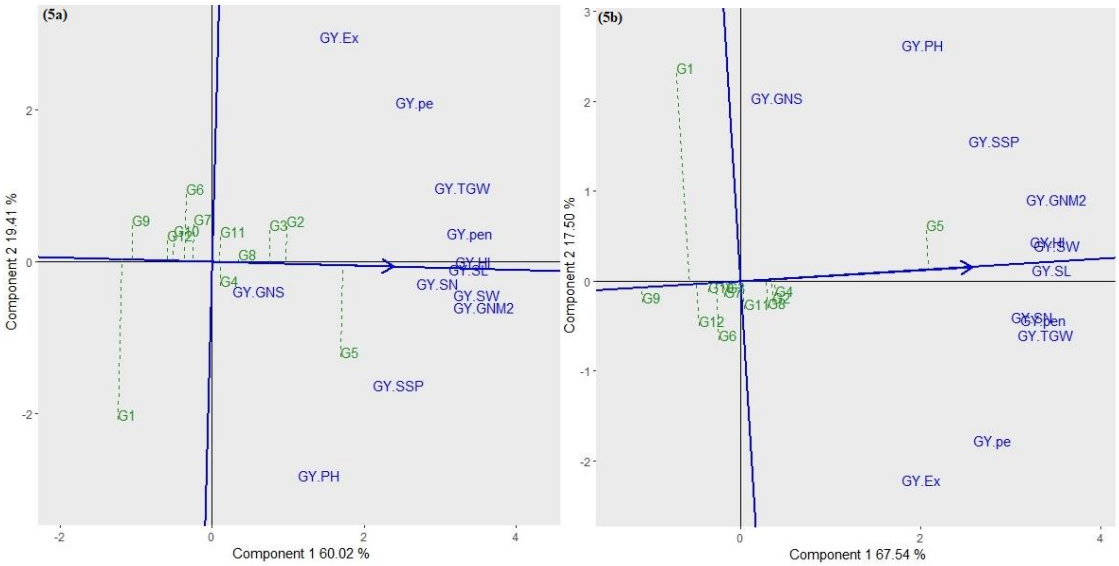


Figure 5. Average Tester Coordination (ATC) view of the GYT biplots under (a) rainfed and (b) supplementary irrigation conditions. Genotypes are ranked based on proximity to the ideal genotype; shorter projection onto the ideal axis indicates superior integrated performance. Trait codes are as defined in Figure 4 and Table 3

Comparison of Rainfed and Irrigated GYT Patterns

Comparative analysis of GYT biplots under rainfed and supplementary irrigation conditions revealed both stable patterns and environment-specific differences (Figure 4a, b). G5 maintained a consistently high ranking across the two moisture regimes, with favorable positions in the ATC

and ideal-genotype projections (Figures 5a, b and 6a, b; Table 6). Under rainfed conditions, G5 demonstrated superiority primarily through yield components, while G2 and G3 showed relative advantages in traits associated with drought adaptation (Figure 4a). Conversely, under irrigation, G1 exhibited enhanced prominence in grain number per spike, and certain genotypes previously limited under drought gained relevance (Figure 4b). Despite these shifts, G5 retained a central and dominant position in both biplots, underscoring its broad adaptation across contrasting moisture regimes.

Genotype Ranking and Identification of Superior Genotypes

Genotype ranking was evaluated using three complementary approaches: the numerical Superiority Index (SI), the Average Tester Coordination (ATC) view, and the Ideal Genotype Distance biplot projection (Figures 5a, b and 6a, b; Table 6). To clarify minor rank fluctuations across these graphical and non-graphical methods, each metric operates on distinct mathematical principles: the Superiority Index (SI) provides an unweighted cumulative mean of standardized yield–trait combinations (Z-scores); the ATC view evaluates average performance relative to overall trait vectors while illustrating stability along the perpendicular axis; and the Ideal Genotype view calculates the Euclidean distance from a hypothetical ideal point exhibiting maximum performance across all evaluated traits.

Across all metrics and environments, G5 attained the highest numerical SI values under both rainfed (SI= 1.44) and supplementary irrigation (SI= 2.08) conditions, primarily driven by its high yield potential (Table 6).

Under rainfed conditions, while G5 yielded the highest numerical SI value, G2 and G3 shared the 2nd rank (SI= 0.83) and were positioned closest to the ideal genotype center in the biplot projection (Figure 6a) due to their balanced projection along the stability axis, exhibiting strong drought tolerance via superior spike density and yield component integration.

Conversely, genotypes G1, G9, and G12 consistently placed at the bottom of the rankings under rainfed conditions (SI= -0.94, -0.88, and -0.66, respectively), reflecting lower multi-trait efficiency under drought stress.

Under supplementary irrigation, G2 ranked second (SI = 0.35), followed by G4 in third place (SI = 0.34) (Table 6). This ranking was also consistent with the graphical representations, where G5 occupied the most favorable position followed by G2 and G4 (Figures 5b, 6b). Genotypes G1,

G12, and G9 recorded the lowest SI values under supplementary irrigation (SI=−0.57, −0.58, and −1.13, respectively; Table 6).

Overall, the ranking pattern was largely consistent between the numerical SI and graphical approaches, with G5 consistently exhibiting the highest SI values across both moisture regimes, while G2 and G4 showed favorable performance under supplementary irrigation (Figures 5b, 6b; Table 6).

Table 6. Superiority Index (SI) values and ranking of bread wheat genotypes based on Genotype-by-Yield ×Trait (GYT) analysis under rainfed and supplementary irrigation conditions across four growing seasons (2019–2023).

Genotype Code	Rainfed		Genotype Code	Supplementary Irrigation	
	SI	Rank		SI	Rank
G5	1.44	1	G5	2.08	1
G2	0.83	2	G4	0.34	2
G3	0.83	2	G2	0.35	3
G8	0.20	4	G8	0.2	4
G4	0.02	5	G3	-0.04	5
G11	0.01	6	G11	-0.08	6
G7	-0.18	7	G7	-0.09	7
G6	-0.27	8	G6	-0.17	8
G10	-0.39	9	G10	-0.31	9
G12	-0.66	10	G1	-0.57	10
G9	-0.88	11	G12	-0.58	11
G1	-0.94	12	G9	-1.13	12

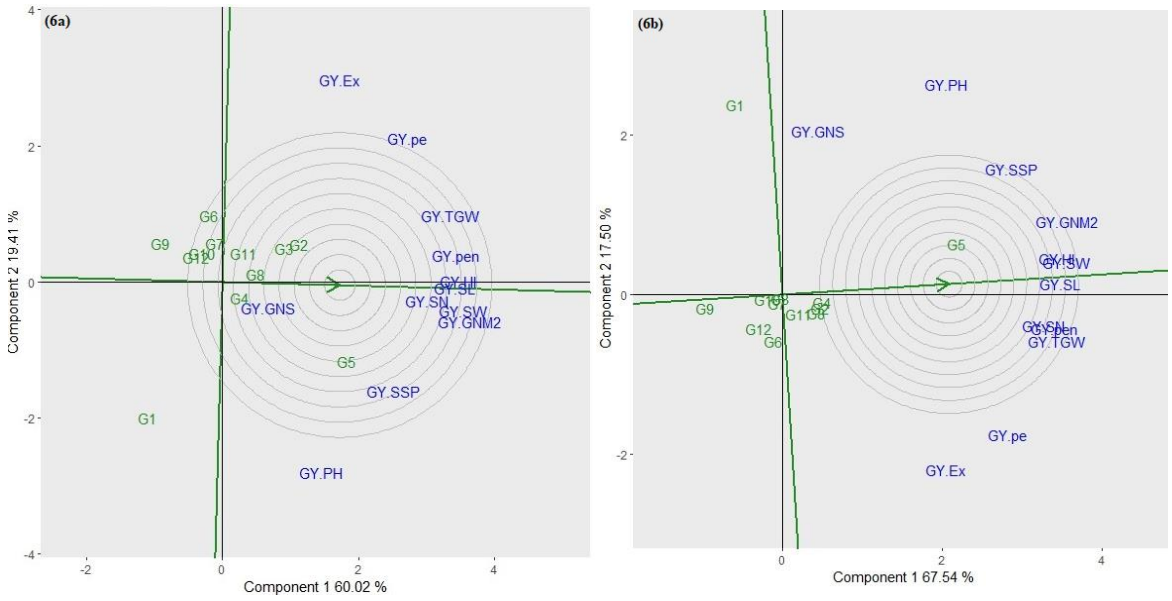


Figure 6. Mean performance and stability ranking of wheat genotypes based on GYT analysis under (a) rainfed and (b) Supplementary irrigation. Distance from the ideal genotype reflects overall yield–trait integration and stability. Trait codes are as defined in Figure 4 and Table 3

Relationship between Drought Tolerance Indices and the Superiority Index

The four-year mean grain yields under rainfed and supplementary irrigation conditions, together with drought tolerance indices, are presented in (Table 7). Considerable variation among genotypes was

observed for tolerance index (TOL), mean productivity (MP), geometric mean productivity (GMP), yield stability index (YSI), harmonic mean (HAM), stress tolerance index (STI), stress susceptibility index (SSI), and yield index (YI). Genotype G5 consistently exhibited the highest MP, GMP, STI, and HAM values (Table 7), confirming its high yield potential and superior productivity under non-stress and favorable conditions. However, G5 also recorded the highest SSI and TOL values, alongside the lowest YSI among all genotypes, indicating high yield susceptibility to moisture deficits and performance reduction under severe rainfed stress.

Under rainfed conditions, the association between YI and the GYT-based Superiority Index (SI) was moderate and non-significant (r = 0.399, ns; Table 10), reflecting the fact that SI integrates multiple agronomic traits simultaneously rather than relying solely on single-trait stress yield response. In agreement with the selection criteria proposed by Mohammadi (2016), classical indices such as GMP, MP, and STI effectively identified high-yielding genotypes under optimal conditions, whereas the GYT SI provided a broader multi-trait framework that penalizes high stress susceptibility while accounting for overall agronomic performance.

Table 7. Mean grain yield and drought tolerance indices of 12 wheat genotypes under rainfed (Y_S) and supplementary irrigation (Y_p) conditions.

Genotypes	Y_S (kg ha^{-1})	Y_P (kg ha^{-1})	TOL (kg ha^{-1})	MP (kg ha^{-1})	GMP (kg ha^{-1})	YSI	HAM (kg ha^{-1})	STI	SSI	YI
G1	2637	3600	963	3118.5	3081.1	0.732	3044.2	0.639	1.168	0.887
G2	3429	4017	588	3723.0	3711.4	0.853	3699.8	0.928	0.639	1.154
G3	2819	3799	980	3309.0	3272.5	0.742	3236.4	0.721	1.126	0.949
G4	2901	3992	1091	3446.5	3403.1	0.726	3360.2	0.780	1.193	0.976
G5	3071	4736	1665	3903.5	3813.7	0.648	3726.0	0.980	1.535	1.034
G6	2704	3704	1000	3204.0	3164.7	0.730	3126.0	0.675	1.179	0.910
G7	2808	3787	979	3297.5	3261.0	0.741	3224.9	0.716	1.129	0.945
G8	3013	4030	1017	3521.5	3484.6	0.747	3448.1	0.818	1.102	1.014
G9	2848	3330	482	3089.0	3079.6	0.855	3070.2	0.639	0.632	0.958
G10	3280	3681	401	3480.5	3474.7	0.891	3469.0	0.813	0.475	1.104
G11	3133	3883	750	3508.0	3487.9	0.806	3467.9	0.819	0.843	1.054
G12	2997	3666	669	3331.5	3314.7	0.817	3297.9	0.740	0.796	1.009

Ys: grain yield under rainfed; Yp: grain yield under supplementary irrigation; TOL: Tolerance Index (Y_P-Y_S); MP: Mean Productivity [(Y_P+Y_S)/2]; GMP: Geometric Mean Productivity ($\sqrt{Y_P}\times\sqrt{Y_S}$); YSI: Yield Stability Index (Y_S/Y_P); HAM: Harmonic Mean ($2\times Y_P\times Y_S/Y_P + Y_S$); STI: Stress Tolerance Index ($Y_P\times Y_S/Y_P^2$); SSI: Stress Susceptibility Index ([1-(Y_S/Y_P)]/[1-($\bar{Y}_S/\bar{Y}_P$)]); YI: Yield Index ($Y_S/\bar{Y}_S$).

Superiority Ranking of Genotypes Based on GYT Biplots

Genotype ranking based on integrated yield–trait performance was performed using the Average Tester Coordination (ATC) view of the GYT biplots (SVP = 1) under both moisture regimes (Figure 5a, b). Under drought conditions (Figure 5a), genotypes G5, G2, and G3 achieved the highest standardized GYT scores (Table 9) and were positioned closest to the ideal genotype axis, indicating superior overall performance (Figure 5a). In contrast, G1, G9, and G12 were

located farthest from the ideal point, reflecting comparatively weaker multi-trait integration under stress.

Genotype G5 demonstrated consistent superiority across nearly all yield–trait combinations, particularly those associated with spikelet number, grain number, and biomass-related indices.

This pattern indicates strong robustness and efficient assimilation partitioning under water-limited conditions. Under supplementary irrigation (Figure 5b), G5 maintained its leading position, followed closely by G2. Although G4, G8, G10, and G11 exhibited superiority in specific traits—such as peduncle length and thousand-grain weight (TGW)—their overall ranking was lower due to weaker integration across other yield–trait combinations. Interestingly, G8 displayed comparatively better consistency under drought than under irrigation, suggesting environment-specific adaptability.

Trait Representativeness and Ideal Yield–Trait Combinations

The discriminating ability and representativeness of yield–trait combinations were evaluated using the concentric circle view of the GYT biplots (Figure 7a, b). Combinations located near the center of the concentric circles with long vectors were considered both highly representative and discriminative. Under rainfed conditions (Figure 7a), GY × HI, GY × SL, and GY × SN were identified as the most balanced and informative combinations, showing strong and consistent associations with other indices. These combinations effectively summarized genotype performance under moisture limitation.

Under supplementary irrigation (Figure 7b), GY × HI, GY × SW, and GY × SL emerged as the most desirable combinations, maintaining close relationships with grain yield and exhibiting strong discriminatory power. The consistent appearance of GY × HI and GY × SL as representative combinations across both environments highlights the importance of harvest index and spike architecture in integrated genotype evaluation. Overall, these yield–trait combinations proved reliable indicators for identifying superior genotypes under both rainfed and supplementary irrigation conditions.

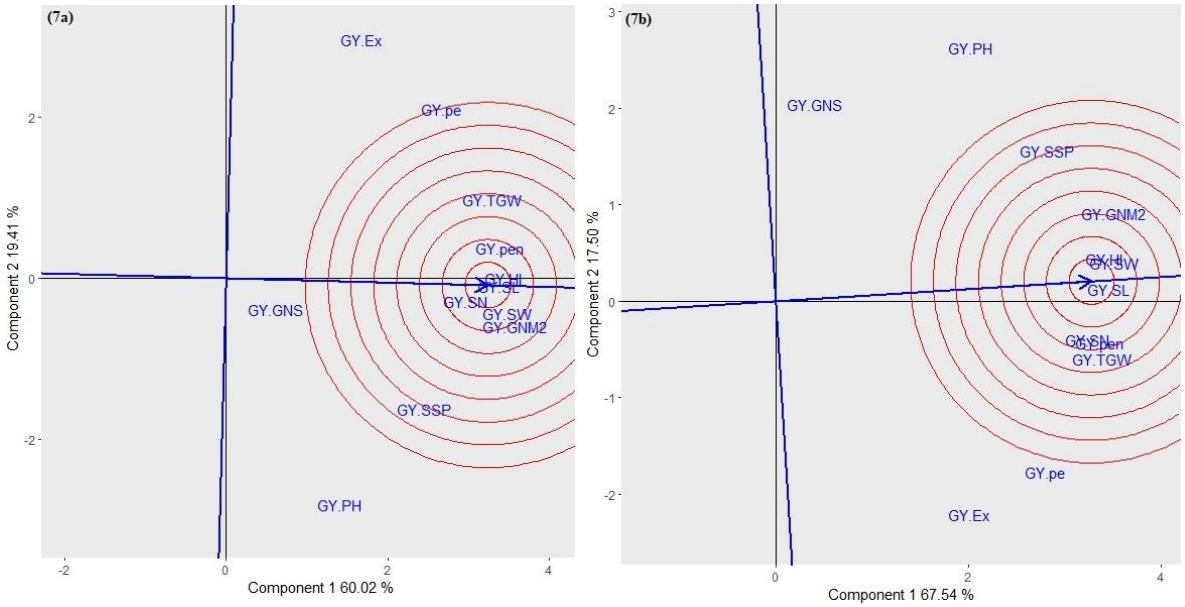


Figure 7. Discriminating ability and representativeness of yield–trait combinations in the GYT biplots under (a) rainfed and (b) Supplementary irrigation conditions. Longer vectors indicate stronger discrimination, while proximity to the average tester axis reflects representativeness. Trait codes are as defined in Figure 4 and Table 3

Ideal Genotype Selection and Ranking

The ideal genotype ranking biplots under rainfed and Supplementary irrigation conditions are presented in (Figure 6a, b), respectively. In these graphs, genotypes were ranked according to their distance from the hypothetical ideal genotype, which represents maximum performance across all yield–trait combinations.

Under drought stress (Figure 6a), genotypes G5, G2, and G3 were positioned closest to the ideal genotype, confirming their superior integrated performance. Although G1 showed relative strength in the GY × GNS combination, it was located far from the ideal point due to weak performance in other indices, indicating poor overall stability. The proximity of G5 to the center of the concentric circles reflects its consistent superiority across most evaluated traits under water-limited conditions.

Under supplementary irrigation (Figure 6b), G5 and G4 ranked highest, indicating stable and high performance across multiple traits under favorable moisture conditions. In contrast, G9 consistently ranked lowest even under irrigation, confirming limited adaptation and weaker multi-trait integration. These results reinforce the broad adaptability of G5 and highlight the environment-dependent performance of several other genotypes.

Interpretation of SI Tables and Comparison of GYT and GT Biplots

The Superiority Index (SI), calculated as the mean of standardized yield–trait combinations, provides a quantitative summary of overall genotype performance (Tables 8, 9). Under supplementary irrigation, G5 achieved the highest SI value (2.08), reflecting balanced superiority across nearly all indices. G2 followed, although minor negative values were observed for GY × SSP and GY × GNS, indicating slight weaknesses in specific combinations. Under rainfed, G5 maintained the highest SI (1.44), followed by G2 (0.83) and G3 (0.83). In contrast, G1 and G9 recorded the lowest SI values, confirming their reduced suitability under moisture limitation.

Comparison of the genotype-by-trait (GT) biplot (Figure 3a, b) with the GYT biplot (Figure 8a, b) revealed clearer and stronger correlations among yield-related combinations in the GYT framework. Weak associations observed in the GT analysis, particularly between GY × SSP and GY × GNS (Figure 3a), were replaced by nearly overlapping vectors in the GYT biplots (Figure 8a, b), indicating enhanced trait synergy when evaluated in combination with yield. This strengthened correlation structure demonstrates the superior discriminatory power of the GYT methodology for breeding-oriented selection.

Table 8. Standardized (Z-score) values of genotype performance for yield–trait combinations under supplementary irrigation.

Name	SI index	GY × SL	GY × SSP	GY × Pen	GY × Pe	GY × Ex	GY / PH	GY × TGW	GY × GNS	GY × GNM^2	GY × SN	GY × SW	GY × HI
G1	-0.57	-0.90	0.55	-1.41	-2.32	-2.54	1.91	-1.45	1.58	-0.09	-1.14	-0.58	-0.48
G10	-0.31	-0.20	-0.05	-0.42	-0.17	0.17	-0.66	-0.34	0.42	-0.72	-0.80	-0.51	-0.47
G11	-0.08	0.32	-0.52	-0.12	-0.14	-0.37	0.00	0.70	-1.19	-0.29	0.52	0.03	0.14
G12	-0.58	-0.52	-1.33	-0.85	-0.43	-0.51	-0.54	-0.09	-1.31	-0.65	0.07	-0.42	-0.41
G2	0.35	0.41	-0.32	0.24	0.56	0.51	0.54	0.84	-0.25	0.47	0.68	0.08	0.48
G3	-0.04	-0.32	-0.19	0.19	0.05	0.79	-0.53	-0.40	1.08	0.03	-0.62	-0.05	-0.50
G4	0.34	0.10	1.02	0.74	0.35	0.55	0.33	0.14	-0.87	0.35	0.74	0.46	0.14
G5	2.08	2.82	2.54	2.58	1.67	0.83	1.59	2.27	0.79	2.66	2.05	2.66	2.54
G6	-0.17	-0.34	-0.03	-0.03	0.81	1.01	-1.20	-0.70	0.48	-0.41	-0.71	-0.43	-0.50
G7	-0.09	-0.16	-0.45	-0.57	0.42	0.54	-0.46	-0.28	0.92	-0.21	-0.52	-0.28	-0.02
G8	0.20	-0.03	-0.40	0.27	0.31	-0.02	0.30	0.50	-1.10	0.34	0.96	0.57	0.71
G9	-1.13	-1.18	-0.82	-0.64	-1.11	-0.96	-1.28	-1.20	-0.54	-1.49	-1.22	-1.53	-1.63

Table 9. Standardized (Z-score) values of genotype performance for yield–trait combinations under rainfed conditions.

Name	SI index	GY × SL	GY × SSP	GY × Pen	GY × Pe	GY × Ex	GY × PH	GY × TGW	GY × GNS	GY × GNM^2	GY × SN	GY × SW	GY × HI
G1	-0.94	-1.45	0.53	-1.40	-2.27	-2.62	1.69	-2.31	0.99	-0.81	-1.27	-1.05	-1.28
G10	-0.39	-0.51	-0.04	-1.09	0.02	0.29	-0.37	-0.10	0.08	-0.91	-0.90	-0.90	-0.23
G11	0.01	-0.16	-0.87	0.21	0.26	0.02	0.09	0.81	-0.85	-0.25	0.36	0.10	0.38
G12	-0.66	-0.25	-1.11	-0.72	-1.09	-0.31	-0.81	-0.11	-1.55	-0.90	0.10	-0.44	-0.78
G2	0.83	0.61	-0.05	1.56	1.41	1.03	0.42	0.87	-0.16	1.15	1.08	0.83	1.20
G3	0.83	0.92	1.29	0.89	1.22	1.39	-0.19	0.52	1.98	0.67	-0.45	0.83	0.85
G4	0.02	-0.25	0.24	0.34	-0.43	-0.24	0.26	-0.11	-0.91	0.43	0.84	0.31	-0.26
G5	1.44	2.52	2.13	1.66	0.38	-0.64	1.73	1.67	0.33	2.03	1.64	1.96	1.85
G6	-0.27	-0.24	-0.06	0.21	0.51	0.64	-1.74	-0.71	0.70	-0.41	-0.79	-0.52	-0.81
G7	-0.18	-0.38	-0.11	-0.41	0.34	0.31	-0.88	-0.27	0.58	-0.14	-0.67	-0.56	0.05
G8	0.20	0.02	-0.42	-0.29	0.25	0.12	0.26	0.40	-1.07	0.58	1.17	0.91	0.45
G9	-0.88	-0.84	-1.51	-0.96	-0.60	0.00	-0.47	-0.65	-0.12	-1.43	-1.12	-1.46	-1.43

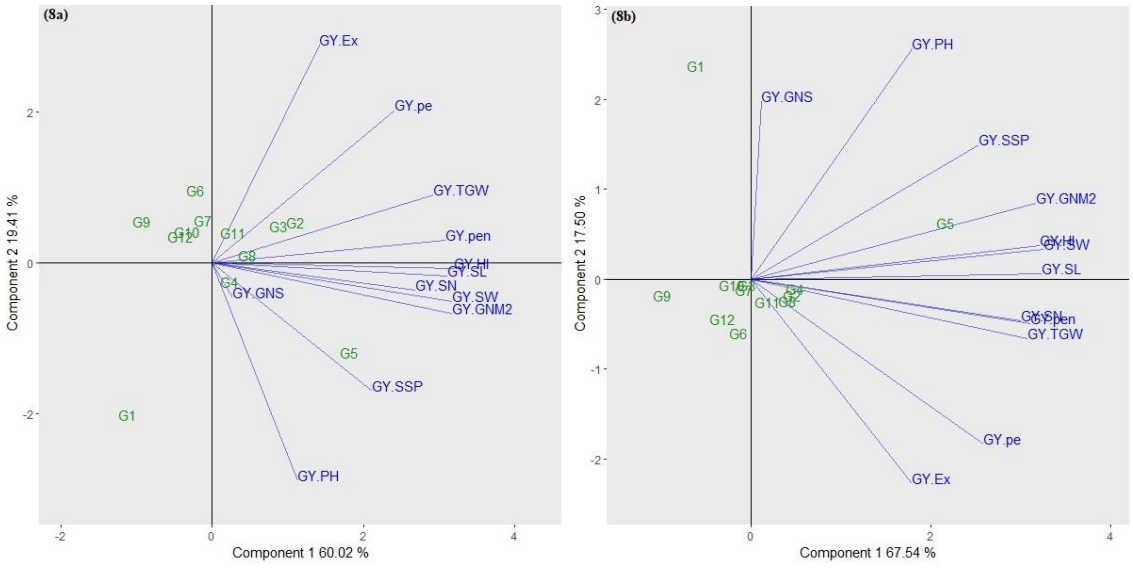


Figure 8. Test vector view of the GYT biplots illustrating associations among yield–trait combinations under (a) Drought stress and (b) Supplementary irrigation. Acute angles indicate positive relationships, obtuse angles indicate negative associations, and right angles suggest independence. Trait codes are as defined in Figure 4 and Table 3

Correlation between Drought Tolerance Indices and Superiority Index

Further evaluation of the GYT approach was conducted through correlation analysis between SI and conventional drought tolerance indices (Table 10). Under rainfed conditions, SI Rainfed exhibited moderate and significant positive correlations with MP (r=0.609, P<0.05), GMP (r=0.589, P<0.05), and STI (r=0.599, P<0.05), whereas its correlations with HAM, YI, and SSI were not statistically significant. In contrast, under supplementary irrigation, SI Supplementary Irrigation showed non-significant correlations with MP, GMP, and STI (r=0.505–0.536, P>0.05), but was positively correlated with non-stress yield (Y p: r=0.575, P<0.05) and

susceptibility/tolerance indices (TOL: r=0.597, P<0.05; SSI: r=0.574, P<0.05). At the genotype level, G5 attained the highest MP, GMP, and STI values (Table 7), driven predominantly by its outstanding yield potential under supplementary irrigation (Y p =4736 kg ha^{-1}), despite exhibiting higher stress susceptibility (SSI=1.535). These relationships demonstrate that while the GYT-derived SI aligns moderately with mean productivity indices under rainfed conditions, it primarily reflects yield potential rather than penalizing stress susceptibility.

Table 10. Pearson correlation coefficients (r) between the Superiority Index (SI) derived from GYT biplots and classical drought tolerance indices across 12 bread wheat genotypes evaluated under rainfed and supplementary irrigation conditions.

Drought Tolerance Index/Traits	$SI_{Supplementary\ Irrigation}$	$SI_{Rainfed}$
Drought Stress Yield (Ys)	0.282^{ns}	0.399^{ns}
Supplementary Irrigation Yield (Yp)	0.575*	0.627*
Tolerance Index (TOL)	0.597*	0.528^{ns}
Mean Productivity (MP)	0.536^{ns}	0.609*
Geometric Mean Productivity (GMP)	0.505^{ns}	0.589*
Yield Stability Index (YSI)	-0.573*	-0.502^{ns}
Harmonic Mean (HAM)	0.467^{ns}	0.563^{ns}
Stress Tolerance Index (STI)	0.518^{ns}	0.599*
Stress Susceptibility Index (SSI)	0.574*	0.503^{ns}
Yield Index (YI)	0.282^{ns}	0.399^{ns}

DISCUSSION

The application of the Genotype-by-Yield × Trait (GYT) biplot analysis in this study provided a robust and selection-oriented framework for identifying superior wheat genotypes under contrasting moisture regimes. As emphasized by Kendal (2019), the GYT methodology integrates yield and secondary traits into a unified yield-based matrix, ensuring that selected genotypes simultaneously express agronomic desirability and commercial yield potential.

In the present investigation, genotype G5 consistently achieved the highest Superiority Index (SI) under both supplementary irrigation (SI = 2.08) and rainfed conditions (SI = 1.44) (Table 6). However, the high SI value of G5 under rainfed conditions should be interpreted with caution, as G5 ranked fourth for grain yield under rainfed conditions (Ys) and exhibited relatively high values of stress sensitivity indices (TOL and SSI) (Table 7). The high values observed in yield–trait combinations such as Yield × HI and Yield × TGW in G5 (GY × HI: 2.54 under irrigation and 1.85 under rainfed; GY × TGW: 2.27 under irrigation and 1.67 under rainfed) are substantially influenced by the grain yield component embedded within all GYT combinations, rather than indicating direct superiority in specific physiological mechanisms under moisture stress (Tables

599 8,9). Therefore, these high GYT values should not be interpreted as direct evidence of superiority
600 in specific physiological mechanisms underlying drought tolerance.
601 From a selection standpoint, while G5 exhibits exceptional performance under favorable
602 environments and maintains high overall multi-trait scores due to its yield potential, its
603 responsiveness to moisture deficit suggests high responsiveness to favorable inputs rather than
604 absolute drought tolerance or broad phenotypic stability. While physiological processes such as
605 assimilate remobilization or grain-filling kinetics were not directly measured in the present study,
606 the GYT approach provided a comprehensive synthesis of yield-weighted structural components,
607 highlighting G5 primarily as a high-yielding genotype with favorable multi-trait integration in
608 well-watered to moderately dry conditions. In contrast, genotypes such as G2, which exhibited
609 superior absolute grain yield under drought stress alongside lower tolerance index (TOL) scores,
610 represent candidates with specific adaptation to water-limited environments.
611 In this context, treating higher values of peduncle length (Pe) and penultimate internode length
612 (Pen) as desirable directions in the GYT combinations was based on their potential contribution to
613 reproductive development and post-anthesis assimilate supply under moisture stress. The upper
614 stem, particularly the peduncle and penultimate internode, represents an important reservoir of
615 water-soluble carbohydrates that can be remobilized to developing grains when current
616 photosynthetic assimilation is constrained by post-anthesis drought (Blum, 1998; Yang and Zhang,
617 2006). Recent physiological evidence further indicates that greater investment in peduncle length
618 is associated with increased stem water-soluble carbohydrate accumulation and with grain weight
619 and yield under water-limited and heat-stress conditions (Ntawuguranayo *et al*., 2024). Therefore,
620 higher Pe and Pen were considered desirable directions in the present GYT analysis because they
621 may indicate greater stem capacity for assimilate storage and subsequent remobilization.
622 Extrusion (Ex), in contrast, was treated separately because its relationship with yield and
623 drought response is less direct. Previous findings showed that Ex decreased under drought stress,
624 although it was not significantly correlated with grain yield (Ghamarirahim *et al*., 2026).
625 Accordingly, Ex was assigned a positive direction in the present GYT analysis as a predefined trait
626 direction, without implying that greater extrusion is universally associated with higher yield or
627 drought tolerance. Conversely, total plant height was treated as an undesirable trait and evaluated
628 as a ratio (GY/PH) to prevent excessive overall plant height and reduce lodging susceptibility.

The moderate and significant positive correlations observed between the rainfed GYT-derived SI and conventional drought tolerance indices (STI, GMP, and MP; r = 0.589–0.609, P < 0.05) partially confirm the consistency between the multivariate yield–trait analysis and traditional indices under stress conditions (Table 10).

However, these relationships must be interpreted with caution because both GYT combinations and classical tolerance indices share grain yield as a primary mathematical component. As emphasized by Bouslama and Schapaugh (1984), evaluating genotypes across moisture regimes requires distinguishing between high yield potential and intrinsic stress resilience. Overall, the GYT biplot approach helped distinguish genotypes with high yield potential, such as G5, from genotypes showing relatively favorable performance under rainfed conditions, such as G2 (Tables 6 and 7).

Taken together, the results confirm that the GYT biplot methodology offers a more comprehensive and breeder-oriented alternative to traditional selection strategies. By directly linking secondary traits to yield performance, the approach improves interpretability and selection accuracy. In agreement with the conceptual framework proposed by Yan and Frégeau-Reid (2018), the integration of yield–trait combinations enables identification of genotypes that combine high yield potential with favorable trait balances. Based on multi-year evaluation and multivariate validation, genotype G5 is recommended primarily for high-input and supplementary irrigation conditions, whereas genotype G2 represents a suitable parent for improving yield under severe dryland conditions.

CONCLUSIONS

This study demonstrated that the Genotype-by-Yield × Trait (GYT) biplot methodology is an effective and breeder-oriented tool for simultaneous evaluation of grain yield and associated agronomic traits under contrasting moisture regimes. By integrating yield with key yield components and morphological traits, the approach enabled precise discrimination among genotypes and ensured that secondary traits contributed positively to productivity.

Across four consecutive growing seasons, genotype G5 consistently achieved the highest Superiority Index under both rainfed and supplementary irrigation conditions, primarily driven by its high yield potential and strong multi-trait integration in favorable environments. Its high SI values were associated with strong Yield × HI, Yield × TGW, Yield × SW, and Yield × GNM^2

combinations; however, these combinations inherently reflect yield-weighted performance rather than direct physiological tolerance. The GYT-derived Superiority Index showed strong alignment with classical drought tolerance indices, largely owing to their shared mathematical dependence on grain yield. Overall, the GYT approach provides an effective framework for simultaneously evaluating yield and associated agronomic traits, helping distinguish high-yielding materials like G5 from specifically adapted stress-tolerant genotypes like G2 for targeted wheat breeding programs in semi-arid regions.

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انتخاب چند صفتی یکپارچه ژنوتیپ‌های گندم نان با استفاده از تحلیل بای‌پلات GYT تحت رژیم‌های متضاد رطوبتی

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چکیده

بهبود عملکرد و پایداری گندم در شرایط متغیر دسترسی به آب، یکی از چالش‌های مهم در اکوسیستم‌های زراعی نیمه‌خشک است. راهبردهای متداول انتخاب اغلب بر عملکرد به‌تنهایی تأکید دارند و تعامل آن با صفات زراعی مهم را نادیده می‌گیرند. هدف این مطالعه، شناسایی ژنوتیپ‌های گندم نان با عملکرد بالا و پایدار با استفاده از روش بای‌پلات ژنوتیپ × عملکرد × صفت (GYT) به‌عنوان رویکردی برای انتخاب چندصفتی بود. دوازده ژنوتیپ طی چهار فصل زراعی (2019-2023) در شرایط دیم و آبیاری تکمیلی در استان کردستان، ایران، ارزیابی شدند. تحلیل بای‌پلات GYT، عملکرد دانه را با دوازده صفت زراعی تلفیق کرد و امکان ارزیابی عملکرد ژنوتیپ‌ها را بر اساس ترکیب‌های عملکرد–صفت، به جای عملکرد به‌تنهایی، فراهم ساخت .تحلیل مؤلفه‌های اصلی به‌ترتیب 79/43 و 85/04 درصد از کل تغییرات را در شرایط دیم و آبیاری توضیح داد. ژنوتیپ G5 به‌طور پایدار بالاترین شاخص برتری (SI) را در هر دو محیط به دست آورد (SI = 2.08 در شرایط آبیاری و 1.44در شرایط دیم). رتبه برتر این ژنوتیپ عمدتاً با ترکیب مطلوب عملکرد با صفات وزن سنبله (SW)، وزن هزار دانه (TGW)و شاخص برداشت (HI) مرتبط بود. این نتایج نشان می‌دهند که G5 تحت رژیم‌های رطوبتی مورد ارزیابی، صفات مطلوب مرتبط با عملکرد را به‌صورت همزمان دارا بود؛ با این حال، سازوکارهای فیزیولوژیکی زیربنای این برتری نیازمند بررسی‌های بیشتر است .همچنین، همبستگی مثبت متوسط تا قوی ($r = 0.59–0.60$ $P < 0.05$) ، بین شاخص برتری (SI) مبتنی بر GYT در شرایط دیم و شاخص‌های متداول تحمل به خشکی، شامل میانگین هندسی بهره‌وری (GMP) و شاخص تحمل به تنش(STI) ، کاربرد این چارچوب چندصفتی را بیشتر تأیید کرد.