Original Article
DOI: https://doi.org/10.70749/ijbr.v4i3.2994

101 RESEARCH (EDUCATION & PUBLICATIONS)

INDUS JOURNAL OF BIOSCIENCE RESEARCH
https://ijbr.com.pk
ISSN: 2960-2793/ 2960-2807

Crossref
OPEN ACCESS

Identification of Drought Tolerant Wheat Genotypes through Multi-Index Approach under Different Irrigation Regimes

Habib Ur Rehman[1], Nanak Khan[1], Jahangir Khan[2], Abdul Razzaq Reki[1], Ghulam Rasool[3], Syed Riaz Ahmed[2], Hafeezullah[1], Amanullah[2], Hassan Akhtar[2], Muhammad Ilyas[1]

[1]Department of Agronomy, Balochistan Agriculture College, Quetta, Pakistan
[2]PARC-Balochistan Agricultural Research and Development Centre, Quetta, Pakistan
[3]Department of Plant Breeding and Genetics, Balochistan Agriculture College, Quetta, Pakistan

ARTICLE INFO

Keywords: Wheat, Drought Tolerance, Genotypes, Grain Yield, Yield Stability, Drought Tolerance Indices

Correspondence to: Dr. Nanak Khan, Department of Agronomy, Balochistan Agriculture College, Quetta, Pakistan.
Email: nanakkan76@gmail.com

Declaration
Authors' Contribution
All authors equally contributed to the study and approved the final manuscript.

Conflict of Interest: No conflict of interest.

Funding: No funding received by the authors.

Article History
Received: 07-01-2026 Revised: 14-03-2026
Accepted: 21-03-2026 Published: 30-03-2026

ABSTRACT

Wheat is a globally important cereal crop that serves as a major staple for billions of people. However, its productivity in rainfed areas is increasingly threatened by drought (one of the most severe abiotic stresses), which is exacerbated by climate change. This study aimed to evaluate the drought tolerance of 33 exotic wheat genotypes along with seven local checks under irrigated and rainfed conditions during the 2023–24 growing season at the Balochistan Agricultural Research and Development Center (BARDC), Quetta. The experiment was conducted using a factorial RCBD design with three replicates. Grain yield under normal (Ypi) and stress (Ysi) conditions was used to compute 11 drought tolerance indices, including Mean Productivity (MP), Geometric Mean Productivity (GMP), Harmonic Mean (HARM), Stress Tolerance Index (STI), and others. Genotypes BARDC-26, BARDC-31, BARDC-24, BARDC-9, BARDC-14, and BARDC-19 consistently exhibited the highest values across multiple indices (MP, GMP, MRP, HARM, MSTIK1, MSTIK2, and REI), as well as superior grain yield under both conditions, classifying them as drought-tolerant and high-yielding. In contrast, BARDC-16, BARDC-15, BARDC-12, BARDC-8, and BARDC-2 exhibited low index values and were identified as drought-sensitive. Correlation analysis revealed strong positive relationships between both Ypi and Ysi with MP, GMP, HARM, REI, and MSTIK1, while TOL was negatively correlated with Ysi, underscoring its inefficiency in selecting drought-tolerant genotypes. PCA showed that the first two components explained 97.7% of the total variation, with drought indices such as MP, GMP, and STI contributing most to genotype differentiation. Cluster analysis grouped the genotypes into four distinct clusters, with Cluster I (including BARDC-26, BARDC-31, BARDC-24, BARDC-9, BARDC-14, BARDC-25, and BARDC-19) comprising the most stable and drought-tolerant genotypes. These findings underscore the effectiveness of multivariate drought indices in identifying stable, high-yield genotypes for both irrigated and rainfed environments. The selected genotypes offer strong potential for future breeding programs targeting drought resilience in arid and semi-arid regions of Balochistan.

INTRODUCTION

Wheat (*Triticum aestivum* L.), often referred to as the king of cereals," holds a vital position among cereal crops globally. (Abd El-Mohsen *et al.*, 2015; Ahmed *et al.*, 2023). It plays a vital role in ensuring global food security, contributing approximately 20% of the world's calorie intake and 21% of its protein requirements (Shiferaw *et al.*, 2013; Nawaz *et al.*, 2025). As the primary staple for nearly two billion individuals, representing approximately 36% of the world's population, wheat is indispensable to human nutrition and livelihoods (Kumar *et al.*, 2024; Guo *et al.*, 2020). Global wheat production reached a record 791.02 million metric tonnes in 2023-24, with projections for 2024-25 estimating a slight increase to 793.24 million metric tonnes (Ulukan, 2024). In Pakistan, the cultivated area under wheat increased by 6.6% from 9.0 million hectares in 2022-23 to 9.6 million ha during 2023-24. During the same period, the production area rose from 28.2 million metric tonnes to 31.4 million metric tonnes, an 11.6% increase. Wheat contributes 2.2% to Pakistan's GDP and accounts for 9.0% of the value added in the agricultural sector (Bajkani *et al.*, 2025). Despite its global and national importance, wheat production faces mounting threats from climate change. Rising temperatures and prolonged dry spells increasingly disrupt wheat growth, development, and yield. Drought, driven by climate change, is among the most significant abiotic stressors, accounting for approximately 60% of crop failures due to climate disasters (Lao *et al.*, 2021; Shahi *et al.*, 2022). In developing regions, drought is the prominent cause of crop yield reduction, a trend that is expected to intensify with ongoing global warming (Shahrokhi *et al.*, 2020). To meet the escalating food demands of a growing global population, particularly in water-scarce regions, it is imperative to enhance wheat productivity and its resilience to drought conditions (Del Pozo *et al.*, 2016; Shahi *et al.*, 2024a). In Pakistan, drought stress has emerged as a critical challenge, especially in arid regions such as Balochistan (Naz *et al.*, 2020; Muhammad *et al.*, 2025; Khan *et al.*, 2013). Rainfed agriculture is heavily reliant on precipitation and is particularly vulnerable to different stresses at different crop stages (Mahmood *et al.*, 2019). During 2023–24, wheat cultivated under rainfed conditions covered 1.14 million hectares and yielded 1.89 million metric tons. In Balochistan alone, 30,000 hectares of rainfed wheat produced only 34,000 metric tons (Durrani *et al.*, 2025).

Drought stress can have more detrimental effects on plant growth than all other environmental stresses combined (Al-Maskri *et al.*, 2016; Shahi *et al.*, 2024b). It is a widespread issue affecting virtually all wheat-growing regions by inducing severe osmotic stress and limiting productivity (Khan *et al.*, 2011; Abhinandan *et al.*, 2018; Ahmed *et al.*, 2024). Wheat is especially sensitive to water deficit at the seedling, mid-season, and reproductive growth stages, making drought a major concern across developmental phases (Mujtaba *et al.*, 2016). Drought negatively affects plant growth parameters, notably plant height, by limiting water availability, disrupting photosynthesis, and hindering nutrient uptake (Sarto *et al.*, 2017; Naveed *et al.*, 2025). Water scarcity during the pre-anthesis stage may delay or suspend flowering, along with causing seed abortion (Ahmed *et al.*, 2020), and stress during the reproductive phase often results in more severe yield losses than the vegetative phase (Wang *et al.*, 2017; Dhakal, 2021). To mitigate drought-induced yield reductions, researchers have increasingly employed drought tolerance indices to identify genotypes capable of maintaining productivity under water stress. These indices assess the relationship between yield under stress (Ys) and non-stress (Yp) conditions, offering valuable insights into genotypic performance (Bennani *et al.*, 2017; Abd El-Aty *et al.*, 2024).

In this context, indices such as Mean Productivity (MP), Geometric Mean Productivity (GMP), and Harmonic Mean (HARM) provide a general measure of overall performance across environments (Yadav *et al.*, 2024). The Stress Susceptibility Index (SSI), Stress Tolerance Index (TOL), and Yield Reduction Ratio (YR) specifically quantify yield decline under drought conditions, highlighting genotypic tolerance or vulnerability (Mubushar *et al.*, 2022). The Stress Tolerance Index (STI) and its modified forms (MSTIk1 and MSTIk2) are particularly effective in identifying genotypes that perform well under both stress and non-stress conditions. Additional indices such as the Yield Index (YI), Relative Drought Index (RDI), and Drought Resistance Index (DI) enable comparative evaluation across genotypes relative to the mean, facilitating the selection of drought-resilient lines (Sofi *et al.*, 2021). Therefore, the present study was undertaken to evaluate drought-tolerant wheat genotypes using multiple drought tolerance indices, compare the effectiveness of different drought resistance indices, and recommend superior genotypes suitable for cultivation in drought-prone regions.

MATERIALS AND METHODS

Study Site Characteristics

The experiment was conducted at the research farm of the Balochistan Agricultural Research and Development Centre (BARDC), Quetta, Pakistan (30◦ .1952296′ N, 66◦ .9637362′ E). The site is located in a semi-arid agro-climatic zone at an elevation of 1,680 m (5,510 ft) above sea level. The region experiences an average annual precipitation of 200 to 250 mm (8 to 10 in), with the majority occurring during the winter months. Summers are typically warm, with average temperatures ranging between 25°C and 35°C but getting hotter due to climate change with a 1–2-degree increase, whereas winters are cold, with temperatures often dropping below the freezing point, ranging from -5°C and 10°C.

Table 1

Monthly Average Temperature and Rainfall Data During 2023/24 Growing Season at BARDC Quetta.

Months	Temperature (°C)		Precipitation (mm)
	Min (Average)	Max (Average)	
November	7.3	22.2	9.38
December	2.9	18.7	3.29
January	3	16.8	23.68
February	2.8	15.9	51.2
March	5.7	16.9	66.4
April	10.3	22.3	128.6
May	17.2	31.4	0

The soil at the experimental site was characterized as silty loam. It exhibited a slightly alkaline pH (7.98), low levels of organic matter (0.91%), nitrogen (0.05%), and phosphorus (5.4 mg/kg), whereas potassium levels were adequate (Table 2). Overall, the soil was considered marginally fertile and suboptimal for crop growth without any agronomic interventions.

Table 2

Soil Physiochemical Properties of Experimental Site.

Properties	Values
Textural Class	Silty Loam
pH	7.98
Electrical Conductivity (dS m^{-1})	0.43
Organic Matter (%)	0.69
Total Nitrogen (%)	0.05
Available Phosphorus (mg kg^{-1})	5.4
Available Potassium (mg kg^{-1})	117

Field Experiment and Treatments

The experiment was conducted during the Rabi season of 2023-24 using a Randomized Complete Block Design (RCBD) with three replications, arranged in a factorial layout involving two irrigation regimes (irrigated and rainfed). A total of 40 wheat genotypes were evaluated, comprising 33 test genotypes and seven check varieties.

The experimental field was initially prepared by ploughing twice using a cultivator. Sowing was performed on 1st November using a manual hand drill, with each plot consisting of two rows, 3 m in length, spaced 20 cm apart. Three irrigations were applied under the irrigated treatment, whereas only one irrigation of 15 mm (equivalent to approximately half an inch) was applied under the rainfed condition on December 17th.

Drought Tolerance Indices

Grain yield data were recorded for each genotype under both irrigated and rainfed conditions. These yield values were used to calculate 11 drought tolerance/resistance indices, which were used to evaluate the performance of genotypes under water-deficit and non-stressed environments. The indices computed are listed in Table 3.

Table 3

Stress Indices, Their Abbreviations, Formulas and References.

S.No	Stress Indices	Formula	Reference
1	Stress Tolerance (TOL)	$Ypi - Ysi$	(Rosielle and Hamblin, 1981)
2	Mean Productivity (MP)	$(Ypi + Ysi)/2$	(Rosielle and Hamblin, 1981)
3	Mean Relative Performance (MRP)	$(Ysi/Ys) + (Ypi/Yp)$	(Hossain et al., 1990)
4	Geometric Mean Productivity (GMP)	$\sqrt{Ypi \times Ysi}$	(Fernandez, 1993)
5	Relative Efficiency Index (REI)	$Ysi/Ys \times Ypi/Yp$	(Hossain et al., 1990)
6	Modified Stress Tolerance Index 1 (MSTIK1)	$((Ypi)^2/(Yp)^2) \times (Ysi \times Ypi)/(Yp)^2$	(Farshadfar and Sutka, 2003)
7	Modified Stress Tolerance Index 2 (MSTIK2)	$((Ysi)^2/(Ys)^2) \times (Ysi \times Ypi)/(Yp)^2$	(Farshadfar and Sutka, 2003)
8	Harmonic Mean Of Yield (HARM)	$2 \times (Ypi \times Ysi)/(Ypi + Ysi)$	(Dadbakhsh et al., 2011)
9	Relative Drought Index (RDI)	$(Ysi/Ypi)/(Ys/Yp)$	(Fischer and Wood, 1979)
10	Drought Resistance Index (DI)	$Ysi \times (Ysi/Ypi)/(Ys)$	(Lan, 1998)
11	Golden Mean (GM)	$(Ypi + Ysi)/(Ypi - Ysi)$	(Moradi et al., 2012)

Statistical analysis

The collected data were subjected to multivariate statistical analyses to comprehensively evaluate genotypic responses under irrigated and rainfed conditions. Analysis of variance (ANOVA) was performed using Statistics 8.1 to determine the significance of the differences among genotypes and treatments. Pearson's correlation analysis was conducted to assess the relationships between drought tolerance indices and yield components. Principal component analysis (PCA) was employed to reduce data dimensionality and identify the most influential indices contributing to drought tolerance. Hierarchical cluster analysis, using Ward's method, was performed to classify genotypes into distinct groups based on their performance under stress and non-stress conditions. All statistical analyses were performed using the Jamovi software.

RESULTS

In the current study, genotypes BARDC-26, BARDC-24, BARDC-9, BARDC-31, BARDC-25, and BARDC-19 showed superior performance with consistently high MP, GMP, HARM, and STI values (Table 5). For instance, BARDC-26 recorded the highest GMP (5316.2), HARM (5229.7), MP (5404.2), and STI (2.55) values Similarly, BARDC-24 and BARDC-9 also showed strong performance across these indices, with GMP values of 5119.9 and 5104.8, respectively, and STI values of 2.45 and 2.44.

Table 4

Mean Values of Yield in Non-Stressed (Ypi), Yield in Stressed (Ysi), Tolerance Index (TOL), Mean Productivity (MP), Mean Relative Performance (MRP), Geometric Mean Productivity (GMP), Relative Efficiency Index (REI), Modified Stress Tolerance.

Genotype	Ysi	Ypi	TOL	MP	MRP	GMP	REI	MSTIK1	MSTIK2	HARM	RDI	DI	GM
BARDC-1	3612.5	5087.5	1475.0	4350.0	2.05	4287.0	1.05	0.89	0.79	4225.0	0.94	0.71	5.90
BARDC-2	2675.0	4616.7	1941.7	3645.9	1.70	3514.2	0.71	0.49	0.29	3387.3	0.77	0.43	3.76
BARDC-3	4116.7	4591.7	475.0	4354.2	2.09	4347.7	1.08	0.74	1.05	4341.2	1.19	1.02	18.33
BARDC-4	3391.7	4833.3	1441.6	4112.5	1.94	4048.8	0.94	0.71	0.62	3986.2	0.93	0.66	5.71
BARDC-5	3541.7	3766.7	225.0	3654.2	1.76	3652.5	0.76	0.35	0.55	3650.7	1.25	0.92	32.48
BARDC-6	4083.3	5208.3	1125.0	4645.8	2.21	4611.6	1.22	1.07	1.16	4577.7	1.04	0.88	8.26
BARDC-7	3133.3	5016.7	1883.4	4075.0	1.91	3964.7	0.90	0.74	0.51	3857.4	0.83	0.54	4.33
BARDC-8	2991.7	3900.0	908.3	3445.9	1.63	3415.8	0.67	0.33	0.34	3386.0	1.02	0.63	7.59
BARDC-9	4358.3	5979.2	1620.9	5168.8	2.44	5104.8	1.49	1.73	1.62	5041.7	0.97	0.88	6.38
BARDC-10	2933.3	4500.0	1566.7	3716.7	1.74	3633.2	0.76	0.50	0.37	3551.5	0.86	0.53	4.74
BARDC-11	3966.7	4816.7	850.0	4391.7	2.09	4371.1	1.09	0.83	0.99	4350.6	1.09	0.90	10.33
BARDC-12	3175.0	3658.3	483.3	3416.7	1.64	3408.1	0.67	0.29	0.38	3399.6	1.15	0.76	14.14
BARDC-13	2900.0	4991.7	2091.7	3945.9	1.84	3804.7	0.83	0.67	0.40	3668.6	0.77	0.46	3.77
BARDC-14	4183.3	6141.7	1958.4	5162.5	2.43	5068.8	1.47	1.80	1.47	4976.8	0.90	0.79	5.27
BARDC-15	3183.3	3541.7	358.4	3362.5	1.61	3357.7	0.65	0.26	0.37	3352.9	1.19	0.79	18.76
BARDC-16	2441.7	4662.5	2220.8	3552.1	1.64	3374.1	0.65	0.46	0.22	3205.0	0.69	0.35	3.20

BARDC-17	2658.3	5408.3	2750.0	4033.3	1.86	3791.7	0.82	0.78	0.33	3564.5	0.65	0.36	2.93
BARDC-18	3525.0	5541.7	2016.7	4533.4	2.12	4419.8	1.12	1.12	0.80	4309.1	0.84	0.62	4.50
BARDC-19	4141.7	5866.7	1725.0	5004.2	2.36	4929.3	1.39	1.56	1.37	4855.5	0.94	0.81	5.80
BARDC-20	3925.0	4166.7	241.7	4045.9	1.95	4044.0	0.94	0.53	0.83	4042.2	1.25	1.02	33.48
BARDC-21	3366.7	4000.0	633.3	3683.4	1.76	3669.7	0.77	0.40	0.50	3656.1	1.12	0.78	11.63
BARDC-22	3891.7	4225.0	333.3	4058.4	1.95	4054.9	0.94	0.55	0.82	4051.5	1.22	0.99	24.35
BARDC-23	3791.7	4116.7	325.0	3954.2	1.90	3950.9	0.89	0.49	0.74	3947.5	1.22	0.96	24.33
BARDC-24	4375.0	5991.7	1616.7	5183.4	2.45	5119.9	1.50	1.75	1.64	5057.3	0.97	0.88	6.41
BARDC-25	4275.0	5591.7	1316.7	4933.4	2.34	4889.2	1.37	1.39	1.43	4845.5	1.01	0.90	7.49
BARDC-26	4433.3	6375.0	1941.7	5404.2	2.55	5316.2	1.62	2.14	1.82	5229.7	0.92	0.85	5.57
BARDC-27	4200.0	5191.7	991.7	4695.9	2.24	4669.6	1.25	1.09	1.26	4643.5	1.07	0.94	9.47
BARDC-28	3791.7	4400.0	608.3	4095.9	1.96	4084.5	0.96	0.60	0.79	4073.3	1.14	0.90	13.47
BARDC-29	2941.7	4825.0	1883.3	3883.4	1.81	3767.5	0.81	0.62	0.40	3655.0	0.81	0.49	4.12
BARDC-30	2925.0	4491.7	1566.7	3708.4	1.74	3624.7	0.75	0.49	0.37	3542.9	0.86	0.53	4.73
BARDC-31	4633.3	5808.3	1175.0	5220.8	2.48	5187.6	1.54	1.69	1.89	5154.7	1.06	1.02	8.89
BARDC-32	3575.0	4216.7	641.7	3895.9	1.86	3882.6	0.86	0.50	0.63	3869.4	1.12	0.84	12.14
BARDC-33	3300.0	4558.3	1258.3	3929.2	1.86	3878.5	0.86	0.58	0.54	3828.4	0.96	0.66	6.25
AZRI-96	3058.3	4383.3	1325.0	3720.8	1.75	3661.3	0.77	0.48	0.41	3602.8	0.93	0.59	5.62
Local White	3916.7	4566.7	650.0	4241.7	2.03	4229.2	1.02	0.69	0.90	4216.8	1.14	0.93	13.05
Pishin local	4125.0	5133.3	1008.3	4629.2	2.20	4601.6	1.21	1.04	1.18	4574.2	1.07	0.91	9.18
Shalkot-14	3987.5	4591.7	604.2	4289.6	2.05	4278.9	1.05	0.72	0.95	4268.3	1.15	0.95	14.20
Tijaban-10	3875.0	4516.7	641.7	4195.9	2.01	4183.6	1.00	0.66	0.86	4171.3	1.14	0.92	13.08
Wadan	3920.8	4475.0	554.2	4197.9	2.01	4188.7	1.00	0.65	0.88	4179.6	1.16	0.95	15.15
Zarghoon-21	3800.0	4800.0	1000.0	4300.0	2.04	4270.8	1.04	0.78	0.86	4241.9	1.05	0.83	8.60
LSD (0.05)	1659.7	1653.4	2262.1	1210.3	0.59	1238.3	0.60	0.98	1.37	1288.4	0.61	0.80	43.97

Conversely, genotypes BARDC-16, BARDC-17, and BARDC-2 exhibited the lowest values across these indices. For example, BARDC-16 showed the lowest GMP (3374.1), HARM (3205.0), and STI (1.64), along with the highest yield reduction (TOL = 2220.8). STI, MSTIk1, MSTIk2, and REI effectively differentiated the high-yielding genotypes. Genotypes BARDC-26, BARDC-31, BARDC-9, and BARDC-24 recorded higher values for MSTIk1 (2.14, 1.69, 1.73, 1.75, respectively) and REI (>1.45), confirming their drought resilience and yield stability. Interestingly, check varieties such as Zarghoon-21, Wadan, and Shalkot-14 also demonstrated good performance under both conditions, suggesting their continued relevance in breeding programs and varietal recommendations for the region. For instance, Zarghoon-21 showed a GMP of 4270.8 and HARM of 4241.9, indicating good adaptability to semi-arid environments. In contrast, genotypes such as BARDC-17, despite showing high yield potential under nonstress conditions (Ypi = 5408.3), recorded poor values for drought indices (e.g., MSTIk2 = 0.33, REI = 0.82), highlighting their susceptibility to water deficit. Traits such as GMP and STI are especially valuable because they combine productivity with stability, aiding in the identification of genotypes with broad adaptability. This aligns with the breeding goal of developing drought-resilient cultivars that not only survive but also thrive in water-limited environments. These findings are particularly relevant for semi-arid and drought-prone regions, such as Balochistan, where rainfed agriculture predominates. The identified high-performing genotypes can serve as potential donors in wheat improvement programs aimed at enhancing drought resilience.

Table 5

Top-Performing Wheat Genotypes (Top 15%) Identified for Each Drought Tolerance Index under Irrigated (Ypi) and Stress (Ysi) Conditions.

Index	Top 15% Genotypes
Ysi	BARDC-31, 26, 24, 9, 25, 27
Ypi	BARDC-26 ,14, 24, 9, 19, 31
TOL (Bottom)	BARDC-5, 20, 23, 22, 15, 3
MP	BARDC-26, 31, 24, 9, 14, 19
MRP	BARDC-26, 31, 24, 9, 14, 19
GMP	BARDC-26, 31, 24, 9, 14, 19
REI	BARDC-26, 31, 24, 9, 14, 19
MSTIK1	BARDC-26, 14, 24, 9, 31, 19
MSTIK2	BARDC-31, 26, 24, 9, 14, 25
HARM	BARDC-26, 31, 24, 9, 14, 19
RDI	BARDC-20, 5, 22, 23, 15, 3
DI	BARDC-20, 31, 3, 22, 23, Shalkot-14
GM	BARDC-20, 5, 22, 23, 15, 3

Correlation Analysis

Correlation analysis among grain yield under stress (Ysi), yield under non-stress (Ypi), and the even drought tolerance indices provides valuable insight into the interrelationship of traits and their effectiveness in genotype evaluation under contrasting environmental conditions. Grain yield under Ysi exhibited strong and highly significant positive correlations with several drought indices MSTIK2 (r = 0.929), HARM (r = 0.917), GMP (r = 0.879), MRP (r = 0.872), DI (r = 870), REI (r = 0.868), and MP (r = 0.829). These strong associations highlight the relevance of these indices in reliably predicting genotype performance under water-limited conditions in the future. Specifically, indices such as HARM, GMP, and DI are recognized for their capacity to stabilize performance under stress by balancing yield level and stress tolerance. In contrast, grain yield under non-stress conditions (Ypi) also exhibited significant positive correlations with indices such as MSTIK1 (r = 0.940), MP (r = 0.894), REI (r = 0.855), MRP (r = 0.855), GMP (r = 0.847), HARM (r = 796), and MSTIK2 (r = 0.744) (Figure 1). These correlations emphasize the consistency of these indices in selecting genotypes with superior yield potential under optimal (irrigated) conditions. Although a moderate positive correlation was observed between Ysi and Ypi (r = 0.493), indicating some shared influences, their responses differed under both conditions. This indicates that while some genotypes may perform well under both conditions, many exhibits divergent responses due to genotype × environment interactions. Interestingly, TOL was negatively correlated with Ysi (r = -0.33) and positively correlated with Ypi (r = 0.656), suggesting that TOL tends to favor high-yielding genotypes under non-stress conditions but penalizes those with stability under drought conditions. Indices such as the RDI and GM exhibited opposing correlation trends: both were positively correlated with Ysi but negatively with Ypi. This pattern further underscores the stress-specific utility of these genes and highlights the trade-offs between drought adaptability and optimal yield expression. Conversely, indices such as MP, GMP, MRP, HARM, and REI maintained strong and positive correlations with both Ysi and Ypi, underscoring their robustness in different environments. Their dual sensitivity to performance in both moisture regimes makes them valuable tools for selecting genotypes with broad adaptability, which is a critical breeding objective in regions prone to fluctuating water availabilities.

Figure 1

Correlation Between Grain Yield (Ypi and Ysi) and Different Stress Indices of Wheat Genotypes.

	Ysi	Ypi	TOL	MP	MRP	GMP	REI	MSTIK1	MSTIK2	HARM	RDI	DI	GM
Ysi	1												
Ypi	0.493	1											
TOL	-0.332	0.656	1										
MP	0.830	0.895	0.251	1									
MRP	0.873	0.855	0.170	0.997	1								
GMP	0.879	0.848	0.157	0.995	0.999	1							
REI	0.868	0.856	0.175	0.995	0.998	0.998	1						
MSTIK1	0.701	0.941	0.412	0.963	0.945	0.943	0.957	1					
MSTIK2	0.930	0.745	0.001	0.955	0.972	0.974	0.979	0.902	1				
HARM	0.918	0.796	0.067	0.982	0.994	0.996	0.992	0.915	0.984	1			
RDI	0.529	-0.471	-0.970	-0.031	0.051	0.063	0.045	-0.197	0.214	0.151	1		
DI	0.871	0.009	-0.746	0.453	0.524	0.533	0.515	0.275	0.650	0.604	0.873	1	
GM	0.258	-0.556	-0.827	-0.224	-0.158	-0.157	-0.171	-0.350	-0.023	-0.091	0.837	0.642	1

Principal Component Analysis

PCA was conducted to explore the multivariate relationships among the drought tolerance indices and to identify the most influential components contributing to the variability in genotype performance. The PCA output is summarized in Table 6, which includes both the component summary and the eigenvalues. The analysis revealed that the first two principal components (PC1 and PC2) had eigenvalues greater than 1 and together explained a substantial 97.7% of the total variation among the traits studied. Specifically, PC1 accounted for 66.6% of the total variance, whereas PC2 contributed an additional 31.1% (Figure 2). This cumulative contribution indicates that most of the variation in drought tolerance among genotypes can be effectively captured in a two-dimensional space. The eigenvalue distribution further supported this result, showing a steep decline beyond PC2, with the third component (PC3) contributing only 1.82% of the variance, and subsequent components contributing less than 1% of the variance each. This clear inflection confirms that only PC1 and PC2 are meaningful for genotype differentiation and trait clustering, whereas the remaining components represent noise or redundancy. From a biological standpoint, the dominance of PC1 suggests that it likely represents a general adaptability axis, incorporating indices associated with overall yield performance and stability across environments, such as MP, GMP, HARM, and Stress STI. These indices are known to strongly correlate with both yield under irrigated and rainfed conditions and have been widely used for the selection of genotypes with broad adaptability. In contrast, PC2 may reflect the differential stress response or specific drought adaptation, capturing variability associated with indices such as TOL, DI, and GM. These indices tend to highlight genotype behavior under stress more explicitly, thus providing complementary insights into the broader patterns observed in PC1. The high explanatory power of these two principal components validated the internal consistency of the drought tolerance indices and confirmed their utility in genotype selection. This also implies that visualizing the genotypes and indices using a biplot based on PC1 and PC2 offers a clear and interpretable clustering of genotypes into tolerant, susceptible, and stable groups. Overall, PCA was an effective statistical tool for data reduction, trait correlation analysis, and selection strategy development in this study.

Figure 2

PCA Biplot Showing the Distribution of Wheat Genotypes and Drought Tolerance Indices Based on the First Two Principal Components.

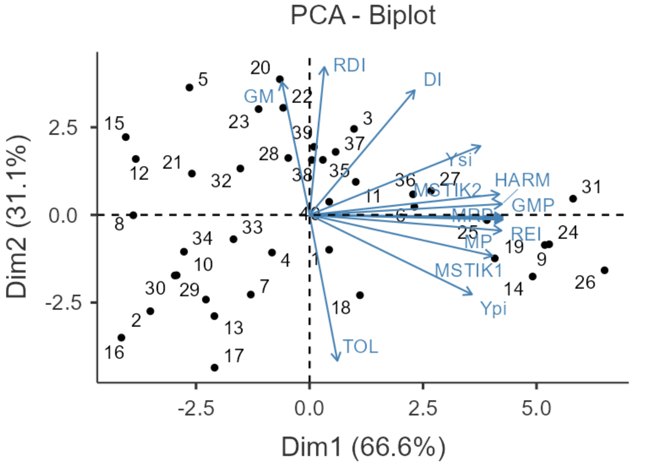


Table 6

Principal Component Analysis Summary Showing Eigenvalues and Variance Explained by the First Two Components for Drought Tolerance Indices.

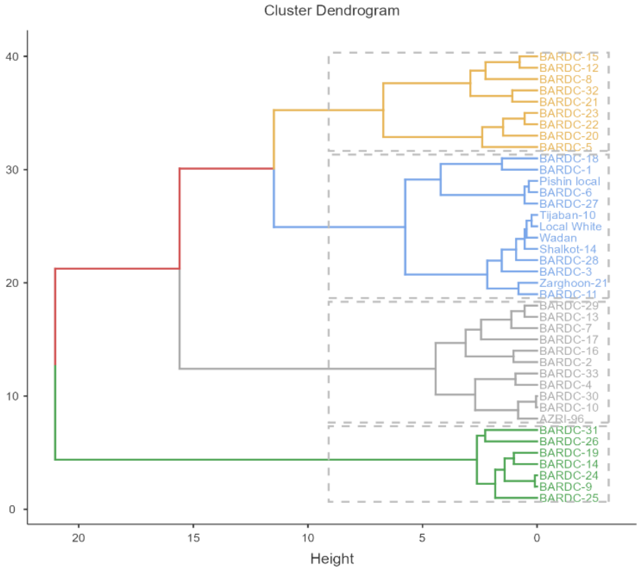
Component	Eigenvalue	% of Variance	Cumulative %
1	8.66131	66.62545	66.6
2	4.03952	31.07324	97.7
3	0.23721	1.82471	99.5
4	0.04662	0.35859	99.9
5	0.01162	0.08940	100.0
6	0.00346	0.02664	100.0
7	2.34e0-4	0.00180	100.0
8	2.00e0-5	1.53e0-4	100.0
9	1.86e0-6	1.43e0-5	100.0
10	1.23e0-9	9.49e0-9	100.0
11	1.39e-15	1.07e-14	100.0
12	-1.29e−16	9.95e-16	100.0
13	-1.70e−16	1.31e-15	100.0

Hierarchical Cluster Analysis

Hierarchical cluster analysis was performed using Ward's method based on grain yield under irrigation (Ypi), stress (Ysi), and associated drought tolerance indices. The resulting dendrogram (Figure 3) grouped the 40 wheat genotypes into four distinct clusters comprising seven, 11, 13, and nine genotypes, respectively. This classification reflects the genetic diversity and differential responses of the genotypes to drought stress. Cluster I included BARDC-31, BARDC-26, BARDC-19, BARDC-14, BARDC-24, BARDC-9, and BARDC-25. These genotypes showed consistently high grain yields under both stress and non-stress conditions, as well as superior values for key indices, such as GMP, MP, HARM, and GM, indicating their broad adaptability and strong drought tolerance. Moderate TOL values suggest manageable yield reduction under stress, whereas high GM values confirm yield stability. These genotypes align with Group A classification, which includes genotypes that are both drought tolerant and high yielding across environments. Hence, Cluster I genotypes are considered the most promising for cultivation in both rainfed and irrigated areas. Cluster II comprised genotypes BARDC-29, BARDC-13, BARDC-7, BARDC-17, BARDC-16, BARDC-2, BARDC-33, BARDC-4, BARDC-30, BARDC-10, and AZRI-96. This cluster had the lowest Ysi and GMP values, along with the highest TOL and reduced REI, reflecting a poor yield performance under drought conditions. These genotypes are the most susceptible to drought, exhibiting high yield losses and limited stress resilience. Cluster III contained genotypes BARDC-18, BARDC-1, Pishin Local, BARDC-6, BARDC-27, Tijaban-10, Local White, Wadan, Shalkot-14, BARDC-28, BARDC-3, Zarghoon-21, and BARDC-11. These genotypes demonstrated moderate Ysi, MP, and GMP values, with an average DI of 0.88, indicating semi-tolerance. Although not as drought-resilient as Cluster I, these genotypes maintained reasonable productivity and could be useful in moderately stressed environments. Cluster IV grouped BARDC-15, BARDC-12, BARDC-8, BARDC-32, BARDC-21, BARDC-23, BARDC-22, BARDC-20, and BARDC-5. This cluster exhibited moderate drought indices, with Ysi, GMP, MP, and DI values slightly lower than those of Cluster III. These genotypes also fell into the semi-tolerant category, although with relatively lower stress tolerance and stability. The clustering pattern reflected clear intragroup homogeneity and intergroup variability, emphasizing that genotypes within each cluster shared similar drought response mechanisms. The dendrogram (Figure 3) clearly illustrates the genetic relationships and performance-based grouping of genotypes. This analysis confirmed the effectiveness of clustering based on drought indices for categorizing genotypes into distinct tolerance groups. Importantly, Cluster I genotypes are strongly recommended for cultivation in the drought-prone and semi-arid environments of Quetta and Balochistan because of their superior performance and yield stability across environments. The observed variability among clusters also highlights the potential for utilizing this genetic diversity in future breeding programs aimed at

Figure 3

Hierarchical Clustering Dendrogram of Wheat Genotypes by Cluster Analysis Based on Drought Tolerance Indices and Yield Performance in Rainfed and Irrigated Environments.



improving drought resilience in wheat crops.

DISCUSSION

The present study demonstrates the effectiveness of multi-index technique in evaluating and distinguishing different wheat genotypes for drought tolerance under irrigated and rainfed conditions in the semi-arid environment of Quetta, Balochistan. By screening and characterizing 40 diverse wheat genotypes through 11 stress tolerance indices, we successfully categorized the genotypes into drought tolerant and drought susceptible groups, providing valuable insight for targeted wheat improvement (Singh *et al.*, 2018). The genotypes such as BARDC-26, BARDC-31, BARDC-24, BARDC-9, BARDC-14, and BARDC-19 exhibited a superior performance across indices such as MP, GMP, HARM, STI, MSTIK1, MSTIK2, and REI. Their consistent yield stability under both irrigated and rainfed conditions reflects a vigorous ability to maintain productivity despite water limitation, which is a primary breeding objective for wheat in drought-prone regions. This finding aligns with previous studies emphasizing the reliability of GMP, HARM, and STI in the accurate identification of high-yielding, stress-resilient cultivars (Yadav *et al.*, 2024; Sofi *et al.*, 2021). The correlation analysis revealed a close association between grain yield and key drought indices. Positive and significant correlations between Ysi, Ypi, and indices like MP, GMP, HARM, and REI indicate their suitability for differentiating genotypes with both high productivity and stability (Poudel *et al.*, 2021). The negative relationship between TOL and Ysi observed in this study emphasize that TOL alone may be less effective in selecting drought tolerant lines, because it might favor genotypes with high potential yield but limited stability (Bennani *et al.*, 2017). Moreover, the harmonic and geometric means served as reliable predictors for genotypic performance across variable environments, supporting their wide adoption in breeding programs (Alhag *et al.*, 2022; Chowdhury *et al.*, 2021). Furthermore, the principal component and cluster analyses further strengthen these findings. For example, PCA revealed that MP, GMP, and STI contributed most significantly to genotype differentiation, collectively explaining nearly all the variance among the tested genotypes (Sedghiyeh *et al.*, 2025; Shivramakrishnan *et al.*, 2016). Cluster analysis quickly described drought-tolerant and stable genotypes by grouping them together in Cluster I, thus offers an efficient strategy for breeding program advancement and future crossings (Thanaa *et al.*, 2019; Bazzaz *et al.*, 2019). The performance of check varieties such as Zarghoon-21 and Wadan as well as high performing lines is of significance. The high and stable yields of their combined populations highlighted the presence of useful allelic variability in local gene pools that could be exploited in forward breeding (Spinoni *et al.*, 2015; Wen *et al.*, 2023). This is in line with worldwide interests in expanding the genetic base for stress tolerance in wheat by focused introgression and selection using molecular markers (Ahmed *et al.*, 2024). Physiological and agronomic, and probably genotypic-level superior drought tolerant cultivars, involve multiple adaptive traits, including root architectural improvement, osmotic adjustment or phenology optimization (Bapela *et al.*, 2022; Alhag *et al.*, 2022). The retained yield potential of some genotypes under water deficit stresses suggests that they have the capacity for efficient water use and acclimation to stresses, in line with the mechanisms described by Al-Maskri *et al.* (2016) and Abhinandan *et al.* (2018). These traits will be major concerns in maintaining the productiveness of wheat under the prospect of the increase of the intensity of abiotic stress that may occur as a result of climate change (Rijal *et al.*, 2024). The evaluated genotypes stand out as exceptional parents for advancing new wheat varieties and for foundational breeding. By implementing multi-index statistical strategies, demonstrated here, we can swiftly and confidently identify lines that not only yield well under drought but are also broadly adaptable. Such methodologies are particularly suited to the pressing food-security issues in arid and semi-arid areas like Balochistan, where the primary agronomic target is stable production despite limited water availability (Bashir *et al.*, 2021; Blum, 2005). In addition, combining multi-index selection with cluster-based strategies creates a robust framework for enhancing drought tolerance in wheat. The standout genotypes singled out here serve not only as valuable breeding stock exhibiting immediate resilience, but they also strengthen long-term initiatives aimed at stabilizing wheat yields under rising climatic unpredictability (Devi *et al.*, 2024).

CONCLUSION

Our study evaluated 40 wheat genotypes under irrigated and rainfed conditions using drought tolerance indices, correlation analysis, PCA, and hierarchical clustering. By integrating these methods, we established a rapid and reliable framework for identifying genotypes with exceptional yield stability and drought resilience. Six genotypes (BARDC-26, BARDC-24, BARDC-9, BARDC-31, BARDC-25, and BARDC-19) consistently outperformed others, exhibiting high MP, GMP, HARM, and STI values, which underscore their adaptability across both stressed and non-stressed environments. Notably, BARDC-26 emerged as a top candidate, achieving the highest GMP, HARM, and STI scores, making it particularly valuable for drought-prone regions. Correlation analysis revealed key relationships: Ysi showed strong associations with MSTIK2, HARM, GMP, MRP, DI, REI, and MP, while Ypi correlated closely with MSTIK1, MP, GMP, MRP, and HARM. These findings emphasize the utility of multi-trait selection for ensuring stability in diverse environments. Among the indices, MP, GMP, HARM, and REI proved most reliable, displaying robust linkages with both Ysi and Ypi (a testament to their effectiveness in dual-environment screening). PCA further reinforced these insights, with the first two principal components explaining 97.7% of total variance (PC1: 66.6%; PC2: 31.1%). Yield-based indices MP, GMP, HARM, and STI were the primary drivers of this variation, solidifying their role in differentiating genotype performance under contrasting water regimes. Hierarchical clustering (Ward's method) classified the genotypes into four distinct groups. Cluster I (BARDC-31, BARDC-26, BARDC-19, BARDC-14, BARDC-24, BARDC-9, and BARDC-25) contained the most drought-tolerant and stable performers, while Clusters III and IV represented intermediate tolerance. In contrast, Cluster II grouped the most susceptible genotypes, characterized by low Ysi, GMP, and high yield reduction under stress. In summary, our multi-analytical approach combining indices, correlation, PCA, and clustering provides a robust strategy for dissecting genotype behavior under drought. The elite genotypes in Cluster I, particularly BARDC-26, hold significant promise for wheat breeding in water-limited regions like Balochistan. We recommend advancing these candidates to multi-location trials for potential release in semi-arid zones.

REFERENCES

1. Abd El-Mohsen, A.A., M.A. Abd El-Shafi, E.M.S. Gheith, and H.S. Suleiman. 2015. Using different statistical procedures for evaluating drought tolerance indices of bread wheat genotypes. Advances in Agriculture and Biology 4:19–30. https://doi.org/10.15192/pscp.aab.2015.4.1.1930
2. Abhinandan, K., L. Skori, M. Stanic, N.M. Hickerson, M. Jamshed, and M.A. Samuel. 2018. Abiotic stress signaling in wheat–an inclusive overview of hormonal interactions during abiotic stress responses in wheat. Frontiers in Plant Science 9:734. https://doi.org/10.3389/fpls.2018.00734
3. Ahmed, K., G. Shabbir, M. Ahmed, and K.N. Shah. 2020. Phenotyping for drought resistance in bread wheat using physiological and biochemical traits. Science of the Total Environment 729:139082. https://doi.org/10.1016/j.scitotenv.2020.139082
4. Ahmed, S.R., M.J. Asghar, A. Hameed, M. Ghaffar, and M. Shahid. 2024. Advancing crop improvement through GWAS and beyond in mung bean. Frontiers in Plant Science 15:1436532. https://doi.org/10.3389/fpls.2024.1436532
5. Ahmed, S.R., Z. Anwar, U. Shahbaz, M. Skalicky, A. Ijaz, M.S. Tariq, and M.M. Zafar. 2023. Potential role of silicon in plants against biotic and abiotic stresses. Silicon 15:3283–3303. https://doi.org/10.1007/s12633-022-02254-w
6. Al-Maskri, A., W. Al-Busaidi, H. Al-Nadabi, A. Al-Fahdi, and M.M. Khan. 2016. Effects of drought stress on wheat (Triticum aestivum L.) cv. Coolly. International Conference on Agricultural, Food and Biological Health Sciences (AFBHS-16), August:22–24. https://doi.org/10.17758/eap.eap816233
7. Alhag, D.D., V. Rashidi, S. Aharizad, F. Farahvash, and B. Mirshekari. 2022. The traits affecting wheat grain yield and determining tolerant genotypes using drought indices. Cereal Research Communications 50:627–636. https://doi.org/10.1007/s42976-021-00225-2
8. Bajkani, J.K., H. Amin, H.A. Samoon, F. Muhammad, N.A. Soomro, and S.P. Tunio. 2025. Impact assessment of zero tillage wheat sowing technology in the rice-wheat farming system of Sindh Province. Research Journal of Social Affairs 3:413–423. https://doi.org/10.71317/rjsa.003.02.0162
9. Bapela, T., H. Shimelis, T.J. Tsilo, and I. Mathew. 2022. Genetic improvement of wheat for drought tolerance: progress, challenges and opportunities. Plants 11:1331. https://doi.org/10.3390/plants11101331
10. Bashir, S.S., A. Hussain, S.J. Hussain, O.A. Wani, S. Zahid Nabi, N.A. Dar, and S. Mansoor. 2021. Plant drought stress tolerance: understanding its physiological, biochemical and molecular mechanisms. Biotechnology & Biotechnological Equipment 35:1912–1925. https://doi.org/10.1080/13102818.2021.2020161
11. Bazzaz, M.M., A. Hossain, Q.A. Khaliq, M.A. Karim, M. Farooq, and J.A. Teixeira da Silva. 2019. Assessment of tolerance to drought stress of thirty-five bread wheat (Triticum aestivum L.) genotypes using boxplots and cluster analysis. Agriculturae Conspectus Scientificus 84:333–345.
12. Bennani, S., N. Nsarellah, M. Jlibene, W. Tadesse, A. Birouk, and H. Ouabbou. 2017. Efficiency of drought tolerance indices under different stress severities for bread wheat selection. Australian Journal of Crop Science 11:4. https://doi.org/10.3390/plants11070986
13. Blum, A. 2005. Drought resistance, water-use efficiency, and yield potential—are they compatible, dissonant, or mutually exclusive? Australian Journal of Agricultural Research 56:1159–1168. https://doi.org/10.1071/ar05069
14. Chowdhury, M.K., M.A. Hasan, M.M. Bahadur, M.R. Islam, M.A. Hakim, M.A. Iqbal, and M.S. Islam. 2021. Evaluation of drought tolerance of some wheat (Triticum aestivum L.) genotypes through phenology, growth, and physiological indices. Agronomy 11:1792. https://doi.org/10.3390/agronomy11091792
15. Dadbakhsh, A., A. Yazdansepas, and M. Ahmadizadeh. 2011. Study drought stress on yield of wheat (Triticum aestivum L.) genotypes by drought tolerance indices. Advances in Environmental Biology 5:1804–1810.
16. Del Pozo, A., A. Yáñez, I.A. Matus, G. Tapia, D. Castillo, L. Sanchez-Jardón, and J.L. Araus. 2016. Physiological traits associated with wheat yield potential and performance under water-stress in a Mediterranean environment. Frontiers in Plant Science 7:987. https://doi.org/10.3389/fpls.2016.00987
17. Devi, S., V. Singh, M. Kumar, S. Yashveer, R. Kumar, S. Sharma, and M. Redhu. 2024. Assessing wheat genotype performance under heat, drought and combined stresses using multiple stress indices. Euphytica 220:164. https://doi.org/10.1007/s10681-024-03424-0
18. Dhakal, A. 2021. Effect of drought stress and management in wheat—A review. Food and Agribusiness Management 2:62–66.
19. Durrani, H., A. Syed, S. Gourdji, G. Murtuza, and A. Mengal. 2025. Exploring farmers' coping strategies and adaptive measures against the extended drought in Balochistan, Province of Pakistan. Environment, Development and Sustainability 27:6663–6682. https://doi.org/10.1007/s10668-023-04161-5
20. El-Aty, A., S. Mohamed, K.M. Gad, Y.A. Hefny, and M.O. Shehata. 2024. Performance of some wheat (Triticum aestivum L.) genotypes and their drought tolerance indices under normal and water stress. Egyptian Journal of Soil Science 64:19–30.
21. Farshadfar, E., and J. Sutka. 2003. Multivariate analysis of drought tolerance in wheat substitution lines. Cereal Research Communications 31:33–40. https://doi.org/10.1007/bf03543247
22. Fernandez, G.C. 1993. Effective selection criteria for assessing plant stress tolerance. In: Proceedings of the International Symposium on Adaptation of Vegetables and Other Food Crops in Temperature and Water Stress. Taiwan, pp. 13–16.
23. Fischer, R.A., and J.T. Wood. 1979. Drought resistance in spring wheat cultivars. III. Yield associations with morpho-physiological traits. Australian Journal of Agricultural Research 30:1001–1020. https://doi.org/10.1071/ar9791001
24. Guo, J., J. Khan, S. Pradhan, D. Shahi, N. Khan, M. Avci, and M.A. Babar. 2020. Multi-trait genomic prediction of yield-related traits in US soft wheat under variable water regimes. Genes 11:1270. https://doi.org/10.3390/genes11111270

25. Hossain, A.B.S., R.G. Sears, T.S. Cox, and G.M. Paulsen. 1990. Desiccation tolerance and its relationship to assimilate partitioning in winter wheat. Crop Science 30:622–627. https://doi.org/10.2135/cropsci1990.0011183x003000030030x
26. Khan, J.H.A.N., K.H. Saifullah, A.M.A. Khetran, N. Sadiq, M. Islam, A. Hanan, and A. Aziz. 2013. Tijaban-10: A drought tolerant and high yielding wheat variety for rainfed/sailaba areas of Balochistan. Pakistan Journal of Botany 45:1357–1362.
27. Khan, S., J. Khan, N. Islam, and M. Islam. 2011. Screening and evaluation of wheat germplasm for yield, drought and disease resistance under rainfed conditions of upland Baluchistan. Pakistan Journal of Botany 43:559–563.
28. Kumar, P., V. Dheer, P. Kumar, J. Singh, K.K. Singh, Y. Kumar, and A.K. Singh. 2024. Effect of irrigation scheduling and different sowing dates on growth and yield of wheat (Triticum aestivum L.). International Journal of Environment and Climate Change 14:155–161. https://doi.org/10.9734/ijecc/2024/v14i13820
29. Lan, J. 1998. Comparison of evaluating methods for agronomic drought resistance in crops. Acta Agriculturae Boreali-occidentalis Sinica 7:85–87.
30. Lao, Y., Y. Dong, Y. Shi, Y. Wang, S. Xu, J. Xue, and X. Zhang. 2021. Evaluation of drought tolerance in maize inbred lines selected from the Shaan A group and Shaan B group. Agriculture 12:11. https://doi.org/10.3390/agriculture12010011
31. Mahmood, N., M. Arshad, H. Kächele, H. Ma, A. Ullah, and K. Müller. 2019. Wheat yield response to input and socioeconomic factors under changing climate: Evidence from rainfed environments of Pakistan. Science of the Total Environment 688:1275–1285.
32. Moradi, H., G.A. Akbari, S.K. Khorasani, and H.A. Ramshini. 2012. Evaluation of drought tolerance in corn (Zea mays L.) new hybrids using stress tolerance indices. European Journal of Sustainable Development 1:543. https://doi.org/10.14207/ejsd.2012.v1n3p543
33. Mubushar, M., S. El-Hendawy, M.U. Tahir, M. Alotaibi, N. Mohammed, Y. Refay, and E. Tola. 2022. Assessing the suitability of multivariate analysis for stress tolerance indices, biomass, and grain yield for detecting salt tolerance in advanced spring wheat lines irrigated with saline water under field conditions. Agronomy 12:3084.
34. Muhammad, B., J. Khan, A.R. Reki, N. Khan, M. Sharif, M. Waris, and N. Sadiq. 2025. Wheat productivity improvement through spike fertility as selection criteria under terminal drought stress conditions. Planta Animalia 4:97–105. https://doi.org/10.71454/pa.004.01.0064
35. Mujtaba, S.M., S. Faisal, M.A. Khan, S. Mumtaz, and B. Khanzada. 2016. Physiological studies on six wheat (Triticum aestivum L.) genotypes for drought stress tolerance at seedling stage. Agricultural Research and Technology Open Access Journal 1:001–005. https://doi.org/10.19080/artoaj.2016.01.555559
36. Naveed, M., M. Aslam, S.R. Ahmed, D.K.Y. Tan, F. De Mastro, M.S. Tariq, and Y. Liu. 2025. An overview of heat stress in chickpea (Cicer arietinum L.): Effects, mechanisms and diverse molecular breeding approaches for enhancing resilience and productivity. Molecular Breeding 45:18. https://doi.org/10.1007/s11032-025-01538-4
37. Nawaz, H., J. Khan, Z.U. Malghani, S.R. Ahmed, A.R. Reki, M.A. Khetran, and B. Ali. 2025. Evaluating the performance of wheat germplasm under drought using morphological and physiological traits. Indus Journal of Biosciences and Research 3:67–75.
38. Naz, F., G.H. Dars, K. Ansari, S. Jamro, and N.Y. Krakauer. 2020. Drought trends in Balochistan. *Water* 12:470. https://doi.org/10.3390/w12020470
39. Poudel, P.B., M.R. Poudel, and R.R. Puri. 2021. Evaluation of heat stress tolerance in spring wheat (*Triticum aestivum* L.) genotypes using stress tolerance indices in western region of Nepal. *Journal of Agriculture and Food Research* 5:100179.
40. Rijal, R.B., P. Bashyal, D.R. Yadav, K. Upadhyay, K.R. Pant, and N.R. Adhikari. 2024. Assessing drought tolerance in advance wheat genotypes using stress tolerance indices. *Archives of Agriculture and Environmental Science* 9:336–344. https://doi.org/10.26832/24566632.2024.0902019
41. Rosielle, A.A., and J. Hamblin. 1981. Theoretical aspects of selection for yield in stress and non-stress environment. *Crop Science* 21:943–946.
42. Sarto, M.V.M., J.R.W. Sarto, L. Rampim, J.S. Rosset, D. Bassegio, P.F. da Costa, and A.M. Inagaki. 2017. Wheat phenology and yield under drought: a review. *Australian Journal of Crop Science* 11:941–946. https://doi.org/10.21475/ajcs.17.11.08.pne351
43. Sedghiyeh, V., F. Shekari, A. Abbasi, N. Sabaghnia, and M. Roustaii. 2025. Evaluation of drought tolerance ability in wheat genotypes through comprehensive stress indices. *HAYATI Journal of Biosciences* 32:117–131.
44. Shahi, D., J. Guo, M.A. Babar, S. Pradhan, M. Avci, N. Khan, and J. Khan. 2024a. Deciphering the genetic basis of novel traits that discriminate useful and non-useful biomass to enhance harvest index in wheat. *The Plant Genome* 17:20512. https://doi.org/10.1002/tpg2.20512
45. Shahi, D., J. Guo, S. Pradhan, J. Khan, M. Avci, N. Khan, and M.A. Babar. 2022. Multi-trait genomic prediction using in-season physiological parameters increases prediction accuracy of complex traits in US wheat. *BMC Genomics* 23:298.
46. Shahi, D., J. Guo, S. Pradhan, M. Avci, G. Bai, J. Khan, and M.A. Babar. 2024b. Genome-wide association study and genomic prediction of soft wheat end-use quality traits under post-anthesis heat-stressed conditions. *Biology* 13:962. https://doi.org/10.3390/biology13120962
47. Shahrokhi, M., S.K. Khorasani, and A. Ebrahimi. 2020. Evaluation of drought tolerance indices for screening some of super sweet maize (*Zea mays* L. var. *saccharata*) inbred lines. *AGRIVITA Journal of Agricultural Science* 42:435–448.
48. Shiferaw, B., M. Smale, H.J. Braun, E. Duveiller, M. Reynolds and G. Muricho. 2013. Crops that feed the world 10. Past successes and future challenges to the role played by wheat in global food security. Food Security 5:291–317. https://doi.org/10.1007/s12571-013-0263-y
49. Shivramakrishnan, R., R. Vinoth, A.J. Arora, G.P. Singh, B. Kumar and V.P. Singh. 2016. Characterization of wheat genotypes for stay green and physiological traits by principal component analysis under drought condition. International Journal of Agricultural Sciences 12:245–251. https://doi.org/10.15740/has/ijas/12.2/245-251
50. Singh, G., P. Kumar, V. Gupta, B.S. Tyagi, C. Singh, A.K. Sharma and G.P. Singh. 2018. Multivariate approach to identify and characterize bread wheat (Triticum aestivum) germplasm for waterlogging tolerance in India. Field Crops Research 221:81–89. https://doi.org/10.1016/j.fcr.2018.02.019
51. Sofi, P.A., S. Shafi, B. Singh, J.P. Jaiswal, V.K. Mishra and R.R. Mir. 2021. Combined selection for productivity and resilience through modified stress tolerance indices in a HUW-234 × HUW-468 derived wheat (Triticum aestivum L.) RIL mapping population for heat stress. Electronic Journal of Plant Breeding 12:612–622. https://doi.org/10.37992/2021.1203.087
52. Spinoni, J., G. Naumann, J. Vogt and P. Barbosa. 2015. European drought climatologies and trends based on a multi-indicator approach. Global and Planetary Change 127:50–57. https://doi.org/10.1016/j.gloplacha.2015.01.012

53. Thanaa, H., E.A.M. Abd El-Monem and M.N.A. El-Keredy. 2019. Tolerance indices and cluster analysis to evaluate some bread wheat genotypes under water deficit conditions. Alexandria Journal of Agricultural Sciences 64:245–256. https://doi.org/10.21608/alexja.2019.70638
54. Ulukan, H. 2024. Wheat production trends and research priorities: a global perspective. In: Advances in Wheat Breeding: Towards Climate Resilience and Nutrient Security. Springer, Singapore:1–22. https://doi.org/10.1007/978-981-99-9478-6_1
55. Wang, J.Y., Y.C. Xiong, F.M. Li, K.H. Siddique and N.C. Turner. 2017. Effects of drought stress on morphophysiological traits, biochemical characteristics, yield, and yield components in different ploidy wheat: a meta-analysis. Advances in Agronomy 143:139–173. https://doi.org/10.1016/bs.agron.2017.01.002
56. Wen, P., Y. Meng, C. Gao, X. Guan, T. Wang and W. Feng. 2023. Field identification of drought tolerant wheat genotypes using canopy vegetation indices instead of plant physiological and biochemical traits. Ecological Indicators 154:110781. https://doi.org/10.1016/j.ecolind.2023.110781
57. Yadav, S., V. Singh, H. Kesh, A. Naruka, M. Kumar, V.S. Mor and S. Yashveer. 2024. Morpho-physiological characterization and selection of heat tolerant wheat lines using selection indices. Electronic Journal of Plant Breeding 15:347–355. https://doi.org/10.37992/2024.1502.056