Research Article

Selection Under Stress: Assessing Wheat Genotypes for Drought Stress Resilience

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Abstract | Post-anthesis drought poses a significant threat to wheat productivity on a global scale. To assess the performance of wheat genotypes under differing moisture regimes, a study was conducted at Agricultural University, Peshawar, using 24 advanced wheat lines alongside four check cultivars grown in irrigated (normal) and rainfed (stress) conditions. All measured traits, except grain weight per seed, showed significant differences ($P \leq 0.01$) amid environments. There was also substantial genetic variation among the wheat lines for all traits with significant genotype × environment interactions, particularly for spike production and grain yield. Compared to irrigated conditions, rainfed conditions caused significant reductions in studied traits in all genotypes. This included a decrease of 117 spikes m^{-2}, 7.0 grains $spike^{-1}$, and a grain yield decline of 399 kg ha^{-1}. Our results revealed that three stress selection indices, mean productivity (MP), geometric mean productivity (GMP), and stress tolerance index (STI), were most efficient in identifying adaptable wheat varieties that performed well under both irrigated and rainfed conditions. Selection based on trait index (TI) demonstrated effectiveness solely for grains $spike^{-1}$ and 1000-grain weight under both conditions. On the contrary, selection based on tolerance (TOL) and trait stability index (TSI) proved most effective for grain yield, irrespective of the environmental conditions. These findings highlight the efficacy of TOL and TSI as primary criteria for genotype selection under irrigated conditions, whereas TI emerges as a appropriate criterion for rainfed environments.

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Introduction

Wheat production faces substantial constraints posed by drought stress in various regions worldwide, including Pakistan (Ali-Dinar *et al.*, 2023). The severity and impact of drought are contingent upon factors such as rainfall patterns, soil attributes, and agronomic practices (Rajaram *et al.*, 1996). An optimal wheat genotype would demonstrate high yield potential under favourable soil moisture conditions while exhibiting minimal reductions in grain yield under water stress conditions (Hamam and Negim, 2014). However, the intricate interplay of physiological and morphological traits contributing to stress tolerance in wheat remains a challenge for breeders, necessitating the development of effective selection criteria (Ludlow and Muchow, 1990).

The imperative to develop cultivars resilient to drought stress is underscored by the critical need to enhance productivity in water-deficient regions (McWilliam, 1989). Nonetheless, progress in breeding drought-tolerant cultivars is hindered by a limited understanding of drought tolerance mechanisms and the absence of robust selection methodologies (Bruckner and Frohberg, 1987; Richards, 1996; Osakabe *et al.*, 2014). Strategies aimed at enhancing drought tolerance encompass selection in low-stress, high-stress, and combined stress and non-stress environments (Byrne *et al.*, 1995; Raza *et al.*, 2019). Notably, selection for high yield under optimal conditions is typically effective due to maximal genetic variation and minimal genotype-by-environment interactions (Richards, 1996). However, the lack of strong correlation between yield stability and overall yield implies that genotypes selected in optimal environments may not perform well under drought stress (Calhoun *et al.*, 1994; Cohen *et al.*, 2021).

Plant breeders have long struggled to improve yield under stressed and drought-prone conditions, with gains in favorable environments often outperforming those in drought-stressed ones (Richards *et al.*, 2002). Drought indices, which measure yield loss under drought compared to normal conditions, are crucial tools for identifying drought-tolerant genotypes across various crops (Mitra, 2001; Cook *et al.*, 2014). These indices typically classify genotypes based on their drought resistance or susceptibility (Fernandez, 1992). Drought resistance refers to a genotype's relative yield compared to others under the same drought stress, while drought susceptibility measures yield reduction under stress (Blum, 1988; Ray *et al.*, 2019). Indices like stress tolerance (TOL) and mean productivity (MP) capture yield differences between stress and non-stress environments. Additionally, the stress tolerance index (STI) provides a comprehensive evaluation of genotypes that maintain high yields under both conditions (Fernandez, 1992; Rosielle and Hamblin, 1981).

Considering these challenges and opportunities, this study aims to evaluate genetic variability among 28 wheat genotypes and assess the efficacy of key selection indices for yield-related traits under both irrigated and rainfed environments.

Materials and Methods

Plant material

This study evaluated the performance of 28 wheat genotypes under irrigated and rainfed conditions. The experiment included 24 advanced breeding lines and four check cultivars as mentioned in Table 1. Check cultivars were chosen based on their existing recommendations for irrigated (Saleem, 2000; Pirsabak, 2008), rainfed (Suleman, 1996), and both environments (Pirsabak, 2005). This facilitated comparisons within and across recommended categories.

Table 1: *List of wheat lines and cultivars used in the study.*

S. No	Genotypes	S. No	Genotypes
1	B-IV (N) 1	15	B-RF 7
2	B-IV (N) 11	16	B-RF 8
3	B-IV (N) 16	17	B-RF 15
4	B-IV (N) 17	18	B-RF 17
5	B-VI (N) 3	19	SAWYT 50
6	B-VI (N) 5	20	B-II (N) 1
7	B-VI (N) 6	21	B-II (N) 3
8	B-VI (N) 8	22	B-III (N) 17
9	B-VI (N) 9	23	B-IV (N) 6
10	B-VI (N) 12	24	B-IV (N) 10
11	B-VI (N) 16	25	Saleem-2000
12	B-VI (N) 17	26	Pirsabak-2005
13	B-RF 1	27	Pirsabak-2008
14	B-RF 3	28	Suleman-96

Experimental design

A randomized complete block design (RCBD) with three replicates was used for both irrigated and rainfed conditions. To minimize environmental variation, both experiments were conducted in the same field. The rainfed plots received no supplemental irrigation throughout the growing season. Each plot consisted of three rows, each measuring 3 meters long and space out 0.30 meters apart. Planting was carried out on October 29^{th} using a hand hoe with a seeding rate of 110 kg ha^{-1}.

Fertilization

Fertilization practices mimicked those commonly used in irrigated and rainfed agriculture. Irrigated plots received split applications of nitrogen (N) and phosphorus (P) at a rate of 120:60 kg ha^{-1}. Rainfed plots received a single, basal application of N and P with a ratio of 60:30 kg ha^{-1} at sowing time.

Data collection

Data on yield related traits that were expected to get affected more severely by drought tolerance was recorded following the standard procedure. The traits studied were Spikes m^{-2}, Grains $spike^{-1}$, 1000-grain weight (g) and Grain yield (kg ha^{-1}). All traits were measured following standard protocols to ensure consistency and accuracy. Quantitative traits like spikes m^{-2}, grains $spike^{-1}$, and 1000-grain weight were measured directly and recorded as their numerical values. Grain yield was also recorded as a numerical value in kilograms per hectare. No additional scoring was applied to these quantitative traits.

Statistical analysis

A mixed-effects model was used to analyze the data, considering production systems as fixed effects and replications and genotypes as random effects. This approach accounts for genotype by environment interactions (G×E), crucial for identifying genotypes with stable performance across diverse environments.

Selection indices

The irrigated and rainfed environments were considered non-stress and stress conditions, respectively, for calculating the following selection indices:

Stress tolerance (TOL): TOL refers to the difference in yield between rainfed (stress) and irrigated (non-stress) environments. Tolerance (TOL) = X_I - X_R (Rosielle and Hamblin, 1981; Hossain *et al*., 1990).

Mean productivity (MP): MP refers to the average yield across rainfed and irrigated environments mean productivity (MP) = $X_I + X_R/2$ (Rosielle and Hamblin, 1981; Hossain *et al*., 1990).

Stress tolerance index (STI): Integrates yield under stress and non-stress conditions to identify genotypes with consistent performance.

Stress tolerance index (STI)=X_I+$X_R/(\bar{X_I})^2$ (Fernandez, 1992)

Geometric mean productivity (GMP): Reflects geometric mean of yield across stress and non-stress environments, emphasizing performance under stress.

Geometric Mean Productivity (GMP)= $\sqrt{X_I \times X_R}$ (Fernandez, 1992; Sivasankar *et al*., 1998)

Trait index (TI): The trait index (TI) is a selection index that combines information from multiple agronomic traits relevant to drought tolerance. Trait index (TI) = + $X_R/\bar{X_R}$ (Gavuzzi *et al*., 1997)

The trait stability index (TSI): Measures the stability of a genotype's performance across different environments. It indicates how consistent a genotype is in expressing a particular trait, regardless of environmental fluctuations.

Trait stability index: (TSI) = $X_R + X_I$ (Boulsama and Schapaugh, 1984)

Where; X_I = This represents the average value (mean) of a specific trait for a particular genotype when grown under irrigated conditions.

X_R = This represents the average value (mean) of a specific trait for a particular genotype when grown under rainfed conditions.

$\bar{X_I}$ = This represents the grand mean of a specific trait under irrigated conditions.

$\bar{X_R}$ = This represents the grand mean of a specific trait under rainfed conditions.

Evaluation of selection indices

Correlation analysis was used to evaluate the effectiveness of different selection indices in identifying elite lines in heterogeneous environments. This technique, as described by Mardeh *et al*. (2006), examines the relationship between individual indices and their performance in irrigated and rainfed conditions. By analyzing these relationships, we aimed to identify the most effective selection indices for selection of elite lines under both environments.

Results and Discussion

Spikes m^{-2}

Spikes m^{-2} stands as a pivotal trait influencing wheat yield, directly correlating with yield per hectare.

Table 2: *Mean squares for spikes m^{-2}, grains spike^{-1}, 1000-grain weight and grain yield of 28 wheat genotypes across two environments (irrigated and rainfed) at The Agriculture University, Peshawar.*

Sources	Degrees of freedom	Spikes m^{-2}	Grains spike^{-1}	1000-grain weight	Grain yield
Environments (E)	1	15812.57**	1981.72**	17.42^{NS}	17759302.88**
Reps w/n E	4	14963.94	528.65	224.85	87876.67
Genotypes (G)	27	573885.48**	155.29**	76.76**	402489.37**
G × E	27	10136.21**	84.9^{NS}	10.36^{NS}	216877.84**
Error	108	3622.37	61.51	19.71	234373.75
CV (%)	----	12.98	14.26	12.21	7.99

Drought conditions significantly impede spike development due to reduced moisture availability (Rickman and Klepper, 1991). Across both production systems, our combined analysis revealed notable differences among environments and genotypes vis-à-vis spikes m^{-2} (Table 2), indicative of genotype by environment interaction influencing spikes production consistency across environments. Notably, genotypes BRF8, BIV(N)1, and BIII(N)1 exhibited maximal spike production (744, 652 and 636 spikes m^{2}, respectively) under irrigated conditions, while under rainfed conditions, genotypes BIV(N)1, Suleman-96, and SAWT50 demonstrated the highest spike counts (491, 469 and 464 spikes m^{2}, respectively) as evident from Table 3.

We used selection indices to identify drought-tolerant genotypes through statistical relationship between favorable and unfavorable conditions. Genotypes BIV(N)1 and BRF8 showed good overall productivity performance, as reflected by their maximum mean productivity (MP), stress tolerance (STI) and geometric mean productivity (GMP) values. Conversely, TOL and TSI values identified only two wheat genotypes, BRF3 and BVI(N)17, as exhibiting enhanced adaptability to rainfed environments, signifying their stress tolerance. Genotypes BRF8, BIII(N)1, and BIV(N)16 exhibited maximum TOL and minimum TSI values, underscoring substantial differences in spikes production between the two production systems and highlighting the efficacy of TOL and TSI in selecting for stress tolerance. Moreover, genotype BIV(N)1, SAWT50, and BIV(N)11 demonstrated maximal trait index (TI) values under stress conditions, suggesting their superior performance in spikes m^{-2} under stress environments.

Correlations calculated for spikes m^{-2} between irrigated and rainfed production systems were negligible, affirming the existence of genotype by environment interaction (Table 7). Strong positive correlations ($P \leq 0.05$) between spikes m^{-2} and MP, GMP, and STI under both environments underscored the utility of these indices in identifying high-yielding genotypes across diverse conditions. These findings align with previous studies by Mardeh *et al.* (2006) and Pireivatlou and Yazdansepas (2008), corroborating the efficacy of MP, GMP, and STI in discerning superior genotypes under both irrigated and rainfed conditions. While TOL and TSI exhibited positive and negative correlations ($P \leq 0.05$) with spikes m^{-2} under irrigated conditions, such correlations were absent under rainfed conditions. This discrepancy is consistent with findings by Pireivatlou and Yazdansepas (2008), emphasizing the potential of TOL-based selection for drought-tolerant genotypes at the expense of grain yield. Furthermore, TI displayed a strong positive correlation with spikes m^{-2} under rainfed conditions, underscoring its effectiveness in selecting genotypes under stressed environments, as suggested by previous researchers (Gavuzzi *et al.*, 1997; Mardeh *et al.*, 2006). These results underscore the importance of employing robust selection indices to identify wheat genotypes with enhanced drought tolerance and spikes production potential across diverse production environments.

Grains spike^{-1}

Grains spike^{-1} stands as a critical determinant of grain yield in wheat, with genotypes exhibiting stability in this trait across environments often displaying enhanced drought tolerance. Shpiler and Blum (1991) advocated for the prioritization of grains spike^{-1} as the primary selection criterion for developing high-yielding wheat varieties, although Riaz (2003) and Metura *et al.* (2023) emphasized the importance of considering grain weight in selection for overall grain yield. Analysis of genotypes and environments revealed significant differences in grains spike^{-1},

Table 3: *Means and selection indices for spikes m^{-2} of 28 genotypes evaluated under irrigated and rainfed environments at The Agriculture University, Peshawar.*

Genotypes	Irrigated	Rainfed	MP	GMP	TOL	STI	TI	TSI
BIV(N)1	652	491	572	566	161	1.18	1.21	0.75
BIV(N)11	526	448	487	485	78	0.86	1.11	0.85
BIV(N)16	556	336	446	432	220	0.68	0.83	0.60
BIV(N)17	476	393	435	433	82	0.69	0.97	0.83
BVI(N)3	601	409	505	496	192	0.90	1.01	0.68
BVI(N)5	524	413	469	465	111	0.79	1.02	0.79
BVI(N)6	497	410	454	452	87	0.75	1.01	0.82
BVI(N)8	547	441	494	491	106	0.89	1.09	0.81
BVI(N)9	519	379	449	443	140	0.72	0.94	0.73
BVI(N)12	414	328	371	368	86	0.50	0.81	0.79
BVI(N)16	374	350	362	362	24	0.48	0.86	0.94
BVI(N)17	391	400	395	395	-9	0.57	0.99	1.02
BRF1	464	442	453	453	22	0.75	1.09	0.95
BRF3	392	417	405	404	-24	0.60	1.03	1.06
BRF7	539	432	486	483	107	0.85	1.07	0.80
BRF8	744	389	566	538	355	1.06	0.96	0.52
BRF15	471	374	423	420	96	0.65	0.92	0.80
BRF17	471	312	391	383	158	0.54	0.77	0.66
SAWT50	532	464	498	497	68	0.91	1.15	0.87
BII(N)1	487	411	449	448	76	0.74	1.02	0.84
BII(N)3	514	409	461	458	105	0.77	1.01	0.80
BIII(N)1	636	343	490	467	292	0.80	0.85	0.54
BIV(N)6	591	420	505	498	171	0.91	1.04	0.71
BIV(N)10	567	413	490	484	154	0.86	1.02	0.73
Suleman-96	601	469	535	531	132	1.03	1.16	0.78
Saleem-2000	506	419	462	460	87	0.78	1.03	0.83
Pirsabak-2005	489	442	466	465	47	0.79	1.09	0.90
Pirsabak-2008	541	390	465	459	151	0.77	0.96	0.72
Mean	522 a	405 b						
LSD for G under each E	92.7	104.0						
LSD for G over E	68.9							
LSD for E	31.9							
LSD for G × E	45.1							

albeit with an absence of genotype × environment interaction (Table 2), implying consistent genotype rankings for this trait across production systems. These findings align with previous studies by Simane (1993) and Moral *et al*. (2003), highlighting grains spike^{-1} as a primary contributor to grain yield variation under different water regimes. Under irrigated conditions, genotypes BRF1 and BIV(N)3 exhibited maximal grains spike^{-1} of 81 and 77, while under rainfed conditions, genotypes BIV(N)11, Saleem-2000, and Pirsabak-2008 demonstrated the highest grain counts of 60, each (Table 4). Genotype BRF1 displayed superior performance across both environments, as evidenced by maximal mean productivity (MP), stress tolerance index (STI), and geometric mean productivity (GMP) values, consistent with the findings of Saba *et al*. (2001) advocating for STI, MP, and GMP as promising selection indices under stress. Notably, genotypes SAWT50 and BRF8 exhibited minimal tolerance to stress (TOL) and maximal stress

Table 4: *Means and selection indices for grains spike^{-1} of 28 genotypes evaluated under irrigated and rainfed environments at Khyber Pakhtunkhwa Agricultural University, Peshawar.*

Genotypes	Irrigated	Rainfed	MP	GMP	TOL	STI	TI	TSI
BIV(N)1	52	53	52	52	-0.33	0.79	1.01	1.01
BIV(N)11	67	60	63	63	6.27	1.15	1.16	0.91
BIV(N)16	63	57	60	60	6.20	1.03	1.10	0.90
BIV(N)17	51	46	49	49	4.33	0.68	0.89	0.91
BVI(N)3	77	50	63	62	27.20	1.10	0.96	0.65
BVI(N)5	64	54	59	58	9.80	0.98	1.03	0.85
BVI(N)6	52	46	49	49	5.60	0.69	0.89	0.89
BVI(N)8	45	51	48	48	-5.87	0.66	0.98	1.13
BVI(N)9	55	47	51	51	7.73	0.75	0.91	0.86
BVI(N)12	73	56	65	64	17.60	1.18	1.07	0.76
BVI(N)16	68	58	63	63	10.60	1.14	1.11	0.85
BVI(N)17	65	55	60	60	10.13	1.04	1.06	0.85
BRF1	81	55	68	66	25.87	1.27	1.05	0.68
BRF3	61	45	53	52	15.73	0.79	0.87	0.74
BRF7	41	47	44	44	-5.33	0.55	0.89	1.13
BRF8	41	53	47	47	-11.67	0.63	1.02	1.28
BRF15	75	45	60	58	30.33	0.97	0.86	0.60
BRF17	55	56	55	55	-0.80	0.88	1.07	1.01
SAWT50	31	50	41	39	-19.07	0.45	0.96	1.62
BII(N)1	60	46	53	53	14.00	0.80	0.89	0.77
BII(N)3	55	49	52	52	5.33	0.78	0.95	0.90
BIII(N)1	52	52	52	52	0.60	0.77	0.99	0.99
BIV(N)6	73	56	64	64	17.27	1.16	1.07	0.76
BIV(N)10	51	44	48	48	6.67	0.65	0.85	0.87
Suleman-96	56	47	51	51	9.53	0.75	0.90	0.83
Saleem-2000	71	60	65	65	10.27	1.22	1.16	0.85
Pirsabak-2005	53	45	49	49	7.40	0.69	0.87	0.86
Pirsabak-2008	64	60	62	62	4.00	1.09	1.15	0.94
Mean	59 a	52 b						
LSD for G under each E	14.7	10.7						
LSD for G over E	9.0							
LSD for E	2.9							
LSD for G × E	NS							

tolerance index (TSI) values, respectively, indicative of their superior performance under stress conditions. Conversely, genotype BIV(N)11 demonstrated the highest trait index (TI) value, suggesting its potential for improving grains spike^{-1} across both production systems.

Significantly, positive correlations for grains spike^{-1} was observed between the two production environments (Table 7) underscored environmental differences influencing this trait. Strong correlations of grains spike^{-1} with STI, MP, GMP under both environments highlighted their effectiveness in selecting desirable genotypes. Conversely, TOL and TSI exhibited strong positive and negative correlations, respectively, with grains spike^{-1} under irrigated conditions, but were not significantly correlated under rainfed conditions. This indicates that selection based on TOL and TSI may not effectively improve grains spike^{-1} under drought stress conditions. However, TI showed strong positive correlations with grains spike^{-1} under both production systems, suggesting its potential for enhancing this

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Table 5: *Means and selection indices for 1000-grain weight (g) of 28 genotypes evaluated under irrigated and rainfed environments at The Agriculture University, Peshawar.*

Genotypes	Irrigated	Rainfed	MP	GMP	TOL	STI	TI	TSI
BIV(N)1	35.29	34.21	34.75	34.7	1.09	0.93	0.93	0.97
BIV(N)11	34.22	37.00	35.61	35.6	-2.79	0.98	1.01	1.08
BIV(N)16	32.67	31.35	32.01	32.0	1.31	0.79	0.85	0.96
BIV(N)17	39.51	40.49	40.00	40.0	-0.98	1.23	1.10	1.02
BVI(N)3	34.15	35.10	34.63	34.6	-0.96	0.92	0.96	1.03
BVI(N)5	36.76	36.86	36.81	36.8	-0.10	1.05	1.00	1.00
BVI(N)6	37.89	36.70	37.30	37.3	1.19	1.07	1.00	0.97
BVI(N)8	36.67	36.24	36.45	36.5	0.44	1.03	0.99	0.99
BVI(N)9	37.96	33.38	35.67	35.6	4.59	0.98	0.91	0.88
BVI(N)12	41.52	43.41	42.46	42.5	-1.89	1.39	1.18	1.05
BVI(N)16	39.96	39.06	39.51	39.5	0.90	1.20	1.06	0.98
BVI(N)17	35.62	38.53	37.08	37.0	-2.90	1.06	1.05	1.08
BRF1	36.78	33.99	35.39	35.4	2.79	0.96	0.93	0.92
BRF3	41.87	40.55	41.21	41.2	1.32	1.31	1.10	0.97
BRF7	32.22	35.29	33.75	33.7	-3.07	0.88	0.96	1.10
BRF8	38.04	38.22	38.13	38.1	-0.17	1.12	1.04	1.00
BRF15	40.80	37.06	38.93	38.9	3.73	1.17	1.01	0.91
BRF17	33.96	38.04	36.00	35.9	-4.09	1.00	1.04	1.12
SAWT50	38.20	35.07	36.64	36.6	3.13	1.03	0.96	0.92
BII(N)1	38.63	38.52	38.58	38.6	0.10	1.15	1.05	1.00
BII(N)3	31.32	34.25	32.78	32.8	-2.94	0.83	0.93	1.09
BIII(N)1	31.18	33.87	32.52	32.5	-2.68	0.81	0.92	1.09
BIV(N)6	31.22	33.43	32.33	32.3	-2.22	0.81	0.91	1.07
BIV(N)10	33.65	32.93	33.29	33.3	0.71	0.86	0.90	0.98
Suleman-96	37.20	38.82	38.01	38.0	-1.63	1.11	1.06	1.04
Saleem-2000	28.41	32.91	30.66	30.6	-4.50	0.72	0.90	1.16
Pirsabak-2005	42.93	49.62	46.27	46.1	-6.69	1.64	1.35	1.16
Pirsabak-2008	30.43	32.18	31.31	31.3	-1.75	0.76	0.88	1.06
Mean	36.04a	36.68a						
LSD for G under each E	6.1	8.3						
LSD for G over E	5.1							
LSD for E	1.0							
LSD for G × E	3.3							

trait. These findings emphasize the importance of selecting appropriate indices for effectively improving grains spike^{-1} under diverse production environments.

1000-grain weight

Grain weight stands as a fundamental yield component in wheat, albeit susceptible to adverse effects under drought stress conditions, where genotypes may exhibit decreased grain weight compared to irrigated conditions (Riaz, 2003). While some studies suggest that grain weight remains unaffected by stress environments (Kirigwi *et al*., 2004; Afiuni *et al*., 2006), our study did not reveal significant differences in grain weight between the two environments (Table 2). Despite significant differences among genotypes for grain weight, genotype × environment interaction was non-significant, indicating consistent genotype rankings for 1000-grain weight across environments (Woźniak *et al*., 2017). This aligns with findings reported by Mardeh *et al*. (2006), highlighting the stability of grain weight in wheat across diverse production conditions.

Across all 28 wheat genotypes, there was no significant difference in average 1000-grain weight between irrigated (36.04 g) and rainfed (36.68 g) conditions. This suggests minimal impact of drought stress on grain size. The slight increase in rainfed grain weight might be due to a three-day extension in grain filling compared to irrigated environments. Genotypes

Table 6: *Means and selection indices for grain yield (kg ha^{-1}) of 28 genotypes evaluated under irrigated and rainfed environments at The Agriculture University, Peshawar.*

Genotypes	Irrigated	Rainfed	MP	GMP	TOL	STI	TI	TSI
BIV(N)1	2963	2930	2947	2947	33	0.95	1.06	0.99
BIV(N)11	4410	2885	3647	3567	1525	1.40	1.05	0.65
BIV(N)16	2864	2083	2473	2442	781	0.66	0.76	0.73
BIV(N)17	3207	2969	3088	3086	238	1.05	1.08	0.93
BVI(N)3	2778	2728	2753	2753	50	0.83	0.99	0.98
BVI(N)5	3235	2829	3032	3025	406	1.01	1.03	0.87
BVI(N)6	3123	2435	2779	2758	689	0.84	0.88	0.78
BVI(N)8	3429	2550	2990	2957	879	0.96	0.93	0.74
BVI(N)9	3446	2160	2803	2728	1286	0.82	0.78	0.63
BVI(N)12	3185	3300	3243	3242	-115	1.15	1.20	1.04
BVI(N)16	2742	2527	2635	2633	215	0.76	0.92	0.92
BVI(N)17	2846	2607	2726	2724	239	0.81	0.95	0.92
BRF1	3420	2903	3161	3151	517	1.09	1.05	0.85
BRF3	3148	4007	3578	3552	-859	1.39	1.46	1.27
BRF7	2857	2590	2723	2720	267	0.81	0.94	0.91
BRF8	2639	2325	2482	2477	314	0.67	0.84	0.88
BRF15	2706	2496	2601	2599	210	0.74	0.91	0.92
BRF17	2867	2750	2808	2807	117	0.87	1.00	0.96
SAWT50	3349	2776	3062	3049	573	1.02	1.01	0.83
BII(N)1	3457	3236	3346	3344	221	1.23	1.18	0.94
BII(N)3	3355	2604	2980	2956	751	0.96	0.95	0.78
BIII(N)1	3000	2317	2658	2636	683	0.76	0.84	0.77
BIV(N)6	3260	2932	3096	3091	328	1.05	1.06	0.90
BIV(N)10	2802	2541	2672	2668	262	0.78	0.92	0.91
Suleman-96	3286	2389	2837	2802	897	0.86	0.87	0.73
Saleem-2000	3669	2775	3222	3191	894	1.12	1.01	0.76
Pirsabak-2005	3107	3570	3339	3331	-463	1.22	1.30	1.15
Pirsabak-2008	3108	2858	2983	2980	250	0.98	1.04	0.92
Mean	3152 a	2753 b						
LSD for G under each E	391	381						
LSD for G over E	270							
LSD for E	189							
LSD for G × E	177							

BRF3 and BVI(N)12 consistently produced the heaviest grains under both irrigated (41.9 and 41.5 g) and rainfed (40.5 and 43.4 g) conditions, respectively (Table 5). These genotypes, along with BIV(N)17, also displayed the highest values for several selection indices: mean productivity (MP), geometric mean productivity (GMP), stress tolerance index (STI), and trait index (TI). Notably, their performance surpassed three out of the four check cultivars. This indicates their suitability for both irrigated and rainfed environments in terms of grain weight. Notably, genotypes BRF17, BRF7, and BII(N)3 showed promising values for tolerance (TOL) and stress tolerance index (TSI), outperforming two of the check cultivars.

The strong correlation between grain weight under irrigated and rainfed conditions suggests minimal genotype-by-environment interaction for this trait. This is further supported by the positive correlations between MP, GMP, STI, and TI with grain weight under both environments. These findings highlight the effectiveness of these indices in selecting superior genotypes for grain weight across different water availability conditions. Conversely, tolerance (TOL) showed no significant relationship with grain weight under either irrigation or rainfed conditions. Furthermore, TSI displayed a negative correlation with grain weight under irrigated conditions. This limited or absent relationship suggests that TOL and TSI might not be ideal for identifying superior genotypes solely based on grain weight under this condition. However, integration of advanced techniques with robust selection indices can accelerate the development of drought-tolerant wheat varieties with enhanced grain weight, thereby contributing to global food security in the face of climate change challenges.

Table 7: *Correlation among production systems and stress selection indices for yield associated traits in 28 wheat genotypes evaluated at The Agriculture University, Peshawar.*

Selection Indices	Irrigated	Rainfed	Irrigated	Rainfed
	Spikes m^{-2}		Grains $spike^{-1}$	
Rainfed	0.26 NS		0.40*	--
MP	0.91**	0.64**	0.95**	0.67**
GMP	0.86**	0.72**	0.94**	0.69**
TOL	0.86**	-0.26 NS	0.90**	-0.03NS
STI	0.86**	0.71**	0.93**	0.71**
TI	0.27NS	1.00**	0.40*	0.99**
TSI	-0.78**	0.37NS	-0.85**	0.05 NS
	1000-grain weight		Grain yield	
Rainfed	**0.76****	--	**0.22NS**	
MP	0.94**	0.94**	0.75**	0.81**
GMP	0.94**	0.94**	0.71**	0.84**
TOL	0.33 NS	-0.36 NS	0.56**	-0.68**
STI	0.92**	0.95**	0.71**	0.84**
TI	0.76**	1.00**	0.22 NS	1.00**
TSI	-0.42*	0.27NS	-0.43*	0.78**

Grain yield

Grain yield displayed significant variations across genotypes, environments (irrigated vs rainfed), and their interaction (Table 2). This highlights a critical point: genotypes excelling under ideal conditions (irrigated) may not perform well under stress (rainfed). This aligns with previous research by Talebi *et al*. (2009) who observed similar variations in wheat genotypes under different water regimes.

Under irrigated conditions, genotypes BIV(N)11, BII(N)1, and BVI(N)9 emerged as the highest yielders with per unit yield of 4410, 3457 and 3446 kg ha^{-1}, respectively (Table 6), surpassing three of the check cultivars. Conversely, under rainfed conditions, BRF3, BVI(N)12, and BII(N)1 excelled with 4007, 3300 and 3236 kg ha^{-1}, respectively, again outperforming three of the check cultivars specific to that environment. Genotype BIV(N)11 stood out with the highest values for mean productivity (MP), geometric mean productivity (GMP), and stress tolerance index (STI), indicating its adaptability and strong performance across both irrigation and rainfed conditions. Interestingly, genotype BRF3 displayed promising values for tolerance (TOL), stress tolerance index (TSI), and trait index (TI), suggesting its stability and resilience under stress. This aligns with Sadiq *et al*. (1994) who emphasized that stress performance reflects both yield potential and stress response. Additionally, Naserian *et al*. (2007) highlighted that yield reduction under stress depends on the genotype and the timing of stress during the growth cycle.

The inconsistent performance of genotypes across environments was further confirmed by the lack of correlation between grain yield in irrigated and rainfed conditions. Interestingly, grain yield showed positive and significant correlations with all stress indices except TOL under rainfed conditions, where TOL exhibited a strong negative relationship. This trend continued with MP, GMP, TOL, and STI demonstrating strong positive correlations ($P \leq 0.01$) with grain yield under rainfed conditions, while TSI exhibited a negative correlation. Notably, TI showed no relationship with grain yield under irrigated conditions. Except for TI, all selection indices displayed desirable correlations with grain yield under both environments. This suggests that selection based on any index (except TI) could lead to improvements. However, TI appears to be most relevant for enhancing grain yield specifically under stress conditions.

Recent studies by Mickelbart *et al*. (2015) and Vassileva *et al*. (2023) have further elucidated the complex mechanisms underlying genotype responses to stress and their implications for grain yield. Integration of these insights with robust selection indices can aid in the development of wheat varieties with enhanced yield stability across diverse environmental conditions, contributing to global food security in the face of climate change-induced challenges.

Conclusions and Recommendations

The study investigates the performance of wheat genotypes, particularly under drought stress, yielding valuable insights into key traits like spikes m^{-2}, grains spike^{-1}, 1000-grain weight, and grain yield across different genotypes and production systems. Variations in responses to stress were observed among genotypes for spikes m^{-2}, with certain ones excelling under irrigated or rainfed conditions. Selection indices such as stress tolerance index (STI), mean productivity (MP), and geometric mean productivity (GMP) effectively categorized genotypes with enhanced drought tolerance and spikes production potential. Similarly, consistent performance across environments was observed for 1000-grain weight, suggesting its stability in wheat across environments. The study underscores the significance of robust selection indices and breeding strategies in developing drought-tolerant wheat varieties resilient to changing climates.

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Novelty Statement

This study proposes TOL (tolerance) and TSI (trait stability index) as novel selection methods for wheat genotypes that maintain grain yield under both well-watered and drought conditions, while TI (trait index) is more effective for rainfed environments.

Author's Contribution

Ihteram Ullah and Iftikhar Hussain Khalil: Planned the experiment. Moreover, Ihteram Ullah wrote draft of the manuscript.
Said Salman and Nasir Mehmood: Analyzed the data.
Abdul Majida and Syed Noor M. Shah: Helped in editing of the manuscript.

Conflict of interest
The authors have declared no conflict of interest.

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