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DROUGHT TOLERANCE IN WHEAT USING STRESS SELECTION INDICES

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ABSTRACT

Drought is one of the most limiting abiotic stresses affecting wheat crops. It is a significant abiotic factor affecting the yield and yield stability of cereal crops, and it simultaneously affects many traits leading to yield reduction. The current research was conducted at the University of Agriculture, Peshawar, during 2021-2022. Twenty wheat genotypes, including two checks, Khaista and Wadan, were evaluated in RCBD under irrigated and rainfed environments for genetic variability, drought tolerance indices, and broad-sense heritability of various traits. Analysis of variance revealed highly significant variation among genotypes for spike length, biological yield, grain yield, and harvest index, while significant variations were observed for spikes m^{-2}, spikelets $spike^{-1,}$ and 1000-grain weight. Significant genotype × environment interaction was observed for all the studied traits. Different tolerance indices, like MP (mean productivity), GMP (geometric mean productivity), TOL (tolerance), SSI (stress susceptibility index), YI (yield index), YSI (yield stability index), and RDI (relative drought index) were estimated based on yield in irrigated and rainfed conditions. Under an irrigated environment, the highest yield was recorded for G-163 (5700.0 kg ha^{-1}) and G-155 (5570.8 kg ha^{-1}), while under a rainfed environment, Wadan (5161.1 kg ha^{-1}) and G-163 (4852.8 kg ha^{-1}) were the highest yielding genotypes. Under an irrigated environment, heritability was high for biological yield (0.71) and harvest index (0.77). Under a rainfed environment, heritability was high for grain yield (0.69) and harvest index (0.77), while

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low heritability was observed for spikelets spike^{-1} (0.22). GMP and MP had a positive, highly significant correlation with all the productive traits under both environments, thus it will be more useful for trait selection under rainfed and irrigated environments. YI was positive and highly significantly correlated with all yield contributing traits in rainfed conditions, thus YI would be a more reliable selection index in a rainfed environment. Wheat genotype G-163 showed the best performance under both tested conditions and can be recommended to be tested in further breeding programs for yield improvement.

Keywords: Wheat; G × E interaction; Tolerance indices; Heritability; Mean productivity; Geometric mean productivity.

INTRODUCTION

Wheat (*Triticum aestivum* L), with a chromosomal count of 2n = 42, is a cereal classified under the Poaceae family. It functions as a fundamental food source for communities throughout Europe, West Asia, and North Africa, and is the most widely farmed crop globally. The domestication of wheat began around 10,000 years ago, ultimately establishing it as a primary global food crop. Wheat is essential for fulfilling the protein and caloric needs of nearly one-third of the global population (Khan and Mohammad, 2018). During the 2020-2021 period, worldwide wheat production exceeded 778.6 million metric tons (Shahbandeh, 2022). In Pakistan, wheat cultivation encompassed 9.17 million hectares in 2021, resulting in a total production of 27.359 million tons. In the Khyber Pakhtunkhwa province, wheat production in 2020-21 amounted to 1.49 million tons (PBS, 2021).

Drought poses a considerable challenge to global crop production and is anticipated to intensify with ongoing global climate change (Akbarian *et al*., 2011). It is the primary environmental stressor impacting around 32% of the 99 million hectares allocated to wheat cultivation in developing countries and at least 60 million hectares in developed countries (Shamsi *et al*., 2011). Pakistan, as an agrarian economy, engages more than 50% of its labor force in agriculture. Wheat is a crucial crop, significantly contributing to the national economy and providing sustenance for both human and animal populations. The adverse impacts of drought stress during essential growth phases, including tillering, booting, anthesis, grain formation, and grain filling, substantially reduce wheat yield. This highlights the necessity for breeders to create varieties that can effectively endure drought stress (Mahpara *et al*., 2014). Drought presents significant challenges for plant breeders globally, with Pakistani scientists primarily concentrating on developing wheat lines for irrigated regions, while rainfed areas receive comparatively less attention. Research on drought predominantly focuses on field conditions characterized by inherent uncertainty and unpredictability, employing traditional methodologies.

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The selection of wheat cultivars according to their yield performance in drought conditions is a prevalent strategy. Consequently, numerous drought stress indices or selection criteria have been suggested by various researchers (Mehraban *et al*., 2018). The focus on yield performance in water stress conditions arises from the significant concern of yield losses for plant breeders (Farshadfar *et al*., 2012). Anwaar *et al*. (2020) employed drought-tolerant indices in wheat and found that under moderate stress, mean productivity (MP), geometric mean productivity (GMP), and stress tolerance index (STI) were notably effective in identifying high-yielding cultivars in both drought-stressed and irrigated environments. Under conditions of severe stress, none of the indices employed were capable of identifying a high-yielding cultivar group. Guttieri et al. (2001) utilized the stress susceptibility index (SSI) criterion, proposing that an SSI value greater than 1.0 signifies above-average susceptibility to drought stress, whereas an SSI value less than 1.0 indicates below-average susceptibility. Ali and El-Sadek (2016) determined that mean productivity (MP), geometric mean productivity (GMP), and stress tolerance index (STI) are the most effective indices for the selection of relatively tolerant lines.

Heritability, a metric of phenotypic variation attributable to genetic factors, serves a predictive function in crop breeding. An effective crop breeding program relies on estimating the potential genetic progress achievable through selection within specific populations (Khan *et al*., 2008).

Keeping in view the importance of wheat, this study was conducted to measure genotype by environment interaction for various morphological traits, to estimate broad sense heritability for various traits under irrigated and rainfed conditions, to determine different drought tolerance indices based on yield under irrigated and rainfed conditions, and to identify desirable genotypes under the two tested environments.

MATERIALS AND METHOD

The present study was conducted at Malakandher Research Farms of the Department of Plant Breeding and Genetics, The University of Agriculture, during the wheat growing season 2021-2022. Twenty bread wheat genotypes (18 advanced lines and 2 local check cultivars) were cultivated under normal (Irrigated) and drought (Rainfed) environments as independent experiments. The irrigated experiment got proper irrigation as per requirement throughout the season, but the rainfed experiment did not get any additional water. Both experiments were planted on November 3, 2021. Wheat Advance lines were obtained from CIMMYT (Table A). For each experiment randomize complete block design with 3 replications was used. Each genotype was planted in 4 rows of 3 m in length with a space of 30 cm. All the cultural and agronomic practices were adopted for both experiments as recommended for the wheat crop.

Data Collection

Data were noted on spikes m^{-2} spike spike length (cm), spikelets $spike^{-1}$, 1000-grain weight (g), biological yield (kg ha^{-1}), grain yield (kg ha^{-1}), and harvest index (%) Data were recorded on spikes m-2, spike length (cm), spikelets spike-1, 1000-grain weight (g), biological yield (kg ha^{-1}), grain yield (kg ha^{-1}) and harvest index (%) using the technique specified for each feature at the appropriate time.

Assessment of Heritability for Traits

Broad sense heritability for each parameter was determined according to the procedure used by Marwede *et al*. (2004).

Genotypic variance = V_g =, Environmental variance = V_e = EMS

Phenotypic variance = $V_p = V_g + V_e$, Heritability = $h^2_{bs} = V_g/V_p$

The genetic advance was calculated by using the following formula of Johnson *et al*. (1955):

$GA = K \times \sqrt{vp} \times h^2$ Where, K = Constant value at 10% selection intensity,

Vp = Phenotypic Variance,

h^2 = Heritability

Estimation of stress tolerance indices

The following stress tolerance indices were calculated by considering the irrigated environment as non-stress and the rainfed environment as a stress environment.

Stress susceptibility index

$SSI = (1-(Yr/Yi))/(1-((\bar{Y}r)/(\bar{Y}i)))$ (Talebi et al. 2009)

Mean productivity

$MP = (Yi+Yr)/2$ (Khayatnezhad et al. 2010)

Geometric mean productivity

$GMP = \sqrt{(Yi \times Yr)}$ (Golabadi et al. 2006)

Yield index

$YI = Yr/(\bar{Y}r)$ (Alla et al. 2019)

Tolerance

$TOL = Yi - Yr$ (Amare et al. 2019)

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Yield stability index

YSI =Yr/Yi   (Amare et al. 2019)

Relative drought index

RDI = ((Yr/Yi))/((Ȳr/Ȳi))   (Ali and El-Sadek. 2016)

Whereas;

Yi = Mean of the genotype of specific characteristics in an irrigated condition.

Yr = Mean of genotype of specific characteristics in a rainfed condition.

Ȳi = Grand mean for the genotype of specific characteristics in an irrigated condition.

Ȳr = Grand mean for the genotype of specific characteristics in a rainfed condition.

The approach of Mardeh et al. (2006) was used to calculate a correlation between two environments and various parameters using the indices mentioned above.

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Table A: List of wheat genotypes evaluated in the experiments during 2021-2022.

S. No	Genotypes	PARENTAGE
1	G 95	WBLL1/KUKUNA//TACUPETOF2001/3/BAJ#1*2/5/SERI.1B//KAUZ/HEVO/3/AMAD*2/4/KIRITATI
2	G 116	WAXWING/KIRITATI/6/PVN//CAR422/ANA/5/BOW/CROW//BUC/PVN/3/YR/4/TRAP#1/7/ SERI.1B//KAUZ/HEVO/3/AMAD*2/ 4/KIRITATI/8/ATTILA*2/PBW65*2/4/BOW/NKT//CBRD/3/CBRD
3	G 125	ATTILA*2/PBW65/5/CNO79//PF70354/MUS/3/PASTOR/4/BAV92/6/TRCH/SRTU// KACHU/7/UP2338*2/KKTS*2//YANAC
4	G 130	ROLF07/SAUAL*2/5/SERI.1B//KAUZ/HEVO/3/AMAD*2/4/KIRITATI
5	G 131	ROLF07/SAUAL*2/5/SERI.1B//KAUZ/HEVO/3/AMAD*2/4/KIRITATI
6	G 131	TACUPETOF2001/BRAMBLING/5/NAC/TH.AC//3*PVN/3/MIRLO/BUC/4/2*PASTOR*2/6/TRCH/SRTU//KACHU
7	G 144	KACHU/SAUAL*2/5/SERI.1B//KAUZ/HEVO/3/AMAD*2/4/KIRITATI
8	G 145	KACHU/SAUAL*2/5/SERI.1B//KAUZ/HEVO/3/AMAD*2/4/KIRITATI
9	G 147	KACHU/SAUAL*2/8/ATTILA*2/PBW65/6/PVN//CAR422/ANA/5/BOW/CROW//BUC/PVN/3/ YR/4/TRAP#1/7/ATTILA/2*PASTOR
10	G 148	KACHU/SAUAL*2/8/ATTILA*2/PBW65/6/PVN//CAR422/ANA/5/BOW/CROW/ /BUC/PVN/3/YR/4/TRAP#1/7/ATTILA/2*PASTOR
11	G 149	KACHU/SAUAL*2/8/ATTILA*2/PBW65/6/PVN//CAR422/ANA/5/BOW/ CROW//BUC/PVN/3/YR/4/TRAP#1/7/ATTILA/2*PASTOR
12	G 155	SAUAL/MUTUS*2/3/TRCH/SRTU//KACHU
13	G 159	SAUAL/MUTUS*2/3/TRCH/SRTU//KACHU
14	G 160	SAUAL/MUTUS*2/3/TRCH/SRTU//KACHU
15	G 163	SAUAL/MUTUS*2//PICAFLOR #1
16	G 197	BCN/RIALTO//2*MUNAL #1
17	G 202	SOKOLL/3/PASTOR//HXL7573/2*BAU/4/SOKOLL//PBW343*2/KUKUNA/3/ATTILA/PASTOR
18	G 206	PASTOR//HXL7573/2*BAU/3/SOKOLL/WBLL1/5/CROC_1/AE.SQUARROSA (213)//PGO/3/CMH81.38/2* KAUZ/4/BERKUT/6/W15.92/4/PASTOR//HXL7573/2*BAU/3/WBLL1
19	Local check Khaista	
20	Local check Wadan	

RESULTS AND DISCUSSION

The analysis of variance across multiple traits revealed significant differences among genotypes, environments, and genotype-by-environment (G×E) interactions, highlighting the influence of environmental conditions on wheat yield potential (Table 1). For spikes m^{-2}, significant genotypic differences were observed, with highly significant differences in environments and G×E interactions, aligning with the findings of Poudel *et al*. (2020). Spike length also showed highly significant differences among genotypes and environments, while G×E interactions were significant, consistent with Mwadzingeni *et al*. (2016) and Khan *et al*. (2010), who emphasized the importance of selecting genotypes with longer spikes to enhance grain yield. Similarly, spikelets spike^{-1} exhibited statistically significant variations for genotypes and G×E interactions, with environments showing highly significant differences, corroborating Chaudhary *et al*. (2022). For 1000-grain weight, both genotypic and G×E variations were significant, with highly significant differences observed between environments, in agreement with Esmail *et al*. (2016) and Khan *et al*. (2021). Biological yield also demonstrated highly significant differences among genotypes and environments, with G×E interactions being significant, supporting findings from Bayisa *et al*. (2020). Grain yield analysis revealed highly significant differences among genotypes and environments (irrigated and rainfed), with significant G×E interactions, aligning with the results of Elhani *et al*. (2007) and Bayisa *et al*. (2020). Finally, the harvest index displayed highly significant variation among genotypes, environments, and G×E interactions, further supported by Bayisa *et al*. (2020), emphasizing the importance of this trait in differentiating potential and actual yield in wheat crops.

Wheat genotypes revealed variation in multiple traits across irrigated and rainfed environments. For spikes m^{-2}, values ranged from 409.00 to 510.00 in the irrigated environment, with genotype G-155 showing the highest value (510.00) and G-159 the lowest (409.00), while in rainfed conditions, G-202 had the maximum spikes m^{-2} (483.00) and G-125 the minimum (350.00), with an overall reduction of 51.8 spikes in drought conditions (Table 3, Fig. 2). Spike length ranged from 9.33 to 12.17 cm in irrigated trials, with G-155 leading at 12.17 cm, and from 7.58 to 12.08 cm in rainfed trials, with local check Wadan showing the highest value (12.08 cm). A net reduction of 0.3 cm was observed in rainfed conditions (Table 4). For spikelets spike^{-1}, the irrigated environment saw ranges from 18.50 to 21.33, with G-134 and local check Khaista (21.33) performing best, whereas rainfed conditions ranged from 17.83 to 20.17, with Khaista maintaining its superior performance (20.17) (Table 5). The 1000-grain weight ranged from 39.77 to 45.80 g in irrigated conditions, with G-149 showing the maximum value (45.80 g), and from 34.17 to 42.12 g in rainfed environments, where G-202 (42.12 g) excelled. A reduction in the 1000-grain weight by 5.7 g was observed under rainfed conditions (Table 6). Biological yield in irrigated conditions ranged from 13,425.9 to 15,011.1 kg ha^{-1}, with G-144 having the highest yield, while rainfed conditions ranged from 12,591.1 to 13,935.1 kg ha^{-1}, with G-116 showing the highest yield. A total reduction of 998.4 kg ha^{-1} was recorded under

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rainfed conditions (Table 7). Grain yield varied between 4,814.8 and 5,700.0 kg ha^{-1} under irrigated conditions, with G-163 showing the maximum yield, while under rainfed conditions, it ranged from 4,031.4 to 5,161.1 kg ha^{-1}, with local check Wadan leading. A net reduction of 720.6 kg ha^{-1} in grain yield was recorded in rainfed conditions (Table 8). The harvest index ranged from 32.70 to 41.03% in irrigated conditions, with local check Wadan leading, and from 29.21 to 39.54% under rainfed conditions, with Wadan again showing the best performance, though a 2.67% decrease was noted in rainfed environments (Table 9).

The genotypic variances for spikes m^{-2} were 635.07 and 892.41, while environmental variances were 1210.21 and 595.07 under irrigated and rainfed environments, respectively. Moderate heritability (0.59) with a genetic advance of 40.60 was calculated for spikes m^{-2} under irrigated conditions, whereas a heritability of 0.34 and a genetic advance of 25.94 were recorded under rainfed conditions (Table 2, Fig. 1), consistent with the findings of Mason *et al*. (2013). Spike length showed genotypic and environmental variances of 0.33 and 0.23 under irrigated and 0.18 and 0.24 under rainfed environments, with moderate heritability (0.58) and a genetic advance of 0.78 in irrigated conditions, and heritability of 0.43 with a genetic advance of 0.49 under rainfed conditions (Table 2, Fig. 1), in agreement with Khan *et al*. (2021). Spikelets $spike^{-1}$ had genotypic and environmental variances of 0.60 and 0.56 in the irrigated environment, and 0.19 and 0.64 in the rainfed trial, with moderate heritability (0.51) and a genetic advance of 0.97 in irrigated conditions, and low heritability (0.22) with a genetic advance of 0.36 in rainfed trials (Table 2, Fig. 1), similar to results by Zemede *et al*. (2019). For 1000-grain weight, moderate heritability was calculated at 0.43 and 0.44 under irrigated and rainfed conditions, respectively, with genotypic variances of 2.82 and 2.84, and environmental variances of 3.73 and 3.55. The genetic advance was 1.93 g in the irrigated environment and 1.97 g under rainfed conditions (Table 2, Fig. 1), aligning with findings from Ikramullah *et al*. (2011) and Ghobadi *et al*. (2012). Biological yield revealed genotypic variances of 196395.10 and 132987.15, and environmental variances of 77506.30 and 92046.77 for irrigated and rainfed conditions, respectively. High heritability (0.71) was recorded for irrigated conditions, and moderate heritability (0.59) was observed for rainfed conditions, with genetic advances of 658.58 kg ha^{-1} and 491.99 kg ha^{-1}, respectively (Table 2, Fig. 1), comparable to results from Ikramullah *et al.* (2011). For grain yield, genotypic variances were 31988.40 and 56200.22, and environmental variances were 70772.32 and 24396.57 for irrigated and rainfed environments. Moderate heritability (0.31) and genetic advance (175.1 kg ha^{-1}) were calculated for irrigated conditions, while high heritability (0.69) and genetic advance (347.01 kg ha^{-1}) were observed under rainfed trials (Table 2, Fig. 1), consistent with findings from Mathew et al. (2018) and Ullah *et al*. (2014). The harvest index showed genotypic and environmental variances of 4.58 and 1.35 under irrigated conditions, and 4.19 and 1.20 under rainfed conditions, with high heritability (0.77) and genetic advances of 3.16 and 3.33, respectively, in line with the results from Gupta and Verma (2001) (Table 2, Fig. 1).

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The highest TOL value (110.00) was observed in genotype G-155, while the lowest value (-6.67) was recorded for G-131 (Table 8). Genotype G-159 showed the lowest MP (389.50) and GMP (389.01), whereas G-202 had the highest MP (492.50) and GMP (492.41). Anwar et al. (2011) suggested that tolerant genotypes can be selected based on high MP and GMP values alongside low SSI and TOL values. Maximum YI (1.14) was recorded for G-202, while G-125 showed the minimum (0.83). G-131 had the highest YSI (1.01) and RDI (1.14), with the lowest values of YSI (0.78) and RDI (0.88) recorded for G-155. Additionally, G-131 had the minimum SSI (-0.13), while G-155 had the highest SSI (1.98) (Table 3, Fig. 2), confirming that SSI is useful for identifying sensitive and resistant genotypes (Winter et al., 1988).

Genotype G-144 displayed the highest TOL (1.14) and SSI (3.86), while G-95 had the lowest TOL (-0.97) and SSI (-3.48). Genotypes with high TOL are generally more sensitive to drought stress, making lower TOL values more desirable (Noreldin & Mahmoud, 2017). Local check Wadan showed the highest MP (11.74), GMP (11.73), and YI (1.10), while G-116 had the lowest MP (9.46), GMP (9.46), and YI (0.87). The highest YSI (1.09) and RDI (1.12) were recorded for G-95, and the lowest YSI (0.90) and RDI (0.93) for G-144 (Table 4). As Farshadfar *et al*. (2012) explained, YSI is critical for identifying drought-resistant cultivars based on yield under rainfed conditions relative to irrigated ones. G-202 showed the lowest TOL (-1.13) and G-147 the highest (2.20) (Table 10). The most desirable genotype was local check Khaista, with the highest MP (20.75), GMP (20.74), and YI (1.07), while G-197 showed the lowest values (18.44, 18.43, and 0.94, respectively). Fernandez (1992) noted that GMP is less sensitive to extreme values, making it a better indicator than MP. G-202 exhibited the highest YSI (1.06), RDI (1.13), and the lowest SSI (-0.99), while G-206 had the lowest YSI (0.89), RDI (0.95), and highest SSI (1.74) (Table 5). Genotype G-148 had the highest TOL (10.50) and G-155 the lowest (2.15) (Table 13). High MP and GMP values were observed in G-202 (43.79 and 43.76), while G-130 displayed the lowest (37.05 and 36.94). The highest YI was observed in G-202 (1.13), and the lowest in G-147 (0.92). Mohammadi *et al*. (2010) emphasized that YI and YSI are effective for selecting genotypes that yield well in both drought and normal conditions. Local check Wadan had the highest YSI (0.95), RDI (1.09), and the lowest SSI (0.40), while G-148 exhibited the lowest YSI (0.77), RDI (0.89), and the highest SSI (1.76) (Table 6). Consistent with many researchers (Mursalova *et al*., 2015), local check Wadan had the lowest TOL (370.37), and G-148 the highest (1705.48). G-144 recorded the highest MP (14411.11), GMP (14398.62), and YI (1.04), while G-197 had the lowest values. Local check Wadan also had the highest YSI (0.97) and RDI (1.04), while G-148 had the lowest (0.88 and 0.95, respectively) (Table 7). The highest TOL was recorded in G-159 (1018.85) and the lowest in G-160 (231.48), with MP, GMP, and YI being the most reliable indices for evaluating grain yield under both conditions (Darzi-Ramandi *et al*., 2016). Akcura *et al*. (2011) emphasized that SSI is a useful index in severe stress conditions, while MP, GMP, and TOL are more reliable under mild stress. G-160 was the most desirable genotype with the lowest TOL (-1.12) and the highest MP (40.28), GMP (40.28), and YI (1.18). Conversely, G-131 had the lowest MP (30.96), GMP (30.91), and YI (0.87) (Table 9).

Non-significant correlations were found between irrigated and rainfed conditions for several traits, such as spikes m^{-2} (0.37^{NS}), spikelets $spike^{-1}$ (0.42^{NS}), and 1000-grain weight (0.42^{NS}). However, a significant correlation (0.53*) was observed for biological yield, grain yield (0.52*), spike length (0.53*), and harvest index (0.78**), indicating some consistency across environments. Under irrigated conditions, spikes m^{-2} showed positive, highly significant correlations with MP (0.82**) and GMP (0.80**), but significant negative correlations with YSI (-0.48*) and RDI (-0.50*), while under rainfed conditions, spikes m^{-2} had strong positive associations with MP (0.83**), GMP (0.85**), YSI (0.62**), and RDI (0.60**), and a negative correlation with TOL (-0.57**) and SSI (-0.62**) (Table 10, Fig. 3). Spike length had a highly significant correlation with MP and GMP (0.90**) in both irrigated and rainfed conditions, while TOL and YSI showed highly significant but opposite correlations under irrigated conditions (0.63** and -0.64**). However, under rainfed conditions, YI had a strong positive association (0.60**) with spike length. Similarly, spikelets $spike^{-1}$ showed positive, highly significant correlations with MP (0.89**), GMP (0.89**), and SSI (0.70**) under irrigated conditions but negative correlations with YSI (-0.70**) and RDI (-0.68**). Under rainfed conditions, spikelets $spike^{-1}$ was strongly correlated with MP (0.78**), GMP (0.78**), and YI (0.99**) (Table 10, Fig. 3). For 1000-grain weight, significant positive correlations with MP (0.84**) and GMP (0.81**) were observed under irrigated conditions, while TOL had a significant negative correlation (-0.53*) under rainfed conditions. Grain yield displayed significant positive correlations with MP (0.86**), GMP (0.84**), and YI (0.51*) under irrigated conditions. Under rainfed conditions, strong positive associations with MP (0.86**), GMP (0.89**), and YI (0.99**) were observed, with negative correlations with SSI (-0.63**) and TOL (-0.54*) (Table 10, Fig. 3). Harvest index demonstrated a significant positive correlation with MP and GMP under both environments (0.94**) and with YSI (0.47*) and RDI (0.47*) under rainfed conditions, while SSI showed a significant negative association (-0.47*). These results suggest that MP and GMP are reliable indicators of yield across both irrigated and rainfed environments, aligning with previous findings from Patel *et al*. (2017) and Ullah *et al*. (2014) (Table 10, Fig. 3).

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Table 1: Means squares of various parameters of 20 wheat genotypes across two environments

SOV	Envir. (1)	Reps (Env) (4)	Genotypes (19)	G×E (19)	Error (119)	CV (%)
Spikes m^{-2}	80491.44*	5082.8	4393.8*	1993.97**	902.64	6.7
Spike length	2.48**	0.1	1.56**	0.49*	0.24	4.39
Spikelets $spike^{-1}$	46.93**	0.55	2.51*	1.08*	0.61	3.98
1000-grain weight	944.84**	6.27	17.25*	7.03*	3.64	4.77
Biological Yield	29898310.76**	328730.41	991516.58**	166183.30*	84776.54	2.09
Grain yield	15578122.8**	196498.79	273032.11**	86402.33*	47584.45	4.47
Harvest index	213.72**	1.02	25.68**	3.19**	1.28	3.32

NS= non-signficant, ** = Significant at ($P \leq 0.1$), * = Significant at ($P \leq 0.5$).

Table 2: Genetic and environmental variances, heritability and genetic advance for different parameters of twenty wheat genotypes in normal and drought environments.

	Normal				**Drought**			
SOV	V_g	V_e	h^2	**GA**	V_g	V_e	h^2	**GA**
Spikes m^{-2}	635.07	1210.21	0.59	40.6	892.41	595.07	0.34	25.94
Spike length	0.33	0.23	0.58	0.78	0.18	0.24	0.43	0.49
Spikelet $spike^{-1}$	0.60	0.56	0.51	0.97	0.19	0.64	0.22	0.36
1000-grain weight	2.82	3.73	0.43	1.93	2.84	3.55	0.44	1.97
Biological yield	196395.1	77506.3	0.71	658.58	132987.15	92046.77	0.59	491.99
Grain yield	31988.4	70772.32	0.31	175.1	56200.22	24396.57	0.69	347.01
Harvest index	4.58	1.35	0.77	3.16	4.19	1.20	0.77	3.30

V_g= Genetic variance, V_e= Environmental variance, h^2 = Heritability and GA= Genetic advance

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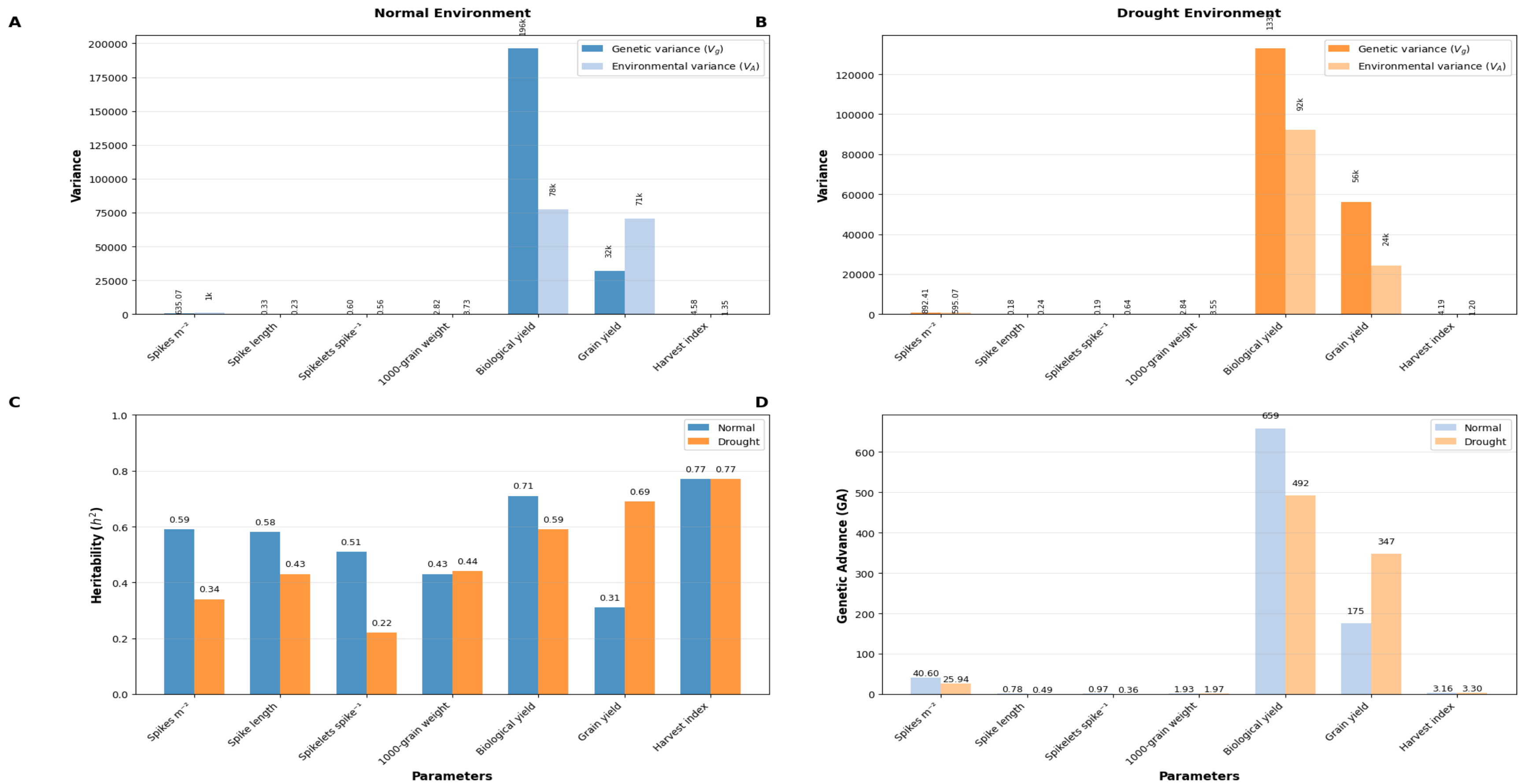

Fig. 1: Genetic parameters and their responses to drought stress in twenty wheat genotypes. (A) Genetic and environmental variances under normal conditions. (B) Genetic and environmental variances under drought conditions. (C) Broad-sense heritability comparison between normal and drought environments. (D) Genetic advance (GA) comparison between normal and drought environments. Key observations: Biological yield showed the highest genetic variance under both environments. Heritability remained stable for harvest index (0.77) but decreased for most traits under drought. Genetic advance for grain yield increased under drought (175.1 to 347.01). Spikelets spike^{-1} exhibited the lowest heritability under drought (0.22).

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Table 3: Means performance and tolerance indices for spikes m^{-2} of twenty wheat genotypes tested in normal and drought environments.

Genotypes	Normal	Drought	TOL	MP	GMP	YI	YSI	SSI	RDI
G-95	495.00	395.00	100.00	445.00	442.18	0.93	0.80	1.85	0.90
G-116	486.78	431.33	55.44	459.06	458.22	1.02	0.89	1.04	0.99
G-125	442.33	350.00	92.33	396.17	393.47	0.83	0.79	1.91	0.89
G-130	492.00	435.00	57.00	463.50	462.62	1.03	0.88	1.06	0.99
G-131	468.67	475.33	-6.67	472.00	471.99	1.12	1.01	-0.13	1.14
G-134	499.00	432.33	66.67	465.67	464.47	1.02	0.87	1.22	0.97
G-144	420.00	415.00	5.00	417.50	417.49	0.98	0.99	0.11	1.11
G-145	476.56	417.78	58.78	447.17	446.20	0.99	0.88	1.13	0.98
G-147	491.00	455.00	36.00	473.00	472.66	1.08	0.93	0.67	1.04
G-148	438.00	432.33	5.67	435.17	435.16	1.02	0.99	0.12	1.11
G-149	489.00	407.00	82.00	448.00	446.12	0.96	0.83	1.54	0.93
G-155	510.00	400.00	110.00	455.00	451.66	0.95	0.78	1.98	0.88
G-159	409.00	370.00	39.00	389.50	389.01	0.88	0.90	0.87	1.02
G-160	483.33	403.00	80.33	443.17	441.34	0.95	0.83	1.52	0.94
G-163	501.00	412.00	89.00	456.50	454.33	0.97	0.82	1.63	0.92
G-197	507.00	416.56	90.44	461.78	459.56	0.99	0.82	1.63	0.92
G-202	502.00	483.00	19.00	492.50	492.41	1.14	0.96	0.35	1.08
G-206	460.00	437.04	22.96	448.52	448.37	1.03	0.95	0.46	1.07
Khaista	417.67	416.00	1.67	416.83	416.83	0.98	1.00	0.04	1.12
Wadan	503.00	471.67	31.33	487.33	487.08	1.12	0.94	0.57	1.05
Mean	474.6	422.8							
$LSD_{0.05}$(G)	22.02								
$LSD_{0.05}$(E)	4.66								
$LSD_{0.05}$(G×E)	28.20								

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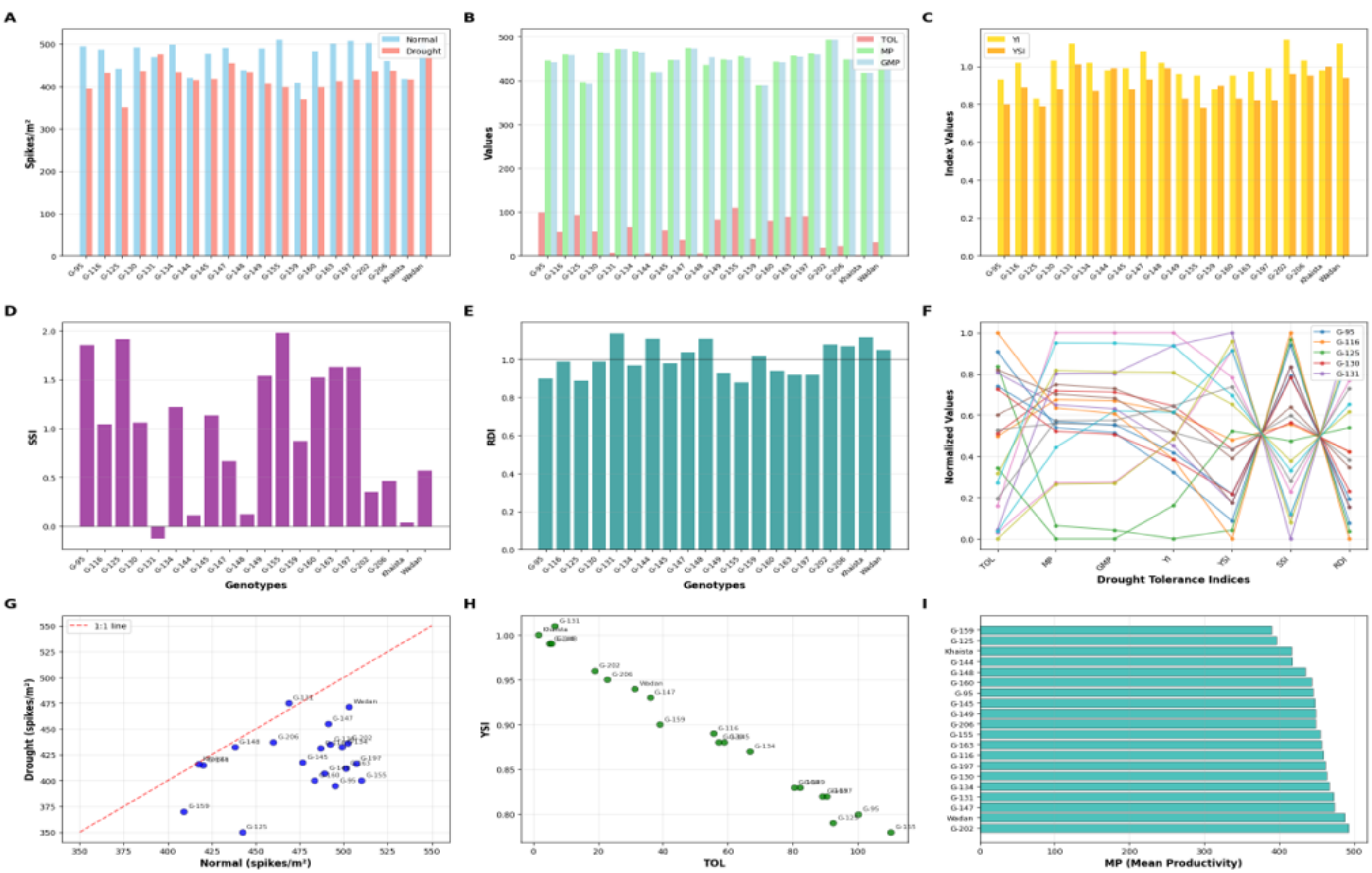

Fig. 2. Performance and drought tolerance indices of twenty wheat genotypes for spikes m^{-2} under normal and drought stress conditions. (A) Spike production per m² under normal (blue) and drought (red) conditions, showing genotype-specific responses to water stress. (B) Tolerance indices, including TOL (Tolerance Index), MP (Mean Productivity), and GMP (Geometric Mean Productivity), represent different aspects of drought tolerance. (C) Yield indices: YI (Yield Index) and YSI (Yield Stability Index), indicating yield performance and stability under stress conditions. (D) Stress Susceptibility Index (SSI) with values >1 indicating high drought susceptibility and values <0 indicating tolerance to drought stress. (E) Relative Drought Index (RDI) with values >1 indicating superior drought tolerance performance. (F) Normalized comparison of all drought tolerance indices across genotypes, enabling cross-index evaluation and identification of consistently performing genotypes. (G) Relationship between normal and drought conditions, with genotypes above the 1:1 line (dashed red) exhibiting better yield maintenance under drought stress. (H) Correlation between Tolerance Index (TOL) and Yield Stability Index (YSI), illustrating the relationship between absolute yield loss and relative yield stability. (I) Genotypes ranked by Mean Productivity (MP), identifying top-performing genotypes under combined normal and stress conditions

Note: Genotypes Khaista and Wadan represent local check varieties for comparison.

Table 4: Means performance and tolerance indices for spike length (cm) of twenty wheat genotypes tested in normal and drought environments.

Genotypes	Normal	Drought	TOL	MP	GMP	YI	YSI	SSI	RDI
G-95	11.00	11.97	-0.97	11.49	11.48	1.09	1.09	-3.48	1.12
G-116	9.33	9.58	-0.25	9.46	9.46	0.87	1.03	-1.06	1.05
G-125	11.81	11.08	0.72	11.45	11.44	1.00	0.94	2.41	0.96
G-130	11.64	11.11	0.53	11.37	11.37	1.01	0.95	1.80	0.98
G-131	11.19	10.83	0.36	11.01	11.01	0.98	0.97	1.27	0.99
G-134	10.83	10.67	0.17	10.75	10.75	0.97	0.98	0.61	1.01
G-144	11.61	10.47	1.14	11.04	11.03	0.95	0.90	3.86	0.93
G-145	11.72	10.97	0.75	11.35	11.34	0.99	0.94	2.52	0.96
G-147	10.56	10.86	-0.30	10.71	10.71	0.98	1.03	-1.14	1.06
G-148	10.89	10.97	-0.08	10.93	10.93	0.99	1.01	-0.30	1.03
G-149	11.67	10.75	0.92	11.21	11.20	0.97	0.92	3.09	0.95
G-155	12.17	11.11	1.06	11.64	11.63	1.01	0.91	3.42	0.94
G-159	11.72	11.56	0.16	11.64	11.64	1.05	0.99	0.55	1.01
G-160	11.28	11.03	0.25	11.15	11.15	1.00	0.98	0.87	1.00
G-163	12.03	11.23	0.80	11.63	11.62	1.02	0.93	2.63	0.96
G-197	11.83	11.31	0.53	11.57	11.57	1.02	0.96	1.76	0.98
G-202	10.75	10.89	-0.14	10.82	10.82	0.99	1.01	-0.51	1.04
G-206	11.66	11.00	0.66	11.33	11.33	1.00	0.94	2.24	0.97
Khaista	11.28	11.14	0.14	11.21	11.21	1.01	0.99	0.49	1.01
Wadan	11.39	12.08	-0.69	11.74	11.73	1.10	1.06	-2.39	1.09
Mean	11.3	11.0							
$LSD_{0.05}$(G)	0.34								
$LSD_{0.05}$(E)	0.02								
$LSD_{0.05}$(G×E)	0.46								

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Table 5: Means performance and tolerance indices for spikelet spike^{-1} of twenty wheat genotypes tested in normal and drought environments.

Genotypes	Normal	Drought	TOL	MP	GMP	YI	YSI	SSI	RDI
G-95	19.61	18.44	1.17	19.03	19.02	0.97	0.94	0.96	1.00
G-116	18.72	19.22	-0.50	18.97	18.97	1.02	1.03	-0.43	1.09
G-125	19.67	18.28	1.39	18.97	18.96	0.97	0.93	1.14	0.99
G-130	20.94	19.28	1.67	20.11	20.09	1.02	0.92	1.28	0.98
G-131	20.11	18.72	1.39	19.42	19.40	0.99	0.93	1.11	0.99
G-134	21.33	19.94	1.39	20.64	20.63	1.05	0.93	1.05	1.00
G-144	20.78	19.61	1.17	20.19	20.19	1.04	0.94	0.91	1.01
G-145	21.31	19.56	1.75	20.44	20.42	1.03	0.92	1.33	0.98
G-147	20.86	18.67	2.20	19.77	19.73	0.99	0.89	1.70	0.95
G-148	20.61	18.69	1.92	19.65	19.63	0.99	0.91	1.51	0.97
G-149	20.78	19.17	1.61	19.97	19.96	1.01	0.92	1.25	0.98
G-155	20.11	18.50	1.61	19.31	19.29	0.98	0.92	1.29	0.98
G-159	19.83	18.44	1.39	19.14	19.13	0.97	0.93	1.13	0.99
G-160	20.89	18.83	2.06	19.86	19.83	1.00	0.90	1.59	0.96
G-163	20.06	18.78	1.28	19.42	19.41	0.99	0.94	1.03	1.00
G-197	19.05	17.83	1.22	18.44	18.43	0.94	0.94	1.03	1.00
G-202	18.50	19.63	-1.13	19.07	19.06	1.04	1.06	-0.99	1.13
G-206	20.08	17.92	2.17	19.00	18.97	0.95	0.89	1.74	0.95
Khaista	21.33	20.17	1.17	20.75	20.74	1.07	0.95	0.88	1.01
Wadan	18.89	18.78	0.11	18.83	18.83	0.99	0.99	0.09	1.06
Mean	20.2	18.9							
$LSD_{0.05}$(G)	0.51								
$LSD_{0.05}$(E)	0.04								
$LSD_{0.05}$(G×E)	0.73								

Table 6: Means performance and tolerance indices for 1000-grain weight (g) of twenty wheat genotypes tested in normal and drought environments.

Genotypes	Normal	Drought	TOL	MP	GMP	YI	YSI	SSI	RDI
G-95	43.07	37.20	5.87	40.13	40.03	1.00	0.86	1.04	0.99
G-116	39.93	34.22	5.72	37.08	36.96	0.92	0.86	1.09	0.99
G-125	41.75	35.45	6.30	38.60	38.47	0.95	0.85	1.15	0.98
G-130	39.77	34.32	5.46	37.05	36.94	0.92	0.86	1.05	0.99
G-131	39.93	35.63	4.30	37.78	37.72	0.96	0.89	0.82	1.03
G-134	40.33	37.37	2.97	38.85	38.82	1.00	0.93	0.56	1.07
G-144	45.12	36.87	8.25	40.99	40.78	0.99	0.82	1.40	0.94
G-145	43.83	38.32	5.52	41.08	40.98	1.03	0.87	0.96	1.01
G-147	42.97	34.17	8.80	38.57	38.31	0.92	0.80	1.56	0.91
G-148	45.62	35.12	10.50	40.37	40.02	0.94	0.77	1.76	0.89
G-149	45.80	38.27	7.53	42.03	41.86	1.03	0.84	1.26	0.96
G-155	44.02	38.03	5.98	41.03	40.92	1.02	0.86	1.04	0.99
G-159	41.70	38.75	2.95	40.23	40.20	1.04	0.93	0.54	1.07
G-160	44.88	37.27	7.62	41.08	40.90	1.00	0.83	1.30	0.96
G-163	43.38	38.38	5.00	40.88	40.81	1.03	0.88	0.88	1.02
G-197	41.63	36.83	4.80	39.23	39.16	0.99	0.88	0.88	1.02
G-202	45.47	42.12	3.35	43.79	43.76	1.13	0.93	0.56	1.07
G-206	44.52	38.58	5.93	41.55	41.44	1.04	0.87	1.02	1.00
Khaista	42.02	38.77	3.25	40.39	40.36	1.04	0.92	0.59	1.06
Wadan	41.48	39.33	2.15	40.41	40.39	1.06	0.95	0.40	1.09
Mean	42.9	37.2							
$LSD_{0.05}$(G)	1.30								
$LSD_{0.05}$(E)	0.16								
$LSD_{0.05}$(G×E)	1.79								

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Table 7: Means performance and tolerance indices for biological yield (kg ha^{-1}) of twenty wheat genotypes tested in normal and drought environments.

Genotypes	Normal	Drought	TOL	MP	GMP	YI	YSI	SSI	RDI
G-95	14262.9	13472.2	790.74	13867.59	13861.96	1.00	0.94	0.80	1.01
G-116	14470.7	13935.1	535.56	14202.96	14200.44	1.04	0.96	0.54	1.03
G-125	14937.0	13872.2	1064.81	14404.63	14394.79	1.03	0.93	1.03	1.00
G-130	14696.3	13842.5	853.70	14269.44	14263.06	1.03	0.94	0.84	1.01
G-131	14719.2	13798.2	921.04	14258.74	14251.30	1.02	0.94	0.91	1.01
G-134	14874.4	13768.8	1105.56	14321.67	14311.00	1.02	0.93	1.08	0.99
G-144	15011.1	13811.1	1200.00	14411.11	14398.62	1.03	0.92	1.16	0.99
G-145	14996.3	13668.5	1327.78	14332.41	14317.02	1.02	0.91	1.28	0.98
G-147	14712.9	13185.1	1527.78	13949.07	13928.14	0.98	0.90	1.50	0.96
G-148	14738.5	13033.0	1705.48	13885.78	13859.57	0.97	0.88	1.68	0.95
G-149	14088.8	13068.6	1020.19	13578.72	13569.14	0.97	0.93	1.05	1.00
G-155	14185.1	12968.3	1216.89	13576.74	13563.10	0.96	0.91	1.24	0.98
G-159	14487.0	13288.1	1198.89	13887.59	13874.65	0.99	0.92	1.20	0.99
G-160	14922.2	13743.7	1178.52	14332.96	14320.84	1.02	0.92	1.14	0.99
G-163	13999.6	12998.9	1000.67	13499.30	13490.02	0.97	0.93	1.04	1.00
G-197	13488.8	12591.1	897.78	13040.00	13032.27	0.94	0.93	0.96	1.00
G-202	14625.9	13796.3	829.63	14211.11	14205.06	1.02	0.94	0.82	1.01
G-206	14600.3	13888.8	711.44	14244.61	14240.17	1.03	0.95	0.71	1.02
Khaista	13981.4	13472.2	509.26	13726.85	13724.49	1.00	0.96	0.53	1.04
Wadan	13425.9	13055.5	370.37	13240.74	13239.45	0.97	0.97	0.40	1.04
Mean	14461.3	13462.9							
$LSD_{0.05}$(G)	201.10								
$LSD_{0.05}$(E)	37.52								
$LSD_{0.05}$(G×E)	273.36								

Table 8: Means performance and tolerance indices for grain yield (kg ha^{-1}) of twenty wheat genotypes tested in normal and drought environments.

Genotypes	Normal	Drought	TOL	MP	GMP	YI	YSI	SSI	RDI
G-95	5000.0	4500.5	499.41	4750.29	4743.73	1.00	0.90	0.73	1.04
G-116	5357.5	4470.3	887.23	4913.95	4893.88	0.99	0.83	1.20	0.97
G-125	5210.8	4288.6	922.21	4749.76	4727.32	0.95	0.82	1.29	0.95
G-130	5316.6	4480.5	836.12	4898.61	4880.74	0.99	0.84	1.14	0.98
G-131	4814.8	4031.4	783.34	4423.15	4405.77	0.89	0.84	1.18	0.97
G-134	5380.3	4596.3	784.04	4988.32	4972.89	1.02	0.85	1.06	0.99
G-144	5399.3	4550.3	849.00	4974.83	4956.69	1.01	0.84	1.14	0.98
G-145	5357.4	4490.8	866.58	4924.12	4905.02	0.99	0.84	1.18	0.97
G-147	5220.9	4302.1	918.72	4761.54	4739.33	0.95	0.82	1.28	0.96
G-148	5294.4	4484.2	810.21	4889.33	4872.52	0.99	0.85	1.11	0.98
G-149	5078.7	4130.7	948.00	4604.78	4580.32	0.91	0.81	1.36	0.94
G-155	5570.8	4720.3	850.48	5145.61	5128.01	1.04	0.85	1.11	0.98
G-159	5409.0	4390.2	1018.86	4899.65	4873.09	0.97	0.81	1.37	0.94
G-160	4907.4	4675.9	231.48	4791.67	4790.27	1.03	0.95	0.34	1.10
G-163	5700.0	4852.8	847.19	5276.45	5259.41	1.07	0.85	1.08	0.99
G-197	5083.3	4322.2	761.11	4702.78	4687.35	0.96	0.85	1.09	0.99
G-202	5150.1	4635.1	514.98	4892.68	4885.90	1.03	0.90	0.73	1.04
G-206	5231.4	4750.1	481.33	4990.82	4985.01	1.05	0.91	0.67	1.05
Khaista	4861.1	4607.4	253.70	4734.26	4732.56	1.02	0.95	0.38	1.10
Wadan	5509.2	5161.1	348.11	5335.17	5332.33	1.14	0.94	0.46	1.09
Mean	5242.7	4522.1							
LSD $_{0.05}$ (G)	145.01								
LSD $_{0.05}$ (E)	29.00								
LSD $_{0.05}$ (G×E)	204.80								

Table 9: Means performance and tolerance indices for harvest index (%) of twenty wheat genotypes tested in normal and drought environments.

Genotypes	**Normal**	**Drought**	TOL	MP	GMP	YI	YSI	SSI	RDI
G-95	35.05	33.43	1.62	34.24	34.23	0.99	0.95	0.63	1.03
G-116	37.00	32.07	4.93	34.54	34.45	0.95	0.87	1.81	0.94
G-125	34.86	30.94	3.92	32.90	32.84	0.92	0.89	1.53	0.96
G-130	36.18	32.38	3.80	34.28	34.23	0.96	0.89	1.43	0.97
G-131	32.70	29.21	3.49	30.96	30.91	0.87	0.89	1.45	0.96
G-134	36.17	33.37	2.80	34.77	34.75	0.99	0.92	1.05	1.00
G-144	35.97	32.95	3.02	34.46	34.43	0.98	0.92	1.14	0.99
G-145	35.73	32.86	2.87	34.29	34.26	0.98	0.92	1.09	0.99
G-147	35.47	32.64	2.83	34.05	34.02	0.97	0.92	1.09	0.99
G-148	35.96	34.41	1.56	35.19	35.18	1.02	0.96	0.59	1.03
G-149	36.06	31.60	4.46	33.83	33.76	0.94	0.88	1.68	0.95
G-155	39.29	36.41	2.88	37.85	37.83	1.08	0.93	1.00	1.00
G-159	37.34	33.03	4.31	35.19	35.12	0.98	0.88	1.57	0.95
G-160	32.90	34.02	-1.12	33.46	33.46	1.01	1.03	-0.46	1.12
G-163	40.69	37.33	3.36	39.01	38.98	1.11	0.92	1.12	0.99
G-197	37.68	34.32	3.36	36.00	35.96	1.02	0.91	1.21	0.98
G-202	35.20	33.63	1.56	34.42	34.41	1.00	0.96	0.60	1.03
G-206	35.85	34.20	1.64	35.03	35.02	1.02	0.95	0.62	1.03
Khaista	34.79	34.19	0.59	34.49	34.49	1.02	0.98	0.23	1.06
Wadan	41.03	39.54	1.49	40.28	40.28	1.18	0.96	0.49	1.04
Mean	36.30	33.63							
$LSD_{0.05}$(G)	0.88								
$LSD_{0.05}$(E)	0.06								

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$LSD_{0.05}$(G×E)	1.06

Table 10: Simple correlation coefficients between environments and drought tolerance indices for different parameters of twenty wheat genotypes tested in normal and drought environments.

SOV		Drought	TOL	MP	GMP	YI	YSI	SSI	RDI
Spikes m^{-2}	Normal	0.37^{NS}	0.54*	0.82**	0.80**	0.38^{NS}	-0.48*	0.48*	-0.50*
	Drought	…	-0.57**	0.83**	0.85**	0.99**	0.62**	-0.62**	0.61**
Spike length	Normal	0.53*	0.63**	0.90**	0.90**	0.02^{NS}	-0.64**	0.51*	-0.66**
	Drought	…	-0.31^{NS}	0.84**	0.84**	0.60**	0.29^{NS}	-0.39^{NS}	0.25^{NS}
Spikelets $spike^{-1}$	Normal	0.42^{NS}	0.73**	0.89**	0.89**	0.41^{NS}	-0.70**	0.70**	-0.68**
	Drought	…	-0.30^{NS}	0.78**	0.78**	0.99**	0.34^{NS}	-0.35^{NS}	0.36^{NS}
1000-grain weight	Normal	0.42^{NS}	0.54*	0.84**	0.81**	0.42^{NS}	-0.43^{NS}	0.45^{*}	-0.44^{NS}
	Drought	…	-0.53*	0.84**	0.86**	0.99**	0.62**	0.62**	0.62**
Biological yield	Normal	0.53*	0.63**	0.90**	0.90**	0.02^{NS}	-0.64**	0.51*	-0.66**
	Drought	…	-0.30^{NS}	0.84**	0.84**	0.60**	0.29^{NS}	-0.39^{NS}	0.25^{NS}
Grain yield	Normal	0.52*	0.43^{NS}	0.86 **	0.84**	0.51*	-0.31^{NS}	0.32^{NS}	-0.30^{NS}
	Drought	…	-0.54*	0.86**	0.89**	0.99**	0.64**	-0.63**	0.65**
Harvest index	Normal	0.78**	0.26^{NS}	0.94**	0.93**	0.77**	-0.17^{NS}	0.18^{NS}	-0.18^{NS}
	Drought	…	-0.39^{NS}	0.94**	0.94**	0.99**	0.47*	-0.47*	0.47*

NS = non-significant, ** = Significant at ($P \leq 0.1$), * = Significant at ($P \leq 0.5$).

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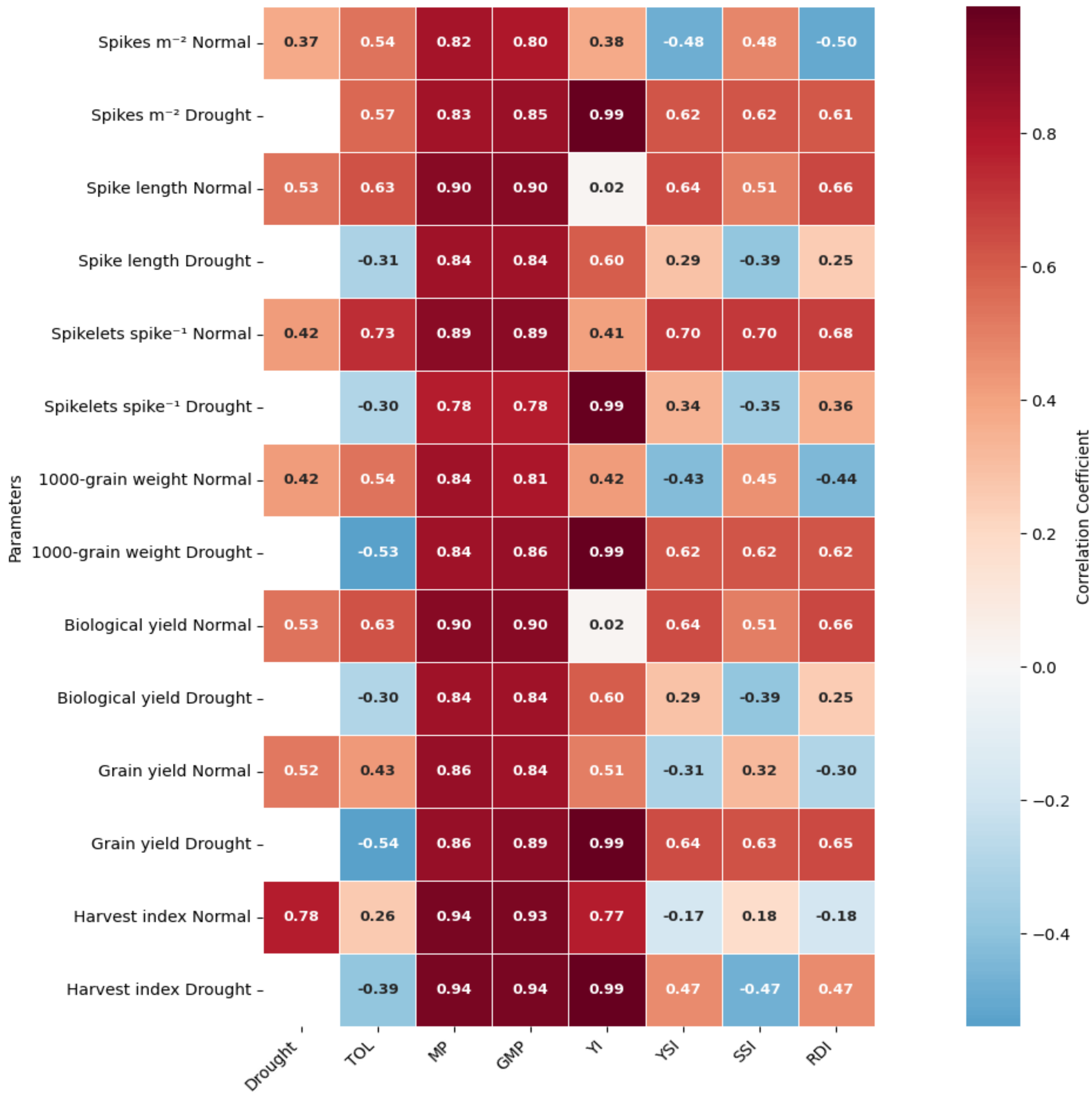

Fig. 3. Correlation matrix between agronomic parameters and drought tolerance indices in wheat genotypes under normal and drought conditions. The heatmap displays Pearson correlation coefficients color-coded from strong negative (blue) to strong positive (red) relationships. Key observations include: MP and GMP show consistently strong positive correlations (>0.78) with most parameters, YI demonstrates near-perfect correlations (0.99) with drought environment parameters, TOL exhibits contrasting relationships between normal and drought conditions, and Stress indices (SSI, RDI) show environment-dependent correlation patterns.

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Note: Blank cells indicate missing correlation data for the drought environment with itself.

CONCLUSIONS AND RECOMMENDATIONS

All the genotypes showed highly significant variation between genotypes spike length, biological yield, grain yield and harvest index while significant variation were observed for spikes m^{-2}, spikelet $spike^{-1}$, and 1000-grain weight. Significant genotype × environment interaction was observed for all the studied traits. GMP and MP had a positive highly significant correlation with all the productive traits under both environments, thus it will be more useful for trait selection under rainfed and irrigated environments. YI was positive and highly significantly correlated with all yield contributing traits in rainfed conditions, thus YI would be more reliable selection index in a rainfed environment. High and moderate heritability and genetic advance were recorded for all characters. Grain yield in irrigated while spikelets $spike^{-1}$ under rainfed conditions had low heritability. In future breeding programs, traits with high heritability might be employed as selection criteria. G-163 and G-155 were the highest yielding genotypes under irrigated conditions while local check Wadan and genotype G-163 had the highest grain yield in a rainfed environment. Therefore, these genotypes could be used in future breeding program and could be further tested across location and years for making solid recommendation.

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