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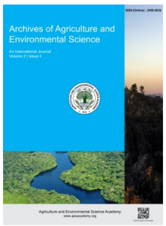

ORIGINAL RESEARCH ARTICLE

Assessing drought tolerance in advance wheat genotypes using stress tolerance indices

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ABSTRACT

Wheat, an important crop of Nepal, is significantly affected by drought, leading to severe yield losses. Thus, an experiment was conducted to assess effect of drought on wheat traits and to identify drought resilient genotypes comparing stress tolerance indices. Altogether seventy-two genotypes including checks were evaluated under drought and non-stress condition in an alpha-lattice design with two replications at the research block of National Rice Research Program, Hardinath, Nepal during winter of 2019/20. Analysis of variance revealed significant genotypic differences ($p<0.01$) in traits such as days to heading, anthesis, and maturity, plant height, flag leaf area, spike length, grains per spike, 1000-grain weight, and grain yield under both conditions. The combined analysis of variance showed that genotype, environment, and their interaction significantly influenced most traits. The environment was the dominant factor, accounting for 86.2% of the variation in grain yield, followed by genotype (9.5%) and genotype-environment interaction (4.3%). Among the nine quantitative traits assessed, grain yield was most severely affected due to drought, experiencing a substantial reduction of 63%. To assess drought tolerance, six indices (TOL, SSI, MP, GMP, HMP, and STI) were calculated based on grain yield data. Most indices identified genotypes NL1373, NL1308, NL1407, BL4868, and BL4947 as highly drought-tolerant. Among the indices, MP, STI, and GMP were the most reliable for measuring stress tolerance due to their strong positive correlation with yield under both conditions. These identified genotypes are promising candidates for breeding programs aimed at developing drought-resilient wheat varieties, thereby enhancing food security in drought-affected regions.

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INTRODUCTION

Wheat (*Triticum aestivum* L.) stands as the world's second most produced cereal, representing 27.7% of global production, with maize leading at 43%, and rice following at 18.5% (Madhukar, 2022). In Nepal, it holds the rank of the third most crucial cereal crop, behind rice and maize in both acreage and yield (MoALD, 2023). The nation dedicates approximately 0.72 million hectares to wheat cultivation, yielding 2.14 million tons, with a productivity rate of 2.99 tons per hectare (MoALD, 2023). Over time, per capita wheat consumption has surged nearly fourfold, escalating from 17.4 kg in 1972, at the time of establishment of the National Wheat Research Program (NWRP), to 69 kg in 2020 (Upadhyaya, 2017), indicating a notable shift in dietary preferences towards wheat. However, Nepal faces challenges in maximizing wheat productivity due to various factors such as erratic rainfall patterns, limited irrigation infrastructure, delayed planting, utilization of substandard seeds, and the influence of biotic and abiotic stressors (Tripati *et al*., 2017). These obstacles significantly impede wheat cultivation and necessitate strategic interventions to enhance productivity and ensure food security. Reduction in yield due to unavailability of adequate water is defined as drought. This challenge is particularly prevalent in semi-arid regions, where approximately 37% of the global wheat cultivation area is situated, posing a significant obstacle to wheat production. In Nepal, a considerable portion, about 36%, of wheat cultivation relies on rainfed farming, with 21% of this cultivation located in the Terai region (Pandey, 2017). Drought stands as a primary environmental constraint that impose limitations on plant growth, metabolism, and overall productivity as high as 60% (Ji *et al*., 2010; Wan *et al*., 2022). Its dramatic impact includes a significant reduction in stomatal conductance and leaf expansion, which can disrupt critical processes within photosynthesis (Passioura, 1994). The closure of stomata can trigger leaf senescence, diminishing the functional leaf area available for photosynthetic activity (Shah & Paulsen, 2003). Furthermore, stress during the reproductive phase may lead to kernel abortion, potentially due to diminished carbohydrate supply and decreased counts of endosperm cells and amyloplasts within wheat grains (Shah & Paulsen, 2003). These cumulative effects detrimentally influence grain accumulation in the spike, ultimately culminating in reduced final harvest yields. Consequently, the urgency of developing wheat varieties capable of effectively tackle these challenges has come to the forefront of agricultural research. Within this framework, this study explores the impacts of drought stress on various quantitative characters of wheat crop, identifies optimal genotypes exhibiting resilience under stress conditions, and conducts a comparative analysis of different stress tolerance indices commonly employed in such investigations.

MATERIALS AND METHODS

A total of 72 advance wheat genotypes, including five checks (Bhrikuti, Vijay, Tilottama, NL971, and BL4341) sourced from the National Wheat Research Program, Bhairahawa, were evaluated in winter season of 2019/20. The details of the genotypes are given in table 1. The experiments were conducted at the research field (non-stress) and rainout shelter (stress) of the National Rice Research Program, Hardinath, Dhanusha, situated at latitude 28°48' N and longitude 85°57' E in the central Terai region of Nepal, at an altitude of 75 masl. The soil type of the research site was loamy. The details of the soil properties are given in table 1. The experiments were laid out an alpha-lattice design with two replications under non-stress and stress conditions. The details of the experiments are given in table 2. Each replication comprised 12 blocks, with 6 plots in each block. Each plot consisted of two rows, each 2 meters in length, with a row-to-row distance of 25 cm, where seeds were sown continuously in a line.

The study recorded days to heading (DH), anthesis/flowering (DF), and maturity (DM), along with plant height (PH), flag leaf area (FLA), spike length (SL), kernels per spike (Knl/spk), thousand kernels weight (TKW), and grain yield (GY; adjusted to 12% moisture level). Stress tolerance indices were calculated to identify drought-tolerant genotypes, using the following formulas:

$$\text{Tolerance index (TOL)} = Y_n - Y_s$$ (Rosielle & Hamblin, 1981)

$$\text{Mean Productivity (MP)} = \frac{Y_n + Y_s}{2}$$ (Rosielle & Hamblin, 1981)

$$\text{Stress Susceptibility Index (SSI)} = \frac{1-(Y_s/Y_n)}{1-(\hat{Y}_s/\hat{Y}_n)}$$ (Fischer & Maurer, 1978)

$$\text{Geometric Mean Productivity (GMP)} = \sqrt{Y_n - Y_s}$$ (Fernandez, 1992)

$$\text{Harmonic Mean Productivity (HMP)} = \frac{2\,(Y_n \text{ x } Y_s)}{Y_n + Y_s}$$ (Fernandez, 1992)

$$\text{Stress Tolerance Index (STI)} = \frac{Y_n + Y_s}{\hat{Y}_n}$$ (Fernandez, 1992)

The equation provided represents the calculation of stress tolerance indices, where Y_s and Y_n denote yield under stress and non-stress conditions, respectively, and $\hat{Y}_s$ and $\hat{Y}_n$ represent the mean yield under stress and non-stress conditions for all genotypes. For statistical analysis, the Genstat software version 15th edition was employed to perform analysis of variance (ANOVA), conduct correlation analysis, and construct the bi-plot graph.

RESULTS AND DISCUSSION

The results from the analysis of variance (ANOVA) showed highly significant (p<0.01) difference due to genotype in almost all the studied traits under both stress and non-stress conditions (Table 3). Only non-significant difference was observed for number of kernels per spike in stress condition. Similarly, the combined ANOVA revealed that all the traits were significantly affected by genotype (G), environment (E), and genotype by environment (GxE) interaction except no GxE was found for spike length and number of kernels per spike. The significant GxE interaction in most of the traits indicated that the relative performances of the genotypes were not consistent in tested environmental conditions and the environments had different effects on the yield potential of the genotypes. In terms of grain yield, the environmental factor accounted 86.2% of the variation, with genotype (G) and genotype-by-environment interaction (GxE) contributing 9.5% and 4.3%, respectively. Remarkably, the influence of the environment outweighed that of genotype by approximately nine fold and the genotype-by-environment interaction by twenty fold. The substantial variability attributed to environmental factors indicates high differences among the tested environmental conditions, and also emphasises the predominant role of environmental factors in shaping the grain yield of wheat genotypes. Tulu & Wondimu (2019); Alemu *et al.* (2021); and Kedir *et al.* (2022) have also reported significant environmental effects, stressing the necessity of breeding program to focus on specific adaptation.

Effects of drought stress on various quantitative traits of wheat genotypes

In drought stress condition, reduction of 12%, 13%, and 16% in days from sowing to heading, anthesis/flowering, and maturity was observed respectively (Figure 2). These reductions indicate a significant alteration in the developmental timeline of the plants under stress, reflecting a substantial impact on their growth and reproductive stages. Previous studies by Qaseem (2018) have documented shorter durations for heading, flowering, and maturity in wheat under stress conditions. This reduction in vegetative period serves as a strategic adaptation by wheat plants to mitigate dehydration risks during critical flowering and post-anthesis grain filling stages, as discussed by Shavrukov *et al.* (2017). Similarly, plant height experienced a notable reduction of 24% under stress condition, indicating a significant negative impact on growth (Figure 3). However, the reduction in spike length was comparatively modest, at 10%. It suggests that while the stress factor influenced plant development, its effect was more pronounced on plant height than on spike length. Among the traits assessed, the flag leaf area was the second most affected by stress, experiencing a reduction of 39%. Following closely behind, the number of kernels per spike decreased by 33%. Interestingly, the 1000-kernel weight exhibited the least sensitivity to stress, with only an 8% reduction (Figure 4). The significantly negative effect of drought stress on plant height, spike length, number of kernels per spike and 1000 -kernel weight has been reported by Pour-Aboughadareh *et al.* (2020), and Chen *et al.* (2021). These findings highlight the varying degrees of susceptibility among different traits to the stress condition, shedding light on the complex response mechanisms of the plant under adverse environmental conditions. Reduced crop duration under stress condition compared to non-stress condition might have led to poor grain development and decreased grain weight.

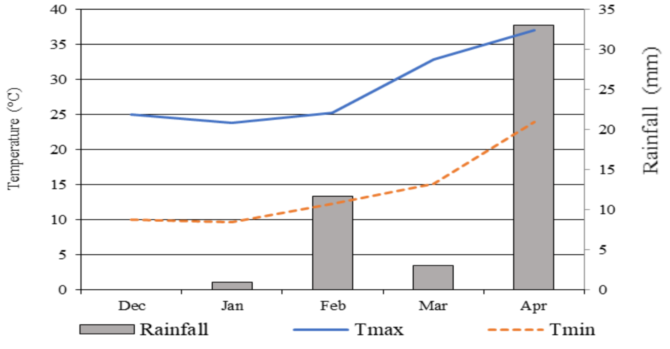

Figure 1. *Agro-meteorological features of the research site during study period showing monthly average maximum temperature (T_{max}), monthly average minimum temperature (T_{min}) and monthly total rainfall.*

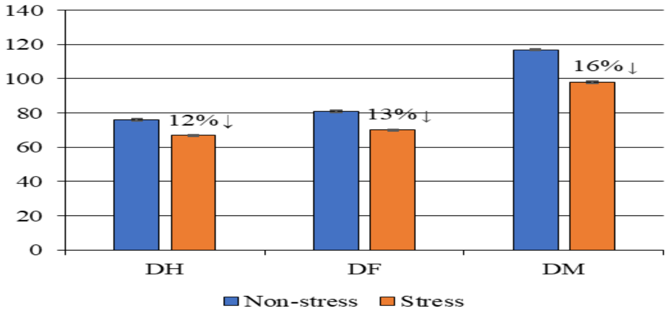

Figure 2. *Comparison of phenological traits; days to heading, days to anthesis/flowering, and days to maturity.*

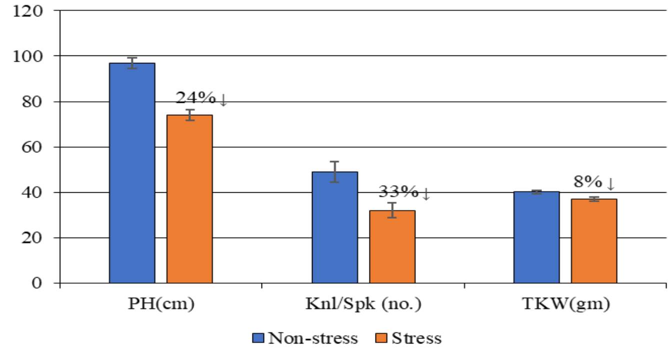

Figure 3. *Comparison of architectural and yield traits; plant height, no. of kernels per spike, and 1000-kernels weight.*

Table 1. Soil properties of experimental plot.

Parameter	Content
Sand	37.2%
Silt	42.0%
Clay	20.8%
pH	6.6
OM	1.02%
N	0.07%
P_2O_5	30.4 ppm
K_2O	41.9 ppm

Effect of drought stress in grain yield

Figure 4 shows the most severe impact of drought was observed in grain yield, with a substantial reduction of 63%. The sharp decrease in yield underlines the significant vulnerability of wheat productivity to water stress, highlighting the critical importance of tolerant varieties in drought-prone environments. The highest yielding genotypes were NL1308 (6.99 t/ha) and BL4947 (6.88 t/ha), NL1407 (6.76 t/ha), BL4868 (6.69 t/ha), NL1372 (6.69 t/ha), NL1369 (6.59 t/ha) and NL1414 (6.24 t/ha) which produced more than 6.00 t/ha of grain yield while NL1303 (3.35 t/ha) was the poorest yielder under non-stress condition (Table 4). Under stress, genotypes NL1308 (2.84 t/ha) followed by NL1310 (2.83 t/ha), NL1202 (2.75 t/ha), NL1373 (2.73 t/ha), NL1375 (2.67 t/ha), BL4448 (2.58 t/ha), NL1407 (2.54 t/ha) and BL4820 (2.53 t/ha) produced grain yield of more than 2.50 t/ha as Tilottama (0.75 t/ha) yielded lowest. Yield differences among genotypes within the same environmental condition might be due to variation in genetic constituents

Table 2. Details of experiment.

Conditions	Non-stress	Stress
1. Date of sowing	4th Dec. 2019	4th Jan. 2020
2. Irrigations		
i. Crown Root Initiation	Fully	Light life saving
ii. Booting	Fully	No
3. 3. Fertilizer dose ($N:P_2O_5:K_2O$ kg/ha) as per recommendation	100:50:20	50:50:20
4. Seed rate (kg/ha)	120	120

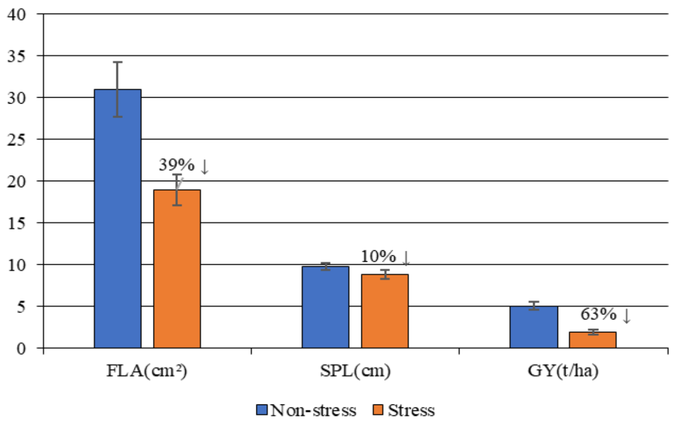

Figure 4. *Comparison of architectural and yield traits; flag leaf area, spike length, and grain yield.*

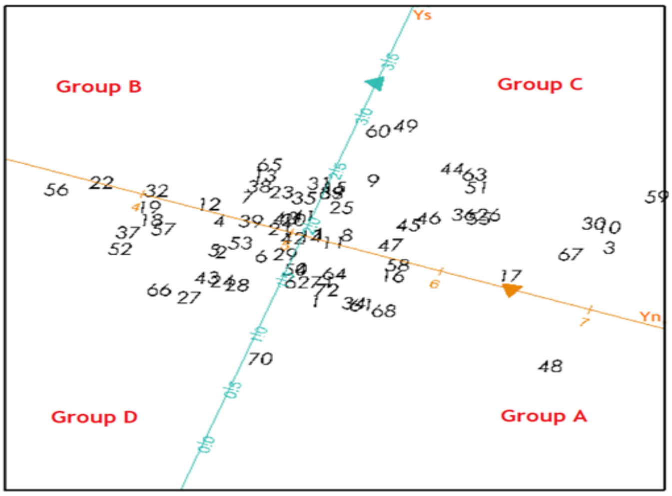

Figure 5. *The bi-plot of grain yield under non-stress (Y_n) versus grain yield under stress (Y_s) conditions.*

among the genotypes. The higher decline in grain yield has been reported in genotypes that require longer days to heading under non-stress condition as discussed by Sattar *et al.* (2010). Thapa *et al.* (2017) underscored the multifaceted nature of drought's impact on crops, influenced by factors including genotype, growth stage, stress severity and duration, physiological growth processes, gene expression patterns, respiration and photosynthesis activity, and prevailing environmental conditions. Grain yield in wheat has direct and positive correlation with attributes such as kernels per spike, 1000-kernel weight, and number of grain filling days (Yao *et al.*, 2019). The reduction in grain yield in this experiment can be attributed to the reduction in these yield traits because of drought. These traits, moreover, possess high heritability and serve as valuable criteria for the selection of high-yielding varieties (Bekele *et al.*, 2020). Other factors such as pollen sterility, accumulation of abscisic acid in spikes, and abscisic acid synthesizing genes in anthers also have negative impact in yield (Ji *et al.*, 2010). Likewise, drought stress influences protein changes, antioxidant production, osmotic adjustment, hormone composition, root depth and extension, opening and closing of stomata, cuticle thickness, inhibition of photosynthesis, decrease in chlorophyll content, reduction in transpiration, and growth inhibition to stand with some osmotic changes in their organs (Seleiman *et al.*, 2021; Dastborhan *et al.*, 2021; Wahab *et al.*, 2022).

Stress tolerance indices under drought condition

Table 4 provides a comprehensive summary of the grain yield performance of all 72 genotypes under both stress and non-stress conditions, accompanied by data on six different toler-

Table 3. Descriptive statistics and mean sum of squares of studied quantitative characters for various parameters (G, E and GxE) under stress, non-stress and combined analysis.

Environments	Non-Stress			Stress			Combined Analysis			
Traits	Range	Mean	G (MS)	Range	Mean	G (MS)	G (MS)	E (MS)	GxE (MS)	Residual (MS)
Degree of freedom	-	-	71	-	-	71	71	1	71	-
DH (days)	70-80	76 ± 0.5	11.0**	64-72	67 ± 0.5	23.4**	12.1**	5706.7**	4.8**	0.6
DF (days)	75-86	81 ± 0.5	11.7**	67-75	70 ± 0.6	27.6**	12.9**	7980.1**	5.2**	0.7
DM (days)	112-123	117 ± 0.4	12.4**	93-104	98 ± 0.6	25.0**	20.3**	25200.1**	6.9**	0.7
PH (cm)	85-130	97 ± 2.4	143.9**	64-91	74 ± 2.4	272.3**	196.4**	38711.5**	32.9**	11.4
SPL (cm)	8.1-11.9	9.8 ± 0.4	1.3**	7.2-10.3	8.8 ± 0.5	65.1**	2.1**	71.1**	0.6^{ns}	0.6
FLA (cm²)	21.2-44.3	31 ± 3.3	54.3**	11.5-30.4	19 ± 1.8	217.3**	60.1**	10551.2**	30.1**	14.4
Knl/spk (no.)	37-65	49 ± 4.5	71.1**	20-45	32 ± 3.4	55.0^{ns}	75.8**	19126.4**	30.7^{ns}	31.5
TKW (g)	33-49	40 ± 0.7	28.1**	31-44	37 ± 0.8	13.0**	31.3**	725.2**	6.8**	1.1
GY (t/ha)	3.35-6.99	5.08 ± 0.5	23.4**	0.75-2.84	1.9 ± 0.3	0.7**	1.1**	725.2**	0.5*	0.3
GY Sum of Squares (%)							80.1 (9.5%)	725.2 (86.2%)	36.4 (4.3%)	

G-Genotype, E-Environment, GXE-Genotype by Environment, MS-Mean sum of squares, DH-days to heading, DF-days to flowering, DM-Days to maturity, PH-plant height, SPL-spike length, FLA-flag leaf area, Knl/spk-no. of kernels per spike, TKW-thousand kernel weight, GY-grain yield, ** Significant at alpha 0.01, * Significant at alpha 0.05, and ns-non-significant.

Table 4. Grain yield under stress and non-stress condition and various tolerance indices of tested genotypes.

E. No.	Genotype	Y_s	Y_n	TOL	MP	SSI	GMP	STI	HMP
1	BL4928	1.4	5.3	3.90	3.30	1.19	2.66	0.28	2.15
2	BL4946	1.6	4.6	3.00	3.05	1.05	2.66	0.27	2.31
3	BL4947	2.4	6.9	4.45	4.63	1.04	4.05	0.64	3.55
4	BL4952	1.8	4.5	2.65	3.13	0.95	2.83	0.31	2.56
5	BL4954	1.6	4.5	2.95	3.03	1.05	2.64	0.27	2.31
6	NL1403	1.6	4.8	3.20	3.20	1.07	2.77	0.30	2.40
7	NL1404	2.1	4.6	2.50	3.30	0.88	3.05	0.36	2.83
8	NL1405	2.0	5.3	3.30	3.60	1.01	3.20	0.40	2.84
9	NL1406	2.5	5.3	2.80	3.85	0.85	3.59	0.50	3.34
10	NL1407	2.6	6.8	4.20	4.65	1.00	4.15	0.67	3.70
11	NL1408	1.9	5.2	3.30	3.50	1.02	3.09	0.37	2.72
12	NL1409	1.9	4.3	2.40	3.10	0.89	2.86	0.32	2.64
13	NL1410	2.3	4.6	2.30	3.40	0.81	3.20	0.40	3.01
14	NL1411	1.9	5.0	3.15	3.43	1.01	3.04	0.36	2.70
15	NL1412	2.3	5.0	2.70	3.65	0.86	3.39	0.45	3.15
16	NL1413	1.7	5.6	3.90	3.65	1.11	3.09	0.37	2.61
17	NL1414	2.0	6.3	4.35	4.13	1.10	3.50	0.48	2.98
18	NL1415	1.7	4.0	2.35	2.83	0.94	2.57	0.26	2.34
19	NL1416	1.8	4.0	2.20	2.85	0.89	2.63	0.27	2.43
20	NL1417	2.0	4.9	2.90	3.40	0.96	3.08	0.37	2.78
21	NL1418	1.9	4.8	2.95	3.33	0.98	2.98	0.34	2.67
22	NL1419	1.9	3.6	1.75	2.73	0.78	2.58	0.26	2.44
23	NL1420	2.2	4.7	2.55	3.43	0.87	3.18	0.39	2.95
24	NL1421	1.3	4.6	3.30	2.95	1.15	2.45	0.23	2.03
25	NL1422	2.2	5.1	2.95	3.63	0.93	3.31	0.43	3.02
26	NL1423	2.4	6.0	3.60	4.20	0.96	3.79	0.56	3.43
27	NL1358	1.1	4.5	3.35	2.78	1.20	2.21	0.19	1.76
28	NL1360	1.3	4.7	3.40	3.00	1.16	2.47	0.24	2.04
29	NL1344	1.7	4.9	3.25	3.28	1.06	2.84	0.31	2.47
30	BL4868	2.6	6.7	4.10	4.60	0.99	4.12	0.66	3.69
31	NL1367	2.3	4.9	2.60	3.60	0.85	3.36	0.44	3.13
32	NL1350	1.9	4.0	2.05	2.93	0.83	2.74	0.29	2.57
33	NL1349	2.3	5.0	2.75	3.63	0.88	3.35	0.44	3.10
34	NL1298	1.4	5.5	4.05	3.43	1.19	2.76	0.30	2.23
35	NL1369	2.2	4.9	2.70	3.50	0.89	3.23	0.40	2.98
36	BL4820	2.4	5.9	3.50	4.10	0.96	3.71	0.53	3.35
37	NL1318	1.5	3.9	2.40	2.70	0.98	2.42	0.23	2.17
38	NL1322	2.2	4.6	2.40	3.35	0.84	3.13	0.38	2.92
39	BL4818	1.9	4.6	2.75	3.23	0.96	2.92	0.33	2.64
40	BL4866	2.0	4.8	2.85	3.38	0.95	3.06	0.36	2.77
41	NL1345	2.0	4.9	2.90	3.45	0.95	3.13	0.38	2.84
42	NL1362	1.8	4.9	3.10	3.35	1.01	2.97	0.34	2.63
43	NL1370	1.3	4.5	3.20	2.90	1.14	2.42	0.23	2.02
44	BL4448	2.7	5.7	2.95	4.18	0.84	3.91	0.59	3.65
45	BL4758	2.2	5.6	3.40	3.85	0.98	3.45	0.46	3.10
46	BL4762	2.3	5.7	3.40	3.95	0.96	3.57	0.49	3.22
47	NL1371	2.0	5.5	3.55	3.73	1.03	3.27	0.42	2.88
48	NL1372	1.3	6.8	5.50	4.05	1.29	2.97	0.34	2.18
49	NL1373	3.0	5.3	2.30	4.10	0.70	3.94	0.60	3.78
50	NL1374	1.6	5.0	3.45	3.28	1.10	2.78	0.30	2.37
51	NL1375	2.6	5.9	3.25	4.23	0.89	3.90	0.59	3.60
52	NL1376	1.4	3.9	2.55	2.63	1.05	2.29	0.20	2.01
53	NL1377	1.7	4.6	2.95	3.13	1.03	2.75	0.29	2.43
54	BL4869	1.6	5.0	3.45	3.28	1.10	2.78	0.30	2.37
55	NL1300	2.4	6.0	3.60	4.15	0.97	3.74	0.54	3.37
56	NL1303	1.7	3.4	1.65	2.53	0.79	2.39	0.22	2.26
57	NL1305	1.6	4.1	2.50	2.85	0.98	2.56	0.25	2.30
58	NL1306	1.8	5.6	3.80	3.70	1.09	3.17	0.39	2.72
59	NL1308	2.9	7.0	4.05	4.93	0.93	4.49	0.78	4.09
60	NL1310	2.9	5.1	2.25	3.98	0.71	3.81	0.56	3.66
61	BL4407	1.4	5.5	4.10	3.45	1.19	2.77	0.30	2.23
62	BL4708	1.5	5.1	3.60	3.25	1.14	2.71	0.28	2.25
63	NL1202	2.7	5.8	3.10	4.25	0.85	3.96	0.61	3.68
64	NL1307	1.6	5.3	3.65	3.43	1.11	2.90	0.33	2.45
65	NL1327	2.4	4.6	2.20	3.45	0.77	3.27	0.41	3.10
66	NL1368	1.1	4.3	3.15	2.68	1.19	2.16	0.18	1.75
67	NL1369	2.3	6.6	4.35	4.43	1.05	3.85	0.58	3.36
68	Bhrikuti (C)	1.4	5.7	4.25	3.53	1.20	2.81	0.31	2.24
69	Vijay (C)	2.3	5.0	2.75	3.63	0.88	3.35	0.44	3.10
70	Tilottama (C)	0.8	5.1	4.30	2.90	1.36	1.95	0.15	1.31
71	NL971 (C)	1.5	5.2	3.70	3.35	1.14	2.79	0.30	2.33
72	BL4341 (C)	1.5	5.3	3.80	3.35	1.16	2.76	0.30	2.27
	Mean	1.9	5.1	3.17	3.49	1.00	3.09	0.38	2.74

E.N. =Entry number of the genotype, Y_s=Yield under stress (t/ha); Y_n=Yield under non-stress (t/ha); TOL=Tolerance; MP=Mean Productivity; SSI=Stress Susceptibility Index; GMP=Geometric Mean Productivity; STI=Stress Tolerance Index; HMP=Harmonic Mean Productivity; BL=Bhairahawa line; NL=Nepal line; C= Released and popular varieties as checks.

ance indices. The genotype NL1372 emerges with the highest tolerance value (TOL) of 5.50, followed closely by BL4947 (4.45), NL1369 (4.35), and NL1414 (4.35), signifying their lower tolerance to stress. The standard check varieties, Tilottama (4.30) and Bhrikuti (4.25), also showed high TOL values. Conversely, genotypes like NL1303 (1.65), NL1419 (1.75), and NL1350 (2.05) displayed the lowest TOL values, underscoring their high resilience to stress. These genotypes exhibited a notable consistency in yield contrasting environments, indicative of stability as proposed by Rosielle & Hamblin (1981). However, it's crucial to note that while this characteristic suggests resilience to fluctuating environments, it does not imply high yield performance. Thus, relying solely on TOL isn't sufficient as the criterion for genotype selection under stress conditions. Likewise, the stress susceptibility index (SSI) revealed notable differences among genotypes. NL1373 showed the lowest SSI value at 0.7, closely followed by NL1310 (0.71) and NL1327 (0.77). A low SSI value suggests genotype with high yield especially under stressed condition. The entries, particularly NL1373 and NL1310, demonstrated high yields across both environments. On the contrary, the genotypes Tilottama (1.36) followed by NL1372 (1.29), NL1358 (1.2) and Bhrikuti (1.2) exhibited the highest SSI, indicating their lower yield under stress. Among the reference varieties, Vijay (0.88) was least stress susceptibility with an SSI of 0.88. Guttieri *et al.* (2001) suggests, more than one SSI implies above-average susceptibility, whereas less than that suggests below-average susceptibility to stress. The genotype with highest percentage of yield reduction showed high stress susceptibility index and the genotype with lowest percentage of yield reduction showed lowest SSI value. Similar results had been previously reported in wheat in Iran Dorostkar *et al.* (2015). Guttieri *et al.* (2001) has also used SSI and grain yield to identify drought-resistant wheat varieties. According to Kamrani *et al.* (2018), SSI identifies high-yielding genotypes under both conditions as stress tolerant, while TOL labels low-yielding ones under both conditions as stress-tolerant. Hence, SSI comes as more reliable parameter to TOL for selecting genotypes under stress conditions.

Based on STI, genotypes NL1308 (0.782), NL1407 (0.668), BL4868 (0.658) and BL4947 (0.638) were superior for stress condition. Similar ranking was observed for mean productivity value (MP). Conversely, the genotypes NL1358, NL1368 and Tilottama showed the lowest STI value of 0.190, 0.181 and 0.147, respectively. With lowest values of mean productivity (MP), genotypes NL1368 (2.675), NL1376 (2.625) and NL1303 (2.525) fell into stress susceptible types. Harmonic mean productivity (HMP) identified NL1308 (4.09), NL1373 (3.78), NL1407 (3.70) and BL4868 (3.69) as stress tolerant genotypes. GMP serves as an additional index commonly utilized by breeders to assess stress-tolerant genotypes, offering a superior means of discerning between sensitive and resistant varieties. STI and GMP prioritize genotypes with high yields in both stressful and non-stress conditions, while SSI focuses on stress specific performance (Kamrani *et al.*, 2018). The genotypes NL1373, NL1308, NL1407, BL4868, and BL4947 were the elite type as conferred by most of the stress tolerance indices.

Correlation analysis among grain yield under stress (Y_s) and non-stress (Y_n) condition and stress tolerance indices

The Pearson's correlation coefficients (r) between Y_n, Y_s, and stress tolerance indices were calculated to identify the most appropriate stress tolerance index (Table 5). A moderate positive correlation between Y_s and Y_n was observed in this study, resembling findings from Kamrani *et al.* (2018). This suggests a modest likelihood of selecting high-yielding genotypes for one environment based on performance in the other. Yield under stress condition (Y_s) displayed a strong positive correlation with several key indices: notably, MP (r=0.74), GMP (r=0.92), STI (r=0.91), and HMP (r=0.98), while showing a strong negative correlation with SSI (r=-0.78). Similarly, a strong positive correlation was observed between grain yield under non-stress (Y_n) conditions and tolerance indices such as TOL (r=0.8), GMP (r=0.74), STI (r=0.75), and MP (r=0.92), with Y_n having moderate positive correlation (r=0.57) with HMP. These results indicate that, especially, GMP, STI, and MP were strongly positively correlated with both Y_n and Y_s. Furthermore, HMP, GMP and STI were found to be very strongly influenced by yield under stress, while MP by yield under non-stress conditions. In addition, the nearly perfect positive correlation (r=0.99) between STI and GMP indicates their remarkable similarity. Likewise, TOL exhibited a weak negative correlation (r=-0.2) with Y_s, and strong positive correlation with Y_n. So, smaller values of TOL provide genotypes with low yield differences (high stability) between stress and non-stress conditions, although the yield level of the genotype remains uncertain. The strong negative correlation of Y_s with SSI indicates that smaller values of SSI provide highly

Table 5. Correlation between grain yield under stress and non-stress condition and stress tolerance indices.

	Y_s	Y_n	TOL	MP	SSI	GMP	STI
Y_n	0.420**						
TOL	-0.2	0.804**					
MP	0.745**	0.918**	0.503**				
SSI	-0.778**	0.226	0.754**	-0.174			
GMP	0.917**	0.741**	0.199	0.946**	-0.473**		
STI	0.905**	0.752**	0.218	0.949**	-0.450**	0.995**	
HMP	0.980**	0.573**	-0.024	0.850**	-0.653**	0.965**	0.965**

* $p<0.05$, ** $p<0.01$, (Y_s)Yield under stress; (Y_n) Yield under non-stress; (TOL) Tolerance; (MP) Mean Productivity; (SSI) Stress Susceptibility Index; (GMP) Geometric Mean Productivity; (STI) Stress Tolerance Index and (HMP) Harmonic Mean Productivity.

stress-tolerant genotypes, aligning with previous findings of Dorostkar (2015) in barley under drought, and wheat under heat stress by Kamrani *et al*. (2018). Analysing the correlation matrix, it can be concluded that MP, GMP, STI, and HMP can be very efficient in selecting stress-tolerant genotypes. However, MP, along with STI and/or GMP can provide genotypes that perform well under both conditions. These findings are consistent with findings of Lestari *et al*. (2019) in rice, Bakhshi *et al.* (2021) and Bavandpouri *et al*. (2021) in wheat. Thus, a judicious combination of these indices provides a useful tool for improving stress tolerance in crops.

Bi-plot graph of the genotypes for grain yield under stress versus grain yield under non-stress conditions

The grouping of genotypes according to their performance under stress and non-stress condition has been suggested by Fernandez (1992). The bi-plot below divides the genotypes into four groups based on their performance under stress and non-stress conditions (Figure 5), which were;

1. Group A comprises fourteen genotypes characterized by low yields under stress and high yields under non-stress conditions. These genotypes are: entry no. 48 (NL1372), 68 (Bhrikuti), 58 (NL1306), 16 (NL1413), 61 (BL4407), 34 (NL1298), 64 (NL1307), 72 (BL4341), 1 (BL4928), 71 (NL 971), 62 (BL4708), 70 (Tilottama), 50 (NL1374), and 54 (BL4869).

2. Group B consists of twelve genotypes that exhibit high yields under stress but low yields under non-stress conditions. These genotypes are: entry no. 65 (NL1327), 31 (NL1367), 13 (NL1410), 35 (NL1369), 23 (NL1420), 38 (NL1322), 7 (NL1404), 41 (NL1345), 20 (NL1417), 40 (BL4866), 12 (NL1409), and 32 (NL1350).

3. Group C encompasses genotypes that produce high yields under both stress and non-stress conditions. In total, twenty-five genotypes fall into this group: entry no. 59 (NL1308), 10 (NL1407), 30 (BL4868), 3 (BL4947), 63 (NL1202), 49 (NL1373), 44 (BL4448), 51 (NL1375), 67 (NL1369), 60 (NL1310), 26 (NL1423), 55 (NL1300), 36 (BL4820), 9 (NL1406), 46 (BL4762), 17 (NL1414), 45 (BL4758), 15 (NL1412), 33 (NL1349), 69 (Vijay), 25 (NL1422), 47 (NL1371), 8 (NL1405), 11 (NL1408), and 14 (NL1411).

4. Group D comprises twelve genotypes that exhibit poor performance under both stress and non-stress conditions. These genotypes are: entry no. 56 (NL1303), 22 (NL1419), 52 (NL1376), 37 (NL1318), 19 (NL1416), 18 (NL1415), 57 (NL1305), 66 (NL1368), 27 (NL1358), 4 (BL4952), 43 (NL1370), 5 (BL4954), 2 (BL4946), 53 (NL1377), 39 (BL4818), 28 (NL1360), 6 (NL1403), 24 (NL1421), 29 (NL1344), 42 (NL1362), and 21 (NL1418).

The genotypes identified as high yielding under both stress and non-stress conditions indicates their possibility for broader adaptation and productivity enhancement in drought affected agricultural settings. The use of bi-plot graphs has been instrumental in identifying stress-tolerant genotypes in various crops. Kandel *et al*. (2019) has utilized this method to group maize genotypes under normal and heat stress conditions and Shojaei (2022) under normal and humidity stress conditions. Yahoueian (2017) used bi-plot graphs in combination with drought tolerance indices to screen drought-tolerant and sensitive genotypes in soybean. These studies collectively demonstrate the effectiveness of bi-plot graphs in identifying stress-tolerant genotypes in various crops.

Conclusion

Water is the most essential component for the growth, development, and reproduction of living organisms, including plants. It plays a crucial role in the synthesis of a wide range of substances within the plant body, from the simplest molecules to the most complex structures. Crop growth and development are significantly hampered by drought conditions. Under irrigated conditions with the appropriate variety and inputs, wheat crops can achieve high yields. Conversely, under moisture-limited conditions, wheat crops experience a drastic reduction in yields. Field-based selection has been largely applied in achieving yield improvements for drought stressed environments. In this experiment, drought exerted severe effects on the morphological, agronomical, and yield attributing traits of the tested genotypes, with the most noticeable impact observed on grain yield. Through stress tolerance indices, certain genotypes—NL1373, NL1308, NL1407, BL4868, and BL4947—stood out for their exceptional performance under both stress and non-stress conditions. Additionally, bi-plot analysis identified twenty-five genotypes as high yielders under both the environmental conditions. These findings underscore the urgency of developing drought-resistant wheat varieties to mitigate the adverse effects of drought on wheat productivity. The identified genotypes hold significant promise for future breeding efforts aimed at enhancing resilience and ensuring food security in the face of increasingly unpredictable climatic conditions.

DECLARATIONS

Author contribution statement

Conceptualization: R.B.R. and P.B.; Methodology: R.B.R.; Software and validation: K.R.P. and R.B.R.; Formal analysis and investigation: R.B.R. and P.B.; Resources: R.B.R. and P.B.; Data curation: R.B.R.; Writing—original draft preparation: R.B.R., D.R.Y. and P.B.; Writing—review and editing: R.B.R., D.R.Y and K.U.; Visualization: K.R.P.; Supervision: N.R.A.; Project administration: R.B.R..; Funding acquisition: R.B.R. and P.B. All authors have read and agreed to the published version of the manuscript.

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