



The traits affecting wheat grain yield and determining tolerant genotypes using drought indices

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Abstract

The determination of genotypes tolerant to drought stress is of major importance in wheat breeding. A two-year split plot field experiment was conducted to determine the traits affecting wheat grain yield and identify the most tolerant genotypes using drought-tolerant indices. Drought stress was applied to 28 genotypes by stoppage of irrigation at the growth stage of 50% inflorescence emergence. Crop yield and growth components were determined. Drought tolerance indices, correlation coefficients, multiple regression as well as path and cluster analyses were applied to determine the most tolerant genotypes. Analysis of variance indicated significant differences among genotypes in terms of growth and yield. The genotype by treatment interaction was also significant. Drought tolerance indices indicated that Darya, Aftab, URBWYT-94-2 and URBWYT-94-4 were the most tolerant genotypes. URBWYT-94-2 had the highest average grain yield under drought stress. Correlation coefficients indicated a significant and positive correlation between geometric mean productivity (GMP) and mean productivity (MP) indices as well as between stress susceptibility (SSI) and drought tolerance (TOL) indices ($p \leq 0.01$). Stress tolerance index (STI) was significantly correlated with MP and GMP. A significant correlation was found between harmonic (HARM), STI, GMP and MP indices ($p \leq 0.01$). STI and GMP were the most suitable indices to identify drought-tolerant wheat. According to path analyses, the correlations among wheat yield components were positive and significant.

Keywords Correlation · Path analysis · Regression · Water stress · Yield components

Abbreviations

GMP	Geometric mean productivity
MP	Mean productivity
SSI	Stress susceptibility
TOL	Drought tolerance
STI	Stress tolerance
HARM	Harmonic index

Introduction

Wheat (*Triticum aestivum* L.) is the most important cereal crop in the world, known as a source of carbohydrate, with economic significance. The sustainable development of high-yielding wheat genotypes is essential for feeding the increasing world population. Since 1960, the global production of wheat and other cereal crops has increased by three times. To meet the global needs, however, it is essential that global wheat production in 2050 increases further by 60% compared to 2010. A significant part of such an increase may be fulfilled by enhancing the grain yield per hectare including an increase of 1.6% each year up to 2050 (Miransari and Smith 2019). In Iran, 67% of wheat is grown in arid areas (Ahmadizadeh et al. 2011).

Drought is among the most complicated and devastating as well as the most important and common stresses negatively affecting plant growth and yield production (Yang and Zhang 2006; Nezhad Ahmadi et al. 2013). Drought affects wheat yield at all growth stages, but the flowering and grain-filling phases are the most sensitive stages (Farooq et al. 2014; Kazemi et al. 2021). Therefore, efficient strategies

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have to be considered to minimize yield reduction under drought stress, especially during the sensitive growth stages (Sallam et al. 2019; Mohammadi 2020). Drought tolerance is the ability of plant to maintain its biomass production under stress conditions (Tardieu et al. 2018).

Drought stress decreases wheat grain yield via the reduction of 1000 grain weight, the number of spikes per area and the number of spikelets per spike (Shamsi et al. 2011; Rahimi et al. 2019).

Severe water shortage significantly affects physiological, metabolic and morphological processes in plants, as demonstrated, e.g., for safflower (Zafari et al. 2020), resulting in the reduction of yield and quality (Zhang et al. 2018). One of the most important goals of breeders is the development of genotypes, which can efficiently grow in different environments. Accordingly, genotypes are tested in multi-environment trials to determine their interactions with each environment (Becker and Léon 1988). To develop genotypes with greater sustainability and stability, the selection of genotypes with superior resistance or tolerance to biotic and abiotic stresses is essential. Rosielle and Hamblin (1981) defined the difference between genotype's yield under stressed and non-stressed conditions as stress tolerance.

A variety of drought tolerance indices has been proposed for the selection of tolerant crop genotypes (Jamshidi and Javanmard 2018) including drought tolerance index (TOL), mean productivity index (MP), stress tolerance index (STI), geometric mean productivity index (GMP), harmonic mean productivity index (HMP) and stress susceptibility index (SSI).

Although there has been research on the use of drought tolerance indices for the selection of tolerant wheat genotypes, continuous research under natural conditions is necessary to identify the most suitable genotypes in the current germplasm for planting under the current climatic conditions in the face of climate change. The present study was an attempt to determine the traits affecting wheat grain yield and to identify the most tolerant wheat genotypes using drought tolerance indices, correlation coefficients, multiple regression, path and cluster analyses.

Materials and methods

Twenty-eight wheat (*Triticum aestivum*) genotypes (i.e., 18 breeding lines and 10 cultivars) were tested in 2016 and 2017 in a split plot design on the basis of a randomized complete block design (RCBD) with three replicates. The experiments were carried out at the Research Station of the Faculty of Agriculture, Islamic Azad University, Tabriz Branch (35° 08' and 35° 12' N, 46° 08' and 46° 40' E; 1360 m a.s.l.). The region is characterized by a semiarid climate with cold winters and an annual long-term mean temperature of 10 °C.

The average yearly temperature of the region was in the range of 6.0–18.3 °C and 8.5–20.7 °C in the first and second year, respectively, with an average yearly rainfall of 264.3 and 313.8 mm (Table S1). The soil of the research fields is a brown soil, and is not deep, with the texture of sandy loam.

One experiment was conducted under irrigation (S1), the other under drought stress (S2) by the stoppage of irrigation at BBCH 55 (50% inflorescence emerged). An experimental plot consisted of 4 m long double rows with 25 cm spacing between rows and 160 plants per row. Planting and harvesting were carried out in mid-April and late August, respectively. Management of the plots (e.g., thinning, weeding, etc.) was the same for all plots in both treatments except for irrigation, which was reduced in the stress treatment.

Ten plants were collected from each plot at different growth stages, and yield-related components, i.e., grain yield (Y), number of spikes (NS), number of grains per spike (NGS), spike length (SL), thousand grain weight (TGW), peduncle length (PL), biomass yield (B), plant height (PH) and harvest index (HI), were measured.

Tolerance indices

Fischer and Maurer (1978) defined the stress susceptibility index (SSI) for the measurement of yield stability and the indication of the changes in both potential and actual yields in different environments as:

$$SSI = \frac{1 - \frac{Y_s}{Y_p}}{1 - \frac{\bar{Y}_s}{\bar{Y}_p}}$$

where Y_p is the potential yield of a genotype under non-stress conditions, Y_s the potential yield of a genotype under drought stress, \bar{Y}_p the average yield of all genotypes under non-stress conditions, and \bar{Y}_s the average yield of all genotypes under drought stress.

Rosielle and Hamblin (1981) defined the mean productivity index (MP) and drought tolerance index (TOL) as

$$MP = \frac{Y_p + Y_s}{2}$$

and

$$TOL = Y_p - Y_s$$

Fernandez (1992) defined the stress tolerance index (STI) and the geometric mean productivity as:

$$STI = \frac{Y_p}{\bar{Y}_p} \times \frac{Y_s}{\bar{Y}_s} \times \frac{\bar{Y}_s}{\bar{Y}_p} = \frac{Y_p \times Y_s}{(\bar{Y}_p)^2}$$

and

$$GMP = \sqrt{Y_s \times Y_p}$$

Accordingly, genotypes with higher values for both parameters are more drought tolerant. Finally, the harmonic mean index (HARM) (Kumar et al. 2016) is defined as:

$$HARM = \frac{2(Y_p \times Y_s)}{Y_p + Y_s}$$

Statistical analysis

Kolmogorov–Smirnov and Bartlett’s tests were used to check for normal distribution and variance homogeneity, respectively. A three-factorial ANOVA with (a) genotypes, (b) years and (c) treatments as factors was conducted for the two years and in both experimental conditions. Least significant difference (LSD) test was used for mean comparisons. Correlation analysis was carried out to determine the relationship between the different stress indices as well as between traits. Moreover, stepwise regression, path and cluster analyses were also performed (Bojarian et al. 2019) to determine the most suitable tolerance indices. SPSS and MSTATC were used for data analysis.

Results

Analysis of variance

Analysis of variance indicated significant genotypic effects ($p \leq 0.01$) on all parameters (Table 1). The $G \times S$ interaction was significant for Y, NGS, PH, HI, TGW and B. The interactions $G \times Y$ and $Y \times G \times S$ significantly affected different

traits. The highest and the lowest coefficients of variation were related to NGS and PH, respectively.

Comparison of genotypes using the drought indices

According to the drought tolerance (SSI) and the TOL indices, Karim, Qaboos, Zagros, Aftab, URBWYT-94-3, URBWYT-94-6, URBWYT-94-7, URBWYT-94-8, URBWYT-94-9, URBWYT-94-2 and URBWYT-94-4 had the highest Y_s values among other genotypes (Table 2). However, MP, Darya, Aftab, ERWYT-94-4, ERWYT-94-7, URBWYT-94-2 and URBWYT-94-4 resulted in the highest yield. For GMP also Darya, Aftab, ERWYT-94-4, URBWYT-94-2 and URBWYT-94-4 had the highest Y_s values. STI was the highest for Darya, Shiroudi, Aftab, ERWYT-94-4, URBWYT-94-6, Roshan, ERWYT-94-7, URBWYT-94-7, URBWYT-94-8, URBWYT-94-9, URBWYT-94-10, URBWYT-94-2 and URBWYT-94-4. The results also showed that Karim, Qaboos, Aftab, URBWYT-94-3, URBWYT-94-7, URBWYT-94-9 and URBWYT-94-2 outperformed other genotypes in terms of SSI. According to the HARM index, Darya, Aftab, URBWYT-94-2 and URBWYT-94-4 were identified as the most drought-tolerant genotypes. It should be noted that URBWYT-94-2 had the highest average yield under drought stress conditions (Table 2).

Correlation among drought tolerance indices

Correlation coefficients among drought tolerance indices indicated that GMP and MP were positively correlated ($p \leq 0.01$; Table 3). The correlations between SSI and TOL as well as between STI, MP and GMP were also found to be significant ($p \leq 0.01$). The HARM and STI as well as the GMP and MP indices were also significantly correlated

Table 1 Combined analysis of variance indicating the effects of different experimental treatments on the measured traits

S.V	d.f	M.S								
		Y	NS	NGS	SL	1000GW	PL	B	PH	HI
Year (Y)	1	11,815.21 ^{ns}	7864.12 ^{ns}	107.63 ^{ns}	5.21 ^{ns}	215.51*	32.06 ^{ns}	81,250.55 ^{ns}	152.33 ^{ns}	97.06 ^{ns}
Stress (S)	1	21,938.36 ^{ns}	6958.27 ^{ns}	289.87 ^{ns}	3.54 ^{ns}	328.36 ^{ns}	42.14 ^{ns}	184,670.34 ^{ns}	271.61 ^{ns}	112.37 ^{ns}
$Y \times S$	1	4115.08 ^{ns}	4715.36 ^{ns}	98.17 ^{ns}	2.73 ^{ns}	63.29 ^{ns}	28.67 ^{ns}	47,181.77 ^{ns}	184.14 ^{ns}	63.59 ^{ns}
E_1	8	2447.17	2518.09	49.33	3.89	26.81	18.23	28,711.07	64.29	28.46
Genotype (G)	27	19,827.01**	17,764.27**	455.33**	15.22**	308.42**	96.81**	256,140.23**	386.35**	148.14**
$Y \times G$	27	6965.04**	6344.25**	152.29**	4.9**	102.67**	36.46*	75,383.66**	127.15**	58.19**
$S \times G$	27	13,462.17*	8547.08 ^{ns}	201.14*	5.8 ^{ns}	228.42**	35.44 ^{ns}	198,269.71**	221.62*	83.26*
$Y \times S \times G$	27	6584.11**	5273.21**	104.14*	3.9**	77.4**	32.38*	65,090.3**	108.36**	40.2*
E_2	216	3481.32	2115.32	65.27	2.08	36.5	20.58	32,039.12	56.67	23.46
CV (%)		15.37	10.34	19.07	15.21	15.62	17.04	18.82	9.52	11.96

ns, ** and * non-significant, and significant at 1 and 5% level of probability, respectively

M.S., mean of square; S.V., source of variation; d.f., degree of freedom; Y, yield; NS, number of spikes; NGS, number of grains per spike; SL, spike length; 1000 GW, 1000-grain weight; PL, peduncle length; B, biomass; PL, plant height; and HI, harvest index

Table 2 Mean of grain yield under non-stress ($Y(p)$) and drought stress conditions ($Y(S)$) and their related drought tolerance indices

Genotype number	Genotype name	$Y(p)$	$Y(S)$	TOL	MP	GMP	STI	SSI	HARM
1	Darya	485.6	268.5	217.07	377.08	361.12	1.28	2.21	345.83
2	Morvarid	351.6	232.0	119.63	291.84	285.64	0.8	1.68	279.58
3	Karim	336.8	271.4	65.44	304.1	302.33	0.9	0.96	300.58
4	Gonbad	359.2	207.1	152.12	283.15	272.74	0.73	2.09	262.72
5	Qaboos	313.0	255.4	57.55	284.2	282.73	0.78	0.91	281.28
6	Zagros	320.4	254.3	66.02	287.35	285.45	0.8	1.02	283.56
7	Shiroudi	345.8	246.7	189.06	341.24	327.89	1.06	2.14	315.05
8	Superhead	347.0	173.5	173.46	260.22	245.34	0.59	2.47	231.31
9	Aftab	380.5	324.7	55.83	352.61	351.5	1.21	0.73	350.4
10	Dehdasht	357.4	195.4	162.01	276.37	264.23	0.69	2.24	252.62
11	Arta	353.8	218.5	135.31	286.17	278.05	0.76	1.89	270.17
12	URBWYT-94-3	306.1	293.8	12.33	299.94	299.87	0.88	0.2	299.81
13	ERWYT-94-4	500.5	250.1	250.46	375.3	353.79	1.23	2.47	333.51
14	ERWYT-94-6	386.5	218.9	167.69	302.71	290.86	0.83	2.14	279.48
15	URBWYT-94-6	366.3	286.5	79.8	326.42	323.97	1.03	1.08	321.54
16	Roshan	399.3	257.2	142.08	328.26	320.48	1.01	1.76	312.89
17	ERWYT-94-7	445.8	268.7	177.1	375.24	346.09	1.18	1.96	335.29
18	URBWYT-94-7	369.0	300.3	68.68	334.62	332.85	1.09	0.92	331.1
19	URBWYT-94-8	371.8	282.5	89.24	327.13	324.07	1.03	1.19	321.04
20	ERWYT-94-8	398.2	242.9	155.22	320.56	311.02	0.95	1.93	301.77
21	ERWYT-94-9	394.2	226.4	167.72	310.31	298.76	0.88	2.1	287.65
22	URBWYT-94-9	376.1	302.1	73.94	339.12	337.1	1.12	0.97	335.09
23	URBWYT-94-10	400.3	283.5	116.74	341.88	336.86	1.11	1.44	331.91
24	123	408.5	211.3	197.18	309.87	293.77	0.85	2.39	278.5
25	URBWYT-94-2	399.9	331.3	68.62	365.63	364.02	1.3	0.85	362.41
26	ERWYT-94-2	396.5	208.1	188.35	302.31	287.26	0.81	2.35	242.97
27	247	384.6	203.8	180.78	294.22	279.99	0.77	2.32	266.45
28	URBWYT-94-4	402.1	314.6	87.56	358.35	355.67	1.24	1.08	353
	Mean	380.6	254.6307	–	–	–	–	–	–

at $p \leq 0.01$. In general, the highest correlation was found between STI and GMP (Table 3).

Cluster analysis

The cluster analysis (dendrogram) of genotypes according to the drought tolerance indices is presented in Fig. 1, which is also a verification to our correlation analysis. According to the canonical detection function presented in Table 4, genotypes could be assigned to two clusters. The mean and standard deviation value of each cluster is presented in Table 6. The first cluster includes Darya, Shiroudi, Aftab, ERWYT-94-4, URBWYT-94-6, Roshan, ERWYT-94-7, URBWYT-94-7, URBWYT-94-8, ERWYT-94-8, URBWYT-94-9, URBWYT-94-10, URBWYT-94-2 and URBWYT-94-4 genotypes. Compared to the genotypes in the second cluster, the genotypes in the first cluster had the least tolerance in terms of TOL and SSI indices and had the highest tolerance in terms of MP,

GMP, STI and HARM indices. The genotypes in this cluster also proved to have higher yield than the second cluster genotypes under both stressed and non-stressed conditions.

The genotypes including Morvarid, Gonbad, Superhead, Dehdasht, Arta, ERWYT-94-6, ERWYT-94-9, 123, ERWYT-94-2, 247, Karim, Qaboos, Zagros and URBWYT-94-3 were on the second cluster. In this cluster, the mean values of TOL and SSI indices were found to be higher than the total mean value, and the mean values of MP, GMP, STI and HARM indices were found to be less than the total mean. Compared to the first cluster, the genotypes in the second cluster had less grain yield under both stressed and non-stressed conditions. In general, the genotypes of the first cluster outperformed the genotypes of the second cluster in terms of yield under both stressed and non-stressed conditions. Since the genotypes in the first cluster were found to be significantly higher in terms of MP, HARM, GMP and STI indices and non-significant

Table 3 Linear correlation coefficients between drought tolerance indices and between measured plant traits (non-stress treatment below the diagonal, drought stress treatment above the diagonal)

	TOL	MP	GMP	SSI	STI	HARM				
TOL	1									
MP	0.08 ^{ns}	1								
GMP	-0.09 ^{ns}	0.98**	1							
SSI	0.96**	-0.15 ^{ns}	-0.32 ^{ns}	1						
STI	-0.08 ^{ns}	0.98**	0.99**	-0.31 ^{ns}	1					
HARM	-0.25 ^{ns}	0.93**	0.98**	-0.47*	0.98**	1				
Traits	Y	NS	NGS	SL	TGW	PL	B	PH	HI	
Y		0.78**	0.86**	0.43*	0.7**	0.45*	0.72**	0.52**	0.69**	
NS	0.75**		0.68**	0.49**	0.58**	0.54**	0.72**	0.61**	0.39*	
NGS	0.86**	0.68**		0.8**	0.48**	0.27 ^{ns}	0.61**	0.51**	0.35 ^{ns}	
SL	0.74**	0.56**	0.85**		0.3 ^{ns}	0.26 ^{ns}	0.47*	0.37 ^{ns}	0.15 ^{ns}	
TGW	0.52**	0.55**	0.39*	0.37*		0.45*	0.47*	0.33 ^{ns}	0.51**	
PL	0.40*	0.47*	0.32 ^{ns}	0.29 ^{ns}	0.28 ^{ns}		0.22 ^{ns}	0.43*	0.44*	
B	0.87**	0.81**	0.79**	0.74**	0.57**	0.48**		0.57**	0.00 ^{ns}	
PH	0.54**	0.50**	0.47**	0.55**	0.52**	0.66**	0.67**		0.17 ^{ns}	
HI	0.05 ^{ns}	-0.28 ^{ns}	-0.006 ^{ns}	-0.14 ^{ns}	-0.23 ^{ns}	-0.25 ^{ns}	0.42*	-0.40*		

ns, ** and *: non-significant, and significant at 1% and 5% level of probability, respectively

performance in terms of TOL and SSI indices, they were identified as drought-tolerant genotypes.

Correlation among traits

In normal (non-stress) conditions, the correlation between Y and NS, NGS, TGW, B, PH and PL was significant (Table 3). Correlation of PL with B and PH and correlation of B and PH and HI were positive and significant at $p \leq 0.01$. Correlation of SL with B and PH and TGW and correlation of TGW with B and PH were positive and significant at $p \leq 0.01$. Correlation of NS with NGS, SL, TGW, B and PH and correlation of NGS with SL, B and PH and TGW were positive and significant. Generally, under non-stress condition, correlation of B and PH with all the traits except HI was positive and significant ($p \leq 0.01$). The highest positive and significant correlation coefficient was related to Y with NGS and B, NS with B and NGS with SL.

In stress treatment, the correlation between Y and NS, NGS, TGW, B and PH and HI and PL and SL was significant (Table 3). The correlation of SL with B and the correlation of TGW with PL and B and HI were positive and significant at $p \leq 0.05$. The correlation of NS with NGS, TGW, PL, B and PH and HI was positive and significant, and the correlation of NGS with SL, TGW, B and PH was positive and significant at $p \leq 0.01$. The correlation of PL, PH and HI and the correlation of B and PH were positive and significant. Generally, under stress conditions, the highest, positive and significant correlation coefficients were related to NGS with SL and Y with NS.

Multiple regression analysis

Stepwise regression was used to determine the traits with the highest influence on Y, and to determine the contribution of each trait under normal and stress conditions. The results of stepwise regression in S1 indicated biomass (B) was the first model variable, which had a positive and high association with Y. In the next step, NGS and NS were tested in the model. Accordingly, the contribution of B, NGS and NS explained 84.8% of yield variations (Tables 4 and 5). In S2, NS, tested in the model, had a positive and high correlation with Y, and B in S1 was confirmed by the model. In the next step, TGW, tested in the model, and accordingly NS and TGW explained 70.9% of yield variations (Tables 4 and 5).

Path analysis

Path analysis was performed to determine the correlation between the number of yield-dependent traits as well as cause-and-effect correlations in the 28 genotypes in S1 and S2 conditions according to the multiple regression analysis.

Path analysis of Y traits in non-stress conditions is presented in Table 6 and Fig. 1A. In non-stress conditions, the direct effect of B, NGS and NS on Y was positive. The correlation coefficient among Y and B, NGS and NS was positive and high. The highest positive direct effect on Y in S1 was related to B and NGS, respectively. The highest positive indirect effect was related to NGS via B, where the lowest positive indirect effect was related to NS via NGS. Path analyses of grain yield traits in S2 are presented in Table 6

Fig. 1 **A** Dendrogram of cluster analysis by Ward's method in the spring wheat genotypes on the basis of drought tolerance indices in the two years, **B** path analysis graph of related traits with yield under non-stress conditions, **C** path analysis graph of related traits with yield under drought stress condition

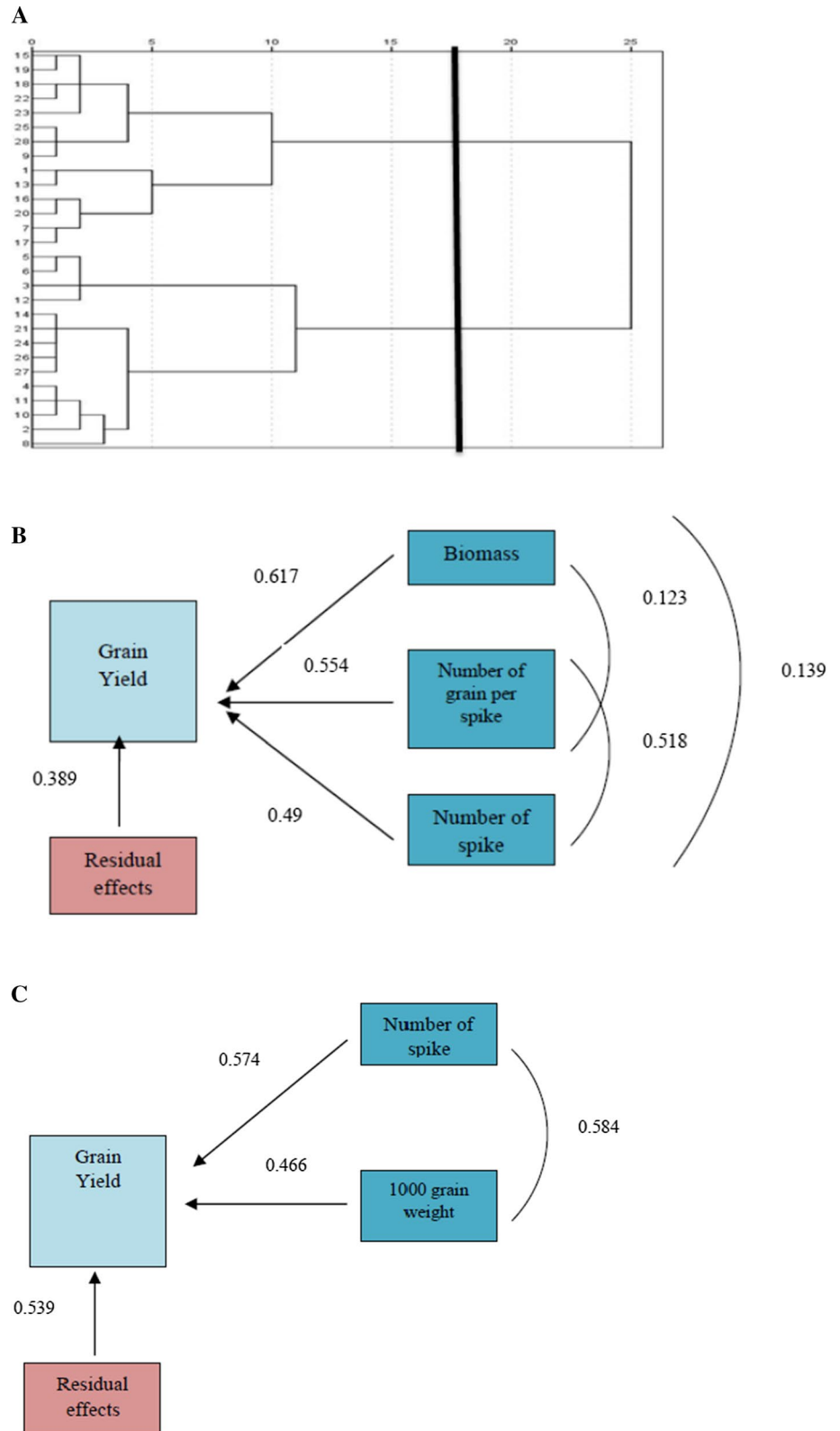


Table 4 Discriminant function analysis or the cutoff point of dendrogram for the clustered genotypes according to the drought tolerance indices

Number of groups	Level of probability		Wilks lambda	Chi-square
2	0.000		0.035	77.138
3	0.061		0.200	37.043
Discrimination function	Eigenvalue	% of Variance	Cumulative %	Canonical correlation
1	4.716	54.1	54.1	0.908
2	4.006	45.9	100	0.895
S.V	<i>d.f.</i>			Mean of square
Regression	2			23,468.926**
Residual	25			336.645
Total	27			R ² =0.848

Eigenvalues, variance, cumulative variance and canonical correlation on the basis of drought tolerance indices in the two years. Multiple regression analysis under non-stress conditions

S.V., source of variation; d.f., degree of freedom

**Significant at 1% level of probability, respectively.

Table 5 Group mean and percentage deviation from the average for the drought tolerance indices

Group	No. of genotype	Cluster	TOL	MP	GMP	SSI	STI	HARM
1	4,11,10,2,28,8,24, 26,27,5,6,3,12,14	Mean	126.53	346.1	339.03	1.48	1.13	332.2
		Percentage deviation from the average	-2.05	8.42	8.95	-8.64	17.71	9.46
2	13,16,20,17,7,22,25, 28,9,1,15,19,18,23	Mean	131.83	292.34	283.36	1.77	0.79	274.76
		Percentage deviation from the average	2.05	-8.42	-8.94	9.26	-17.71	-9.46
		Total mean of indices	129.18	319.22	311.19	1.62	0.96	303.48
Model	Non-standardized regression coefficient		Standard error				Standardized regression coefficient	
Constant	-30.543		40.603					
B	0.192		0.408				0.517	
NGS	5.480		1.557				0.454	
NS	1.15		0.07				0.39	
S.V	<i>d.f.</i>			Mean of square				
Regression	2			16,531.307**				
Residual	25			543.586				
Total	27			R ² =0.709				
Model	Non-standardized regression coefficient		Standard error				Standardized regression coefficient	
Constant	-16.342		41.994					
NS	0.296		0.069				0.574	
1000 GW	4.375		1.591				0.336	

Stepwise regression analysis of yield (dependent variable) with the measured traits (independent variable) under non-stress conditions. Multiple regression analysis under drought stress conditions. Stepwise regression analysis of yield (dependent variable) with the measured traits (independent variable) under drought stress conditions

Table 6 Path analysis of related traits with yield under non-stress condition. Path analysis of related traits with yield under drought stress condition

Traits	Direct effect	Indirect effects via			Liner correlation coefficient via grain yield
		B	NGS	NS	
B	0.617	–	0.123	0.139	0.87**
NGS	0.554	0.216	–	0.096	0.86**
NS	0.49	0.186	0.076	–	0.75**
Residual effects	0.389				

Traits	Direct effect	Indirect effects via		Liner correlation coefficient via grain yield
		NS	1000 GW	
NS	0.574	–	0.124	0.78**
1000 GW	0.466	0.235	–	0.70**
Residual effects	0.539			

**Significant at 1% level of probability, respectively

and Fig. 1B, C. Under stress conditions, the direct effects of NS and TGW on Y were positive. The correlation coefficient between Y and TGW and NS was positive and high. The highest positive direct effect on Y in S2 was resulted by NS. The highest positive indirect effect of TGW was via NS.

Discussion

The results indicated that GMP and STI are the indices, which are the most indicative with respect to wheat drought tolerance. A similar conclusion was obtained by Jamshidi and Javanmard (2018) for barley. They determined the most tolerant genotypes of 26 barley genotypes under salinity stress using the stress tolerance indices in two different fields. They accordingly recognized 10 of the genotypes as the most tolerant ones. The stress tolerance indices were highly and significantly correlated indicating their usability for the determination of the relative salt tolerance of the genotypes. Coefficients of variation were also used to determine the salt tolerance of the genotypes by indicating the plant traits with the highest and the least variation under salinity stress.

Geravandi et al. (2011) also investigated STI in 20 wheat genotypes and indicated its high and significant correlation with the plant physiological traits including stability of cell membrane, retention of leaf water and reduction of leaf water as the most suitable measures to determine the most tolerant wheat genotypes under drought stress. Sio-Se Mardeh et al. (2006) found that the effectiveness of drought tolerance indices is determined by the severity of stress. Accordingly, wheat breeders must select the more suitable indices according to the severity of drought stress. The breeders can improve plant drought tolerance under stress, if they can enhance grain yield and stress tolerance, at the same time (Sallam et al. 2019).

The definition of drought tolerance for breeders is a complex trait indicating the interaction level of genotype \times environment ($G \times E$) (Touzy et al. 2019). The TOL index indicates a genotype yield under stressed and non-stressed conditions, and MP is the arithmetic mean productivity in the non-stressed and stressed conditions. High TOL values are the indicative of genotypes with high susceptibility, under stress, and fewer values indicate the favorable genotypes.

Generally, the indices, which are significantly correlated with crop yield under non-stress and drought stress conditions, can be used as suitable criteria for genotype selection, because such indices can detect high-yielding genotypes under both non-stress and stress conditions (Baenziger 2016; Mohammadi 2020). The results indicated that STI, GMP and MP can effectively identify high-yielding and drought-tolerant cultivars under mild drought stress conditions. Under severe drought stress conditions, however, SSI can be more appropriate (Sioseh Mardeh et al. 2006; Amiri et al. 2014).

Correlation analyses between grain yield and drought tolerance indices indicated that STI, GMP, HARM and MP had the most significant positive correlation with grain yield under both stressed and non-stressed conditions. Therefore, Mondal et al. (2016) and Rahimi et al. (2019) suggested these indices as the most appropriate criteria for detecting drought-tolerant and high-yielding genotypes in both conditions. Similar to our results, Rahimi et al. (2019) identified seed number per spike and 1000-grain weight as the most effective parameters determining wheat grain yield in 320 Iranian bread wheat genotypes. They also found high and significant ($p < 0.01$) correlations between drought-stressed grain yield and yield index (the ratio of yield under stress to the mean yield of all genotypes under stress conditions) ($r = 1^{**}$), geometric mean productivity ($r = 0.86^{**}$), harmonic mean ($r = 0.94^{**}$) and stress tolerance index

($r=0.86^{**}$), which were also confirmed by neural network and cluster analyses. According to their cluster analyses, the higher-yielding wheat genotypes were in the same cluster with the drought-tolerant ones. Their final conclusion was that it is possible to determine the most tolerant wheat genotypes with respect to their morphological and physiological traits and drought tolerance indices, and neural network is a useful tool to determine the relative significance of drought tolerance indices in wheat genotypes.

Correlation analyses between grain yield and drought tolerance indices showed that MP, HMP, GMP and the stress tolerance index STI: (1) had the most significant positive correlations with yield and (2) are the most appropriate criteria for the detection of drought-tolerant genotypes in both experiments. Different researches have indicated MP, GMP and STI are the most suitable criteria for identification of tolerant wheat genotypes (Nouri et al. 2011; Farooq et al. 2014; Chaichi et al. 2019; Poudel et al. 2021). Although correlation coefficients between morphological and agronomic traits are useful in determining the contribution of each yield component to the final yield, simple correlation coefficients do not explain the nature of the traits in general (Albayrak and Tongel 2006). Accordingly, path analysis was suggested by Pearl and Mackenzie (2018) as a direct method of causal inference techniques, used by some researchers in wheat. In the study of traits related to yield, path analysis is used to investigate the effects of traits on yield and the relationship between traits. By using path analysis, it is possible to analyze yield correlation with its components and determine the direct and indirect effects (Ali and Shakor 2012; Tsenov et al. 2021).

Taheri et al. (2011) showed a positive and direct correlation between stress tolerance indices with grain yield, biomass and harvest indices in normal conditions. In stress condition, the significant relationship between stress tolerance indices and awn length, spike length and plant height was observed. The results of path analysis indicated that in all moisture conditions, the most direct effect on stress tolerance indices was related to grain yield. Although yield is commonly used as the main selection index under drought stress, the use of selection indices is more effective than direct selection for grain yield alone. When the selection is based on two or more traits, the relative efficiency will be greater than the independent use of each trait. However, the disadvantage of using indices is that a control/irrigated trial is also required besides the naturally stressed trial. This means the double of work/input. Therefore, this selection strategy is unsuitable for early generation (still segregating) testing but only suitable for advanced breeding lines, which were already selected for other agronomic/quality/resistance traits (Feng et al. 2018).

The obtained indices and correlation coefficients were highly and positively correlated indicating that it is possible

to use such values with high reliability for the proper investigation of wheat responses under drought stress. This is especially important for a sustainable high wheat production under drought conditions (Rahimi et al. 2019).

Similar to the results of other researchers, our study indicated that (1) the indices including geometric mean productivity (GMP) and stress tolerance (STI) are best suitable to identify drought-tolerant wheat genotypes, (2) the most tolerant wheat genotypes under drought stress, which can be used for further research in this respect as well as for the higher production of wheat yield under drought stress and (3) the contribution of each yield and growth component to the final yield under non-stress and stress conditions. Such results are of environmental and economic significance for the farmers and breeders. Drought tolerance indices indicated that Darya, Aftab, URBWYT-94-2 and URBWYT-94-4 were the most tolerant genotypes, and URBWYT-94-2 had the highest average grain yield under drought stress. Such genotypes are available in the Iranian germplasm and can be used by breeders and farmers for a higher yield production under drought stress. Such genotypes can also be available to CIMMYT germplasm and be used by breeders and farmers, worldwide.

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