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Evaluating the effects of genotype mixture and stress tolerant indices in durum wheat (*Triticum durum* Desf.) under drought stress

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ABSTRACT - Drought stress is one of the major limitations in crop production worldwide. Genotype mixture has been evaluated as a new way to increase yield in different crops. In this study, different genotype mix systems in durum wheat (*Triticum durum* Desf.) as impacted by drought stress were investigated. The experiments were conducted under normal and water-stressed conditions in the form of randomized complete block designs, each with three replicates, in the research farm of the College of Agriculture and Natural Resources of Darab, Shiraz University for two years (2016-2017 and 2017 - 2018). Monocultures of four durum wheat genotypes including Shabrang and Behrang cultivars and DW-92-4, DW-94-14 lines and their binary and quadruple mixing combinations were used in the cropping systems. Drought tolerance indices, including stability tolerance index (STI), mean productivity (MP), geometric mean productivity (GMP), stress susceptibility index (SSI), tolerance index (TOL), yield index (YI), yield stability index (YSI) and a new criterion designated as SIIG (Selection Index of Ideal Genotype) were used and evaluated to identify the best cropping system. Behrang+DW-94-14 cropping system showed the highest GMP, STI and MP values of drought indices, while the highest value (0.890) of SIIG index was identified in the Shabrang+DW-94-14 cropping system. Positive correlations were found among GMP, STI, and MP with YP. Moreover, biplot analysis of these indices using principle component analysis revealed strong positive correlations among GMP, STI and MP while SIIG index was closely related to YSI index. GMP, MP, and STI indices were identified as the best criteria to identify cropping systems in water-stressed conditions. In both normal and water-stressed circumstances, quadruple genotype culture yielded better yields than monoculture and most binary cultures. However, the highest seed yield was obtained in the normal and water-stressed treatments in the Behrang + DW-94-14 cultivation system with an average of 8815 and 7342 kg ha-1, respectively.

INTRODUCTION

Agriculture is the biggest consumer of water resources. Water stress or drought is the most challenging environmental stress regarding crop productivity (Mishra and Singh 2010; Farooq et al., 2012). Drought has a significant impact on plant growth traits, including plant growth and development, as well as yield. Water-stressed has a different effect on field crops than it does on wild plants. Water-stressed occurs in many places during grain loading when evapotranspiration is strong owing to increasing air temperatures. Moreover, it has been shown that leaf wilting as one of the first signs of water-stressed in plants happens and then a decrease in plant height, number, and area of leaves and a delay in flowering occurs (Talebi, 2009).

Durum wheat is cultivated on approximately 21 million hectares throughout the world (FAO, 2016), and its products have been a part of the human diet for many years. Currently, most of the durum wheat is grown in the rain-fed and irrigated areas of the Mediterranean region where the plants experience water-stressed and variable environmental conditions during growth and development (Nouri et al., 2011). As a result, the steady performance of the crop during times of water scarcity is crucial for durum wheat production in these locations. A well-known strategy for selecting drought-resistant genotypes is to measure genotype yield in water-stressed and well-watered conditions.

Drought indices can give a gauge of drought impacts based on yield loss during drought compared with normal circumstances (Mitra, 2001). Many breeders have used drought indices to select stable genotypes based on their performance under favorable and stressful conditions (Moosavi et al., 2008; Farshadfar et al., 2013, Mursalova et al., 2015).

There are several selection indices for screening drought resistance genotypes such as stability tolerance index (STI), mean productivity (MP), geometric mean productivity (GMP), stress susceptibility index (SSI), yield index (YI) and yield stability index (YSI), that identify susceptible and resistance (tolerant) genotypes based on their yields in stressed and non-stressed environments. A powerful drought stress index should be able to discriminate genotypes that are superior in the stressed and non-stressed environment. Fernández (1992) indicated that mungbean (*Vigna radiata* L.) genotype selection based on STI and GMP indices resulted in genotypes with higher yields and higher drought tolerance. Clarke et al. (1992) used the SSI index to differentiate among wheat (*Triticum aestivum* L.) genotypes. Sio-Se Mardeh et al. (2006) stated that MP, GMP, and STI are the best indices under moderate stressed conditions in wheat. Ilker et al (2011) showed that MP, GMP, and STI values are suitable parameters to select high-yielding wheat genotypes at both stressed and non-stressed conditions, whereas TOL and SSI parameters are best-fitted values to determine tolerance levels. Nouri et al. (2011) showed that drought stress decreased the yield of some durum wheat genotypes, while other genotypes were resistant to drought. A combination of varying stressed indices has been examined in various crops. For instance, SSI, STI, and GMP were proved to be the most effective criteria to select heat-tolerant and high-yielding genotypes of maize (*Zea mays* L) (Khodarahmpour et al., 2011). Mohammadi and Abdulahi (2017) stated that the SI index is a potent factor in the selection of durum wheat genotypes at water-stressed conditions.

Considering mixed cultivation of various varieties and genotypes of durum wheat may result in more efficient use of water and nutrients and reduce the effect of water-stressed, this study aimed to evaluate different drought tolerance indices and use the SIIG index as an advanced criterion, and also to identify drought-tolerant cropping system in durum wheat genotypes.

MATERIALS AND METHODS

Plant Materials and Experimental Setup

The experiments were conducted as randomized complete block design with three replicates for two years in both normal and water-stressed settings at the research farm of Darab College of Agriculture and Natural Resources, Shiraz University in 2016-1018. Each year was composed of two experiments one at normal irrigation conditions and the second one at water-stressed conditions. The cropping system included the monocultures of four wheat genotypes (monocultures of DW-92-4 and DW-94-14 lines and Shabrang and Behrang cultivars) and their mixed dual culture with a ratio of 50:50 including the mixed culture of DW-92-4 + Shabrang, mixed culture of DW-92-4 + DW-94-14, mixed culture of DW-92-4 + Behrang, mixed culture of Shabrang + DW-94-14, mixed Culture of Shabrang + Behrang, mixed culture of DW-94-14 + Behrang and Quaternary and mixed culture of DW-94-14 + Behrang + DW-92-4 + Shabrang. Behrang and Shabrang genotypes and promising lines DW-92-4 and DW-94-14 were selected among 20 varieties and genotypes of durum wheat so that they had different plant characteristics such as plant height (81-99 cm) and in terms of the sufficient number of days until maturity (145-155 d), they showed approximately the same time.

The characteristics of used genotypes and varieties are shown in Table 1. Each experimental plot (2 × 3 m) consisted of ten rows of plants separated by 20 cm apart.

There were sufficient potassium and phosphorus found in the soil. The total amount of urea used was 350 kg per hectare, which was applied as 15% at planting time, 40% during the tillering stage, 30% during booting, and 15% at the flowering stage. Those plots with normal irrigation treatments received sufficient water during the experiment. Irrigation cut-off was applied after the flowering stage. Experimental plots were harvested after removing the marginal rows and 0.5 m at the beginning and the end of each row to avoid the margin effects.

Sampling, Measurements and Data Analysis

Drought resistance indices were calculated using the following equations:

(1) SSI = [1 - (YS / YP)]/ SI; SI = 1- $\frac{\overline{YS}}{\overline{YP}}$ (Fischer and Maurer, 1978), where YS is the yield of cultivar under water-stressed conditions, YP is the yield of genotypes normal under irrigated conditions, $\overline{YS}$ and $\overline{YP}$ are the mean yields of all genotypes under stressed and non-stressed conditions, respectively, and 1 - YS /YP is the stress intensity.

(2) Tolerance index (TOL) = YP – YS (Hossain et al., 1990)

(3) Mean productivity (MP) = (YP + YS) / 2 (Hossain et al., 1990)

(4) Geometric mean productivity (GMP) $=\sqrt{Yp \times Ys}$ (Fernández, 1992)

(5) Stability tolerance index (STI) = (YS)(YP) /(YP) ^{2} (Fernández, 1992)

(6) Yield index (YI) = YS/$\overline{YS}$ (Gavuzzi et al., 1997; Lin et al., 1986)

(7) Yield stability index (YSI) = YPi / YSi (Bouslama and Schapaugh Jr, 1984).

To integrate different morphological traits, the SIIG index was used as follows:

1- Formation of the data matrix

Regarding the number of genotypes and the number of different indices or descriptors, the data matrix was formed as follows:

$$D=\begin{bmatrix} X_{11} & X_{12} & \cdots & X_{1m} \\ X_{21} & X_{22} & \cdots & X_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ X_{n1} & X_{n2} & \cdots & X_{nm} \end{bmatrix} \quad (1)$$

In this x_{ij} matrix, the value of the index i (i = 1, 2,...n) is concerning the genotype j (j = 1, 2, ... m).

2- Converting the matrix of data to a normal matrix. The following equation was used to normalize the data:

$$r_{ij}=\frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \qquad i = 1,\ldots, n. \quad j = 1, \ldots, m. \quad (2)$$

The matrix R is defined as follows:

$$R=\begin{bmatrix} R_{11} & R_{12} & \cdots & R_{1m} \\ R_{21} & R_{22} & \cdots & R_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ R_{n1} & R_{n2} & \cdots & R_{nm} \end{bmatrix} \quad (3)$$

3- Finding the ideal genotype and non-ideal genotype (weak genotype)

At this stage, the best and worst selected genotype was selected for each indicator or attribute.

Table 1. Characteristics of durum wheat genotypes

Durum wheat genotypes	Ph	TSW	Y (kg. ha^{-1})	DPM	NDS
DW-92-4	99 cm	38 g	7960	145	109
Shabrang	83 cm	39 g	7000	150	114
DW-94-14	81 cm	45 g	6900	155	101
Behrang	93 cm	37 g	4490	148	120

Ph: Plant height, TSW: 1000 seed weight, Y: yield, DPM: Days to physiological maturity, NDS: Number of days to spike

4- Calculating the distance between the ideal genotype and the weak genotype

In this stage, for each indicator, the distance from the ideal genotype (di^+) and the weak genotype (di^-) was calculated from the following equations, respectively:

$$d_i^+ = \sqrt{\sum_{j=1}^{m}(r_{ij-}r_j^+)^2} \quad i= 1, \dots n \qquad (4)$$

$$d_i^- = \sqrt{\sum_{j=1}^{m}(r_{ij-}r_j^-)^2} \quad i= 1, \dots n \qquad (5)$$

In the above equations, r_{ij} is the normalized value of the i index (i = 1, 2,... n) concerning the genotype j (j = 1, 2, ... m). ri^+ and ri^- are the normalized values of the ideal genotype and the weak genotype for each i index (i = 1, 2, ... n), respectively. Furthermore, di^+ is the distance from the ideal genotype and di^- is the distance from the weak genotype. Calculating the selection index of ideal genotype (SIIG)

At the last stage, the selection index of the ideal genotype was calculated from the following equation:

$$\text{SIIG} = \frac{d_i^-}{d_i^+ + d_i^-} \quad 0 \leq SIIG \leq 1 \quad i= 1,2,\dots, m \qquad (6)$$

SIIG value is ranged between zero and one, and the closest value to one corresponds to the closest genotype to the ideal genotype. According to this method, the ideal genotype was obtained from the sum of the ideal values of each index, while the weak genotype was obtained from the sum of the weak values of each index as discussed by Zali et al. (2015) and Zali et al. (2016).

Statistical Analysis

The combined analysis of variance from two years of the experiment was performed using SAS (9.2) statistical software at a probability level of 5%. Variables of year and treatments were assumed as fixed models in data analysis. The average value of two years of study was considered for mean comparisons and calculations of drought indices. The graphs were drawn using Excel and Statistica software. Also, principal component analysis was carried out using Minitab (16.0) software.

RESULTS AND DISCUSSION

The significance of the effect of the year indicated that the environmental conditions of two years of study were different as it is also shown in Table 2. For instance, the total precipitation (627mm) of the 2016-2017 cropping year was much more than that (152.7 mm) of the 2017-2018 cropping year. The results of the combined analysis of variance showed that the effects of year and irrigation were significant (Table 3). Moreover, the significance of irrigation treatment in the experiment demonstrated that water deficiency affects crop yields. The data of the second part of the Table indicated that the effects of cropping systems and the interactions of cropping system * year and cropping system * irrigation were significant but the interaction of cropping system * year * irrigation was non-significant.

The highest grain yield (8815 kg ha^{-1}) was found in the binary mixed culture of Behrang+DW-94-14 genotypes, followed by the grain yield (8800 kg ha^{-1}) of the quadruple mixed culture of 4 genotypes (Shabrang+Dw-92-4 + Behrang + DW-94-14) at normal irrigation conditions (Fig. 1 and Table 4). Pure culture of genotype DW-92-4 produced a high yield at both normal irrigation and water-stressed conditions.

Drought tolerance indices determine different aspects of drought tolerance of genotypes or cropping systems, However, a full agreement between them is not normally occurred (Lepekhov and Khlebova, 2018). Cropping system drought-stressed indicators used in this study are provided in Table 4. For breeders, the variance of these indices might be perplexing at times. Two genotypes with a high or poor yield at both stressed and ideal watering circumstances, for example, have the same SSI. To study the relationships of these different indices, correlation coefficients were calculated, which are presented in Table 5. The correlation between YP and YS was significant in terms of the possibility of indirect selection for drought tolerance genotypes or cropping systems in different conditions. Results of the analysis of correlation coefficients showed that there is a low relationship between YS and YP (r = 0.396). Many studies showed similar results indicating no or weak relationship between YP and YS (Zebarjadi et al., 2012; Yasir et al., 2013; Lepekhov and Khlebova, 2018), although there are other reports which indicated positive and significant relationships between YS and YP (Farshadfar et al., 2013; Abdolshahi et al., 2013; Patel et al., 2019).

Geometric Mean Production (GMP) and Mean Production (MP) are among the most common drought tolerance indices and both of them indicate the average amount of grain yield under optimal and conditions. The range of GMP was between 8302.73 (pure culture of DW-92-4) and 3879.03 (DW-92-4+Behrang). A similar result was obtained for the MP index with the highest value of MP (8310.16) for DW-92-4, but the lowest value of MP (4165.9) belonged to the pure culture of Behrang. Furthermore, STI and YI indices followed the same trend as GMP and MP indices in which the highest STI and YI indices belonged to DW-92-4, but the lowest values of STI (0.34) and YI (0.39) indices were related to DW-92-4 + Behrang cropping system (Table 4).

Table 2. Meteorological details in Fars-Darab Agricultural Research Station for two successive growing seasons (2016-2018).

	2016-2017				2017-2018			
Month	Precipitation (mm)	Absolute temp (°C)		Mean temp	Precipitation (mm)	Absolute temp (°C)		Mean temp
		Min.	Max.			Min.	Max.	
Oct.	0	11.6	38.8	25.2	0	11.8	35.8	24.5
Nov.	0	6.4	31.4	19.2	1.9	4.8	32.4	18.5
Dec.	27.5	0.2	27	13.8	26.2	0	24.4	12.1
Jan.	7.4	-0.4	26.8	13.2	1.3	-1	25	11.7
Feb.	422.9	-0.4	18.8	10.4	0.4	-0.8	27.4	12.9
Mar.	93.5	3.2	25.4	13.8	62	4.4	27	15.6
Apr.	47.8	3.8	28.2	17.8	55.2	8.6	34	19.7
May.	0	10.4	40.4	26.2	1.2	13.6	38	26.2
Jun.	0	16.8	42.4	29.2	0	16	43	31.1
Jul.	0	23.2	43.6	34.3	4.5	21.8	43.6	33.9
Aug.	27.9	19.4	43.8	33.6	0	22.2	42.4	34
Sep.	0	18	41.2	31	0	17.8	39.4	29.8
Total	627	-	-	-	152.7	-	-	-

Table 3. Combined analysis of variance for grain yield in different experiments

Source of variation (SOV)	df	Grain yield
Year (Y)	1	942505**
Irrigation (I)	1	1098164**
Replication (R) * Y * I (error a)	8	73214
Cropping system (C)	10	12562787**
C * Y	10	6105804**
C * I	10	2892346**
C * Y * I	10	61756^{ns}
error b	80	50373
CV (%)		21.3

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

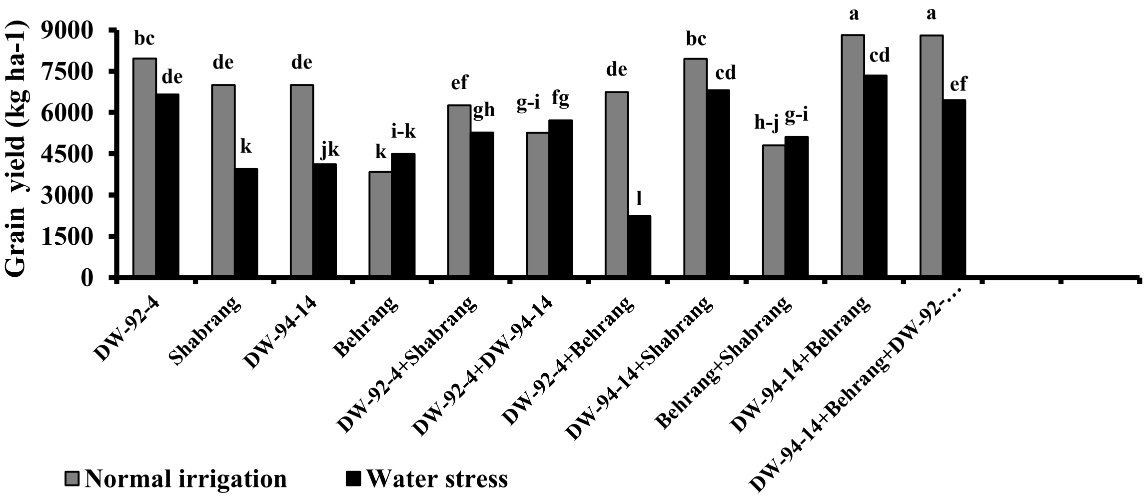

Fig. 1. Grain yield of durum wheat cropping systems under normal and water-stressed conditions. Means followed by the same letter(s) are not significantly different at 1% probability.

Analysis of the coefficient of correlations showed that there was a strong and positive correlation between MP and GMP (r = 0.994**), GMP and STI (r = 0.995**), GMP and YI (0.908**), MP and STI (r = 0.994**) and STI and YI (r = 0.899**) (Table 5). Many researchers reported similar results (Mohammadi et al., 2010; Farshadfar et al., 2013; Lepekhov and Khlebova 2018; Patel et al., 2019). Because genotype DW-92-4 showed the highest value of these indices in this study, it is introduced as a viable cultivar for durum wheat producers in normal and water-stressed settings. Furthermore, following this genotype, it was a mixed culture of DW-94-14+Behrang which showed the highest value of GMP, MP, STI, and YI after pure culture of DW-92-4 treatment. This was followed by quadruple culture of 4 genotypes (DW-92-4+DW-94-

14+Behrang+Shabrang), and then by DW-94-14+Shabrang (Table 4). These results demonstrated that these mixed cultivations of genotypes are successful cropping systems and the strategy of mixed cultures of genotypes can be an agro-ecologic way to reduce the negative effects of water deficiency in dry regions.

On the other hand, results showed that TOL and SSI indices have opposite rankings compared to GMP, MP, STI and YI indices. These indices both designated that mixed culture of DW-92-4 + Behrang (TOL= 4503.43 and SSI= 4.47) followed by a pure culture of Shabrang genotype (TOL= 3055.43 and SSI= 2.92) followed by the pure culture of Dw-94-14 genotype (TOL= 2868.7 and SSI= 2.74) had the highest of TOL index among the cropping systems indicating the sensitivity of these cropping systems to water deficiency. Other drought tolerance indicators such as GMP, MP, STI, and YI have previously revealed the lowest values for these cropping systems. DW-92-4 (TOL= -702.4 and SSI= -0.59), on the other hand, was one of the most tolerant genotypes in this study, and other mixed cultures, such as DW-94-14 + Shabrang (TOL=-1355.0 and SSI=-1.40), had a low amount of these values among the other cropping systems, indicating that TOL and SSI indices have inverse rankings when compared to GMP and MP indices.

The analysis of correlation coefficients (Table 5) showed that there are very significant associations ($r = 0.994^{*}$) between TOL and SSI indices. Another strong negative correlation was obtained between SSI and YSI ($r = -1.0^{**}$), and TOL and YSI ($r = -0.993^{**}$) indices.

According to the yield index (YI), DW-92-4 (1.53), DW-94-14+Shabrang (1.38), DW-94-14+Behrang (1.30), DW-94-14+Behrang+DW-92-4+Shabrang (1.14) and DW-94-14+DW-92-4 (1.01) cropping systems were chosen as the most tolerant cropping systems. Based on the SSI index, the cropping systems of DW-94-14+Shabrang (-1.40) and pure Behrang genotype (-1.14) displayed the lowest value of SSI (Table 4).

The TOL index measures the absolute difference in yield between favorable and drought circumstances for a genotype or cropping system. This disparity may be explained by a drop in production during drought and an increase in yield under favorable circumstances in a moisture-deficient environment. So, the TOL index explains the sensitivity of yield under optimal and water-stressed conditions (Fernández, 1992). Similarly, the lower value of the SSI index indicates small changes in the yield of a genotype or cropping system under water-stressed conditions compared to normal conditions, and therefore the stability of the genotype's yield under normal conditions is higher. (Table 4). Yasir et al. (2013) reported that bread wheat genotypes with high values of TOL and SSI were able to produce high yields only in a non-stressed environment. Mevlut and Sait (2011) stated that genotypes or cultivars with high STI normally have a high difference in yield at two different conditions. They found that the genotypes scored similarly on the GMP and MP parameters, as well as the STI index, indicating that these factors are almost comparable for identifying drought-tolerant genotypes or cropping systems.

According to the YSI index, genotypes with higher values of this index were more stable under water-stressed conditions. Thus, the DW-94-14 + Shabrang cropping system with the highest value (1.21) of this index was the most stable cropping system under water-stressed conditions in the current study (Table 4), indicating that mixed culture of genotypes is a useful strategy to reduce the effect of water-stressed conditions.

Table 4. Grain yield of durum wheat cropping systems under normal and water-stressed conditions, and drought tolerance indices of durum wheat cropping systems

Cropping system	YS	YP	GMP	MP	TOL	STI	YI	YSI	SSI
DW-92-4	8661.4	7958.93	8302.73	8310.16	-702.47	1.56	1.53	1.08	-0.59
Shabrang	3942.2	6997.63	5252.24	5469.91	3055.43	0.62	0.69	0.563	2.92
DW-94-14	4123.8	6992.50	5369.88	5558.15	2868.7	0.65	0.73	0.589	2.74
Behrang	4493.3	3838.50	4153.01	4165.9	-654.8	0.39	0.79	1.17	-1.14
DW-92-4 + Shabrang	5265.95	6260.63	5741.79	5763.29	994.68	0.75	0.93	0.841	1.06
DW-94-14 + DW-92-4	5710.6	5263.63	5482.56	5487.11	-446.97	0.68	1.01	1.08	-0.56
DW-92-4 + Behrang	2233.5	6736.93	3879.03	4485.21	4503.43	0.34	0.39	0.331	4.47
DW-94-14 +Shabrang	7804.9	7949.30	7095.09	7127.37	-1355.05	1.14	1.38	1.21	-1.40
Shabrang + Behrang	5112.3	4807.50	4957.55	4959.9	-304.8	0.55	0.90	1.063	-0.42
DW-94-14 + Behrang	7341.7	8815.50	8044.92	8078.6	1473.8	1.47	1.30	0.832	1.12
DW-94-14 + DW-92-4+ Behrang + Shabrang	6447.83	8799.90	7532.61	7623.86	2352.07	1.29	1.14	0.732	1.79

Grain yield (kg ha^{-1}) of cropping systems under water-stressed conditions (YS); Grain yield (kg ha^{-1}) of cropping systems under irrigation conditions (YP) ; Geometric mean productivity (GMP); Tolerance index (TOL); and Mean productivity (MP); Stress tolerance index (STI); Yield index (YI); Yield stability index (YSI); Stress susceptibility index (SSI); Selection index of ideal genotype (SIIG).

Table 5. Correlation coefficients between drought tolerance indices and grain yield of durum wheat genotypes under normal and water-stressed conditions

	YS	YP	GMP	MP	TOL	STI	YI	YSI	SSI	SIIG
YS	1	0.494^{ns}	0.907^{**}	0.867^{**}	-0.661^{*}	0.899^{**}	1.0^{**}	0.657^{*}	-0.660^{*}	0.831^{**}
YP		1	0.787^{**}	0.843^{**}	0.298^{ns}	0.790^{**}	0.496^{ns}	-0.299^{ns}	0.289^{ns}	-0.060^{ns}
GMP			1	0.994^{**}	-0.287^{ns}	0.995^{**}	0.908^{**}	0.289^{ns}	-0.292^{ns}	0.525^{ns}
MP				1	-0.200^{ns}	0.994^{**}	0.868^{**}	0.199^{ns}	-0.202^{ns}	0.445^{ns}
TOL					1	-0.271^{ns}	-0.660^{*}	-0.993^{**}	0.994^{**}	-0.965^{**}
STI						1	0.899^{**}	0.274^{ns}	-0.277^{ns}	0.509^{ns}
YI							1	0.656^{*}	-0.658^{*}	0.830^{**}
YSI								1	-1.0^{**}	0.962^{**}
SSI									1	-0.963^{*}
SIIG										1

Grain yield (kg ha^{-1}) of cropping systems under water-stressed conditions (YS); Grain yield (kg ha^{-1}) of cropping systems under irrigation conditions (YP) ; Geometric mean productivity (GMP); Tolerance index (TOL); and Mean productivity (MP); Stress tolerance index (STI); Yield index (YI); Yield stability index (YSI); Stress susceptibility index (SSI); Selection index of ideal genotype (SIIG).

ns: no significant, ** and *significant at 1% and 5% probability

A Selection Index of Ideal Genotype (SIIG)

Researchers have used different methods of tolerant indices to identify genotypes in terms of drought tolerance. In addition to other drought tolerance indices, the selection index of ideal genotype (SIIG) can combine all of the indices to identify the genotype with the best drought tolerant ability. In this research, the approach was utilized to determine the optimal cropping scheme. Table 6 shows the normalized values of the genotypes' and cropping systems' drought tolerance indices. Regarding the fact that the value of this index is between zero and one, cropping systems whose values are close to one is introduced as the highest (ideal) genotypes or cropping systems and genotypes or cropping systems whose SIIG values are near zero, is considered as one of the weakest genotypes or cropping systems. In Table 6, drought tolerance indices such as GMP, tolerance index (TOL), mean productivity index (MP), drought sensitivity index (SSI), stress tolerance index (STI), performance stability index (YSI), yield index (YI), yield under normal conditions (YP) and yield under water-stressed conditions (YS) are presented. Tables 7 and 8 provide the processes for computing the optimum genotype selection index to help the reader understand how to calculate it.

To evaluate the drought tolerance of genotypes or cropping systems, the SIIG index was used as shown in Table 7. The SIIG index was calculated based on GMP, TOL, MP, SSI, STI, YSI, SSI, and YI indices (Tables 6 and 7). Moreover, the Shabrang+DW-94-14 treatment with the highest SIIG index value (0.890) was the most tolerant cropping system in terms of drought stress. On the other side, the DW-92-4 + Behrang cropping system had the least amount of SIIG (0.011), which is introduced as the most sensitive cropping system compared to other cropping systems. Therefore, it can be inferred that in this research, Shabrang + DW-94-14 cropping system showed a higher drought tolerance than those of other cropping systems, particularly when compared to the pure culture of each genotype.

In general, the SIIG index is a selective model and is used to choose the best genotype under stressed and non-stressed conditions or in different environments. Researchers have utilized the SIIG Index to find the best genotypes based on additional drought tolerance indicators, stability factors, or features in other plants. In this circumstance, improved genotype selection may be more precise and dependable (Zali et al., 2015; Zali et al., 2016). Fernández (1992) described that genotypes could be divided into four groups based on their yield performance in stressed and non-stressed conditions: genotypes that have a high yield in both stressed and non-stressed environments (group A), genotypes that have high yield only in non-stressed conditions (group B), genotypes which have only high yields in stressed environments (group C) and the genotypes with low yield in bathwater stressed and non-water stressed conditions (group D).

The distribution of cropping systems based on their grain yield under normal conditions (YP) and stressed conditions (YS) and SIIG index in a 3-dimensional graph are shown in Fig. 2. Cropping systems of DW-92-4, Shabrang+DW-92-4, Shabrang+DW-94-14, DW-94-14+Behrang, and DW-92-4+Behrang+Shabrang +DW-94-14 in group A indicated that these cropping systems have a high yield in both stressed and non-stressed conditions. The cropping systems of Shabrang, DW-94-14, and Behrang+ DW-92-4 in group B indicated that these cropping systems have only high yields in stressed environments. The cropping system of DW-92-4+DW-94-14 in group C indicated high yield under stressed conditionsand low yield under normal conditions. Cropping systems, including Behrang and Shabrang+Behrangin in group D indicated low yield in both stressed and non-stressed conditions.

According to the results of this study, cropping systems of DW-92-4, Shabrang+ DW-92-4, Shabrang+ DW-94-14, DW-94-14+Behrang and DW-92-4+Behrang+Shabrang +DW-94-14 indicated the best cropping systems compared to the pure culture of other genotypes or other genotype combinations, and they showed higher yields both in normal and water-stressed conditions.

Moreover, Patel et al. (2019) found a negative correlation between the SSI index and the YS index. The study of correlations between drought tolerance indices and yield in normal and stressed conditions showed that the GMP index and MP index were suitable indices in Table 5. GMP, MP, and STI indices had a positive and significant correlation with grain yield in normal irrigation conditions with correlation coefficients of $r = 0.787^{**}$, $r = 0.843^{**}$ and r = 0.790**, respectively. Moreover, GMP, YSI, YI, STI, MP, and SIIG showed a positive and significant correlation with grain yield in stress conditions which indicated that the selection of genotypes for these indices would improve yield under stress conditions as described by Farshadfar and Javadinia. (2011). The correlation coefficients of TOL and SSI indices with grain yield under stressed conditions (YS) were r = -0.661* and r = -0.660*, respectively (Table 5). This indicated that these indices were more effective to identify the high-n other studiesyielding genotypes under optimal conditions rather than stressed conditions.

Table 6. Normalized drought tolerance indices in different cropping systems

Treatment	YI	STI	TOL	MP	GMP	YSI	SSI
DW-92-4	0.447	0.495	-0.100	0.401	0.407	0.360	-0.087
Shabrang	0.203	0.198	0.434	0.264	0.257	0.188	0.432
DW-94-14	0.213	0.207	0.407	0.268	0.263	0.196	0.406
Behrang	0.232	0.124	-0.093	0.201	0.203	0.390	-0.169
DW-92-4+Shabrang	0.272	0.237	0.141	0.278	0.281	0.280	0.157
DW-92-4+DW-94-14	0.295	0.216	-0.063	0.265	0.268	0.360	-0.084
DW-92-4+Behrang	0.115	0.108	0.640	0.216	0.190	0.110	0.661
Shabrang+DW-94-14	0.403	0.361	-0.192	0.344	0.347	0.403	-0.208
Shabrang+Behrang	0.264	0.176	-0.043	0.239	0.243	0.354	-0.063
DW-94-14+Behrang	0.379	0.465	0.209	0.390	0.394	0.277	0.165
DW-92-4+Behrang+Shabrang+DW-94-14	0.333	0.407	0.334	0.368	0.369	0.244	0.264

Grain yield (kg ha^{-1}) of cropping systems under water-stressed conditions (YS); Grain yield (kg ha^{-1}) of cropping systems under irrigation conditions (YP) ; Geometric mean productivity (GMP); Tolerance index (TOL); and Mean productivity (MP); Stress tolerance index (STI); Yield index (YI); Yield stability index (YSI); Stress susceptibility index (SSI); Selection index of ideal genotype (SIIG).

Table 7. Selection index of ideal genotype (SIIG) values and distance from ideal genotype or cropping systems (d+) and distance from non-ideal genotype (d-) and ranking of cropping systems

Treatment	d+	d-	SIIG	Ranking
DW-92-4	0.158	1.231	0.886	2
Shabrang	1.018	0.354	0.258	10
DW-94-14	0.977	0.394	0.288	9
Behrang	0.526	1.148	0.686	4
DW-92-4+Shabrang	0.623	0.766	0.552	7
DW-92-4+DW-94-14	0.415	1.080	0.722	3
DW-92-4+Behrang	1.36	0.015	0.011	11
Shabrang+DW-94-14	0.163	1.313	0.890	1
Shabrang+Behrang	0.483	1.039	0.683	5
DW-94-14+Behrang	0.568	0.856	0.601	6
DW-92-4+Behrang+Shabrang+DW-94-14	0.741	0.682	0.479	8

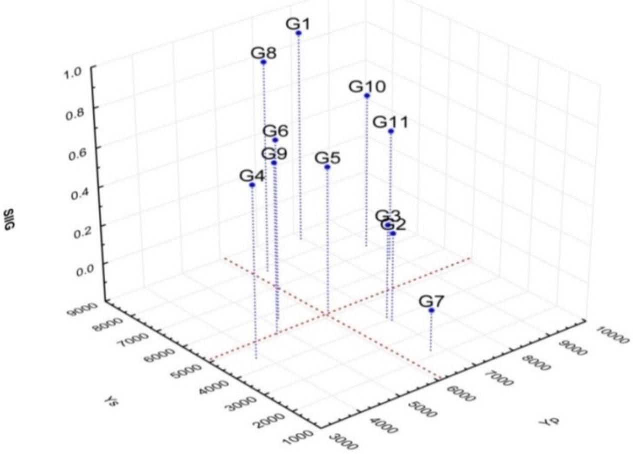

Fig. 2. 3D graph of drought-tolerant cropping systems using selection index of ideal genotype (SIIG), yield under non-stressed conditions (YP), and yield under stressed conditions (YS)
G1: DW-92-4, G2: Shabrang, G3: DW-94-14, G4: Behrang, G5: DW-92-4+Shabrang, G6: DW-92-4+DW-94-14, G7: DW-92-4+Behrang, G8: Shabrang+DW-94-14, G9: Shabrang+Behrang, G10: DW-94-14+Behrang, G11: DW-92-4+Behrang+Shabrang +DW-94-14.
A= G1, G5, G8, G10, G11, B= G2, G3, G7, C= G6, D= G4, G9.

In this study, there was no correlation between YP and YS. Some other researchers have also reported the absence of a positive or a non-significant correlation between YS and YP (Sio-Se Mardeh et al., 2006; Zebarjadi et al., 2012; Yasir et al., 2013). However, in other studies, a positive correlation between YS and YP has been found (Farshadfar et al., 2013; Abdolshahi et al, 2013). In this case, this indicates that indirect selection for drought-stressed conditions based on the result of normal conditions would be efficient. Patel et al. (2019), found a significant positive correlation between YP and YS ($r=0.68^{*}$) which indicated that high yield performance under favorable conditions resulted in relatively high yield under stressed conditions.

In order to analyze these indices and their correlations with durum wheat cropping systems under water-stressed and normal irrigation circumstances, practically all of the drought tolerance indicators were used in this study. The selection index of ideal genotype (SIIG) is a criterion that considers several significant drought indices into a single value. The results showed that the SIIG index also had a positive correlation coefficient with some most used drought indices such as YS, YI, and YSI. Based on the results, Shabrang + DW-94-14 cropping system with the highest SIIG index value (0.890) was the most tolerant cropping system for drought stress suggesting that the mixture of durum wheat varieties can be introduced as an agro-ecological solution to decrease the negative effects of drought stress. The SIIG index was utilized by NajafiMirak et al. (2018) to integrate multiple stability factors in durum wheat, and they concluded that the SIIG index is a good tool for integrating several traits or indices to make genotype selection decisions. Zali et al. (2016) used the SIIG index to integrate various indices of drought tolerance in rapeseed (*Brassica napus* subsp. *napus*) and revealed that the SIIG index is a suitable method to select drought-tolerant or susceptible genotypes based on different tolerance indices to drought.

Furthermore, drought stress significantly reduced the grain yield of most of the genotypes and cropping systems. The selection of drought-tolerant lines should be well adapted to stressed and non-stressed conditions. A high positive correlation was found between grain yield and drought indices studied. Besides, it was found that MP, GMP, and STI are the best indices to select drought-tolerant cropping systems. The significant and positive correlation of MP, GMP and STI with both YS and YP suggested that these criteria indices are quite useful in identifying high-yielding cropping systems under optimal and stressed conditions. When selecting an index, plant breeders should also consider the intensity of the environment's stress. Finally, based on the STI, MP, and GMP indices, genotype DW-92-4 was discovered to be a tolerant genotype in the current study. This genotype is valuable for selection in water-stressed areas and has the potential to be introduced as a cultivar. Considering there are many introduced drought tolerance indices by researchers, the SIIG index with the integration of these indices can be a convenient way for selecting ideal genotypes or cropping systems under water-stressed conditions.

Indices that had a high correlation with grain yield at stressed and non-stressed conditions were selected as the best indices because these indices were able to isolate and identify cropping systems with high grain yield performance at both conditions. ‹Thus, the GMP, MP, and STI indices showed a positive and significant positive correlation with grain yield in normal (optimal) conditions. Moreover, the GMP, MP, STI, YI, YSI, and SIIG indices had a positive and significant correlation with grain yield under water-stressed conditions (Table 5).

Principal Component Analysis

Principal component analysis (PCA) based on the correlation matrix of indices was used to better understand the linkages, similarities, and differences among drought tolerance indices. The relationships among different indices are graphically presented in a biplot of PCA1 and PCA2 (Fig. 3). The PCA1 and PCA2, which justify 99.8% of the total variation, mainly distinguish the indices in different groups (TOL and SSI indices were placed in group 1. PCs axes separated YSI and SIIG in group 2. YS and YI were separated as group 3 (r = +1.0, Table 5). GMP, STI, and MP were separated as group four, and YP in group 5. Similar results were found in the studies of Sio-Se Mardeh et al., (2006); Mohammadi and Abdulahi (2017), and Patel et al., (2019). It is interesting to know that interpretations of this plot can be obtained through the cosine of the angle between the vectors of two indices, which is nearly the correlation coefficient among them. The cosine of the angles does relatively express correlation coefficients since the plot of principal components analysis does explain most of the variation in a data set. Therefore, it could be concluded that GMP, MP, YI, STI, YSI, SSIG, and YS indices are positively correlated with each other (Fig. 3). Moreover, positive correlations were found between GMP, STI, and MP with YP. Results of the principal component analysis showed that PC1 explained 65.9% of the variation with a positive correlation with all indices except TOL and SSI. Patel et al. (2019) discovered similar findings. This component (PC1) demonstrated a poor association (0.110) with the yield in a non-stressed environment and a modest positive correlation (0.386) with the yield in a stressed environment. Except for the YSI and SIIG, the PC2, which accounted for only 33.9 percent of the overall variance, exhibited a positive association with all indices (Table 8). The second component (PC2) had a low correlation (0.066) with the yield under the stressed environment and a positive correlation (0.521) with the yield under the non-stressed environment. The relationships among the indices were graphically presented in biplots of the PC1 and PC2 (Fig. 3). Also, PC1 and PC2 values for each cropping system are shown in Table 9.

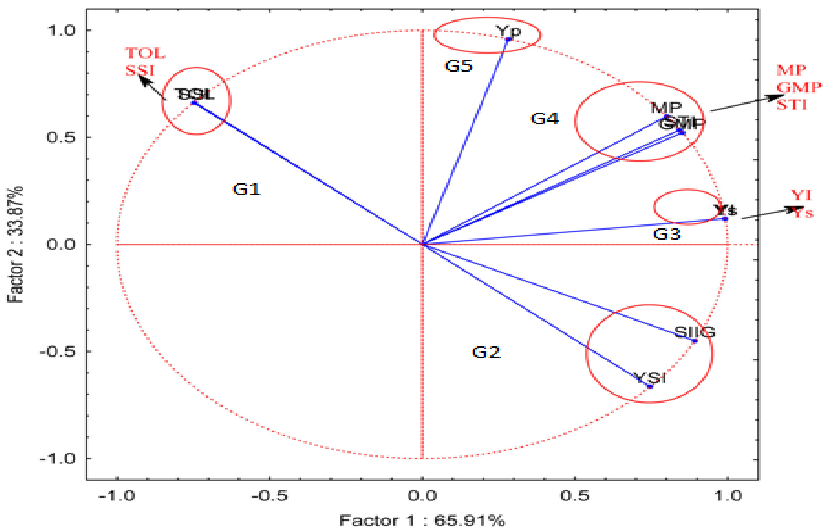

Fig. 3. Biplot analysis of drought tolerance criteria in durum wheat based on the first two-component axes (PC1 and PC2) for 11 cropping systems across drought indices

G1: DW-92-4, G2: Shabrang, G3: DW-94-14, G4: Behrang, G5: DW-92-4+Shabrang, G6: DW-92-4+DW-94-14, G7: DW-92-4+Behrang, G8: Shabrang+DW-94-14, G9: Shabrang+Behrang, G10: DW-94-14+Behrang, G11: DW-92-4+Behrang+Shabrang +DW-94-14.

Grain yield (kg ha^{-1}) of cropping systems under water-stressed conditions (YS); Grain yield (kg ha^{-1}) of cropping systems under irrigation conditions (YP) ; Geometric mean productivity (GMP); Tolerance index (TOL); and Mean productivity (MP); Stress tolerance index (STI); Yield index (YI); Yield stability index (YSI); Stress susceptibility index (SSI); Selection index of ideal genotype (SIIG).

Table 8. The first two principal components (i.e. Eigen value >1) were extracted by PCA, which explains 99.8% of the total variation.

Cropping systems	PC1	PC2
DW-92-4	4.02206	0.87261
Shabrang	-2.38865	0.96616
DW-94-14	-2.12942	0.91036
Behrang	-0.74396	-3.30609
DW-92-4+ Shabrang	-0.38711	-0.29582
DW-94-14+ DW-92-4	0.48430	-1.78122
DW-92-4+ Behrang	-4.83628	1.16877
DW-94-14+Shabrang	3.08677	-0.90492
Shabrang+Behrang	-0.22532	-2.16352
DW-94-14+Behrang	2.16108	2.19746
Behrang+DW-94-14+DW-92-4+ Shabrang	0.95653	2.33620

Eigenvalue— The scalar that is used to transform (stretch) an Eigenvector.

Table 9. Eigen value of two principal components for cropping systems of durum wheat.

PC	Eigen value	Proportion	YS	YP	GMP	MP	TOL	STI	YI	YSI	SSI	SIIG
PC1	6.59	65.9	0.386	0.110	0.332	0.312	-0.290	0.328	0.386	0.290	-0.291	0.348
PC2	3.38	33.9	0.066	0.521	0.284	0.325	0.361	0.290	0.066	-0.361	0.359	-0.244

Principal component (PC); Grain yield (kg ha^{-1}) of cropping systems under water-stressed conditions (YS); Grain yield (kg ha^{-1}) of cropping systems under irrigation conditions (YP); Geometric mean productivity (GMP); Tolerance index (TOL); and Mean productivity (MP); Stressed tolerance index (STI); Yield index (YI); Yield stability index(YSI); Stressed susceptibility index (SSI); Selection index of ideal genotype (SIIG).

CONCLUSIONS

Quadruple culture of genotypes in this study showed higher yields compared to the monoculture of genotypes and most of the binary cultures both in normal and water-stressed conditions. The highest grain yield (8815 kg ha-^{1}) resulted from the blended culture of Behrang + DW-94-14. It is interesting that none of these two genotypes had the highest yield in their monoculture cultivation, but their mixtures and interactions together resulted in the highest yield performance. Moreover, results showed that there are significant differences among the treatments. With the exception of the monoculture of DW-92-4 as a high potential promising line even under water-stressed conditions, most of the other genotype blends had a higher yield performance compared to a monoculture of genotypes under water-stressed conditions.

Considering there are many introduced drought tolerance indices by researchers, the SIIG index with the integration of these indices can be a suitable index for the selection of ideal genotypes or cropping systems under water-stressed conditions. The highest SIIG index (0.890) belonged to Shabrang+DW-94-14 which was among the highest grain yield in different cropping systems but according to the results of this study, it seems that GMP, MP, TOL and STI indices are better choices as drought resistance indices.

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ارزیابی اثرات مخلوط ژنوتیپی و شاخص‌های تحمل به تنش در گندم دوروم(*Triticum durum* Desf.) تحت تنش خشکی

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عملکرد

گندم دوروم

چکیده - تنش‌خشکی یکی از محدودیت‌های عمده در تولید محصولات زراعی در سراسر جهان است. مخلوط ژنوتیپ‌ها به عنوان روشی جدید برای افزایش عملکرد در محصولات گوناگون مورد ارزیابی قرار گرفته است. در این مطالعه، سامانه‌های مخلوط ژنوتیپ‌های گوناگون گندم دوروم (*Triticum durum* Desf.) تحت تأثیر تنش‌آبی مورد ارزیابی قرار گرفت. آزمایش‌ها در دو شرایط معمولی و تنش‌آبی در قالب طرح های بلوک های کامل تصادفی، هر کدام با سه تکرار، در مزرعه تحقیقاتی دانشکده کشاورزی و منابع طبیعی داراب، دانشگاه شیراز به مدت دو سال (۱۳۹۶-۱۳۹۵ و ۱۳۹۷-۱۳۹۶) انجام شد. از تک‌کشت‌های چهار ژنوتیپ گندم دوروم شامل ارقام شبرنگ و بهرنگ و لاین‌های DW-92-4، DW-94-14 و ترکیب دوتایی و چهارگانه آنها در سامانه‌های کشت استفاده شد. شاخص های تحمل به خشکی شامل شاخص تحمل پایداری (STI)، میانگین بهره‌وری (MP)، میانگین هندسی بهره وری (GMP)، شاخص حساسیت به تنش (SSI)، شاخص تحمل (TOL)،شاخص عملکرد (YI) و شاخص پایداری عملکرد (YSI) و یک معیار جدید با عنوان SIIG (شاخص انتخاب ژنوتیپ ایده آل) برای شناسایی بهترین سامانه کشت مورد استفاده و ارزیابی قرار گرفت. سامانه کشت بهرنگ + DW-94-14 بالاترین مقادیر GMP، STI و MP را در شاخص های خشکی نشان داد و بیشترین مقدار SIIG (۰.۸۹۰) در سامانه کشت ژنوتیپ شبرنگ + DW-94-14 شناسایی شد. همبستگی مثبتی بین GMP، STI و MP با YP پیدا شد. علاوه بر این، تجزیه و تحلیل بای‌پلات این شاخص ها با استفاده از تحلیل مؤلفه های اصلی، همبستگی مثبت قوی را بین GMP، STI و MP نشان داد در حالی که شاخص SIIG ارتباط نزدیکی با شاخص YSI داشت. در این مطالعه، شاخص‌های GMP، MP و STI به عنوان بهترین معیار برای شناسایی سامانه‌های کشت در شرایط تنش‌آبی شناسایی شدند. کشت چهارتایی ژنوتیپ‌ها در مقایسه با کشت‌خالص ژنوتیپ‌ها و اکثر کشت های دوتایی هم در شرایط نرمال و هم در شرایط تنش‌آبی عملکرد بالاتری را نشان داد. اما بیشترین عملکرد دانه در تیمارهای نرمال و تنش آبی در سامانه کشت بهرنگ + DW-94-14 به ترتیب با میانگین ۸۸۱۵ و ۷۳۴۲ کیلوگرم در هکتار به دست آمد.