Evaluation of some durum wheat genotypes for drought tolerance using stress selection indices

G. Afrooz[1], N. Sabaghnia[1,*], R. Karimizadeh[2] and F. Shekari[1]

[1] Department of Genetics and Plant Production, Faculty of Agriculture, University of Maragheh, Maragheh 55181−83111, Iran

[2] Dryland Agricultural Research Institute (DARI), Agricultural Research Education and Extension Organization (AREEO), Gachsaran 75916−11740, Iran

* Corresponding author: sabaghnia@yahoo.com

Submission: 3 August 2021 Revised: 29 November 2021 Accepted: 7 December 2021

ABSTRACT

Drought stress is a widespread problem influencing durum wheat production, but the development of tolerant genotypes is hampered by the lack of effective selection criteria. The objective of this investigation was to evaluate the ability of several selection indices to identify tolerant genotypes. Fourteen durum wheat genotypes were evaluated under both drought stress and non-stress environments using a randomized complete block design with four replications. Twelve drought tolerance indices were used based on grain yield under stress (YP) and non-stress (YS) conditions. Genotypes G3 (4,032 ± 448 kg ha^{-1}) and G4 (4,025 ± 444 kg ha^{-1}) had the highest yield under non-stress condition, while genotype G8 (2,702 ± 336 kg ha^{-1}) displayed the highest performance under stress conditions. Some genotypes including G1, G3, G6, G8, and G14 had high performances in both stress and non-stress conditions. Genotypes performed differently to drought stress, which justifies screening durum wheat for both yield and drought tolerance. Therefore, the modified stress susceptibility index (STI)-based indices (K_1STI and K_2STI) can discriminate drought tolerant genotypes with high grain yield under both non-stress and stress conditions. Finally, the genotype G3 (4,032 kg ha^{-1} in non-stress and 2,573 kg ha^{-1} in stress conditions) besides genotype G8 (3,773 kg ha^{-1} at non-stress and 2,702 kg ha^{-1} at stress conditions) were the most favorable genotypes and could be recommended for future recommendation.

Keywords: Durum wheat, principal component analysis, correlation, tolerance indices

Thai J. Agric. Sci. (2021) Vol. 54(3): 163−177

INTRODUCTION

Grain yield can be assessed in terms of diverse yield component traits, some of them can assume more important than the others, depending upon the time and intensity of abiotic stresses and their temporal development. In the Mediterranean areas most, rain falls during the autumn and winter, and water deficit occurs in the spring, resulting in the moderate drought stress for rainfed durum wheat around anthesis and throughout the grain filling period (Karimizadeh *et al.,* 2012; Barati *et al.,* 2020). This stress may lead to a loss in yield; particularly severe deficit at the anthesis stage has serious effects on durum wheat yield, reducing numbers of spike and spikelet and decreasing the fertility of spikelets. Loss of grain yield is the main concern of durum wheat breeders and they emphasize yield performance under drought stress conditions (Thumjamras *et al.,* 2019; Rawtiya and Kasal, 2021). Breeding for drought tolerance is complicated by the lack of proper screening methods and the inability to create repeatable drought conditions where large populations can be evaluated efficiently.

To differentiate drought tolerant genotypes, several selection indices have been suggested based on a relationship between non-stress and stress conditions. These indices provide a measure of drought according to loss of yield under drought stress conditions in comparison to non-stress conditions. Fischer and Maurer (1978) proposed the stress susceptibility index and Rosielle and Hamblin (1981) defined stress tolerance and mean productivity for the evaluation of genotypes for drought tolerance. The stress susceptibility index is the yield of a genotype under stress conditions as a function of the yield without stress. Stress tolerance is the difference in yield between the stress and non-stress conditions, and the mean productivity is the average yield in both conditions. Bouslama and Schapaugh Jr. (1984) suggested a yield stability index and Lin and Binns (1988) used the superiority index as estimates of genotype adaptability over a range of environments. The superiority index is the mean square of the distance of the yield performance of a genotype from the maximum observed yield of all genotypes at stress or non-stress conditions. Fernandez (1992) has been suggested stress tolerance index, geometric mean productivity, and harmonic mean for screening breeding materials for stress. Gavuzzi *et al.* (1997) and Sadiki (2006) proposed yield index and relative reduction to screening drought tolerant genotypes, respectively.

The ideal selection index should distinguish genotypes superiority in both stress and non-stress conditions from the genotypes that are favorable only in one condition. Among the different indices, selection based on stress susceptibility index and stress tolerance criteria favors genotypes with low yield potential under non-stress conditions and high yield under stress conditions, and selection based on these indices will result in genotypes with higher stress tolerance and yield potential will be selected (Sadiki, 2006). Ayed *et al.* (2021) used stress susceptibility index and stress tolerance index to evaluate drought tolerance in durum wheat genotypes and reported a year-to-year variation in these indices for genotypes and their ranking pattern. Mohammadi *et al.* (2010) found that geometric mean productivity and stress susceptibility index as the mathematical derivations of the same yield data, selection based on a combination of both indices may provide a more desirable criterion for improving drought tolerance in durum wheat. Thus, drought stress is one of the important stresses which influences the yield performance of durum wheat, especially in arid and semi-arid areas. However, the objectives of this investigation were to (i) identify drought tolerant durum wheat genotype under drought stress, (ii) determine the efficiency of screening methods to classify genotypes into tolerant/sensitive, and (iii) study interrelationships among the screening indices.

MATERIALS AND METHODS

Trials

In this investigation, fourteen (14) durum wheat genotypes including thirteen (13) new improved genotypes from International Center for Agricultural Research in the Dry Areas (ICARDA) and one (1) check cultivar from Iran (Dehdasht, moderate drought tolerant) were studied under dry-land condition of Gachsaran Research Experimental Station, Iran (50° 50′ E, 30° 20′ N) in the growing season during 2012–2013. The pedigree and origin of genotypes studied are given in Table 1.

Sowing occurred between the end of November and the middle of December 2012 and the harvest is performed in the middle of April 2013. Each plot consisted of six rows spaced 20 cm apart and row length was 6 m (7.2 m^2). An area of 4 m^2 (4 rows with 5 m long) was harvested. The experiments were conducted by a randomized complete block design (RCBD) with four replications under non-stress (supplementary irrigation with twice 50 mm irrigation at heading and grain filling) and stress conditions at the same time and one field. Each replication is assumed as a block which contained all 14 genotypes while two non-stress and stress conditions were assumed as splits with 10 m distance. Rainfall during the growing season was recorded at 336.9 mm. Plants were fertilized with nitrogen at the rate of 50 kg ha^{-1} urea and phosphorus at the rate of 120 kg ha^{-1} ammonium phosphate. Proper agronomic management practices were adopted throughout the growing season to ensure good crop growth. No important disease was identified during the growth season, and weed control was done by chemical method via topic and granstar herbicides. After physiological maturity, plots were harvested, and grain yield was adjusted to 12.5% seed moisture content.

Table 1 Pedigree and origin of the 14 durum wheat genotypes

Code	Pedigree	Origin
G1	Dehdasht	Iran
G2	LILE/3/SORA/2*PLATA_12//SOMAT_3CDSS02Y00114S–0Y–0M–7Y–0Y	ICARDA
G3	BCRIS/BICUM//LLARETA INIA/3/DUKEM_12/ 2* RASCON _21CDSS99B01189T–0TOPY–0M–0Y–81Y–0M–0Y–1M–0Y	ICARDA
G4	ZHONG ZUO/2*GREEN_3//SORA/2*PLATA _12/ 10 /PLATA _10/6/ MQUE/4/ USDA 573 //QFN/AA _7 /3/ALBA–D/5/AVO/HUI /7/ PLATA_13 /8/THKN E E_11/9/CHEN/ ALTAR 84/3/HUI/ POC// BUB/RU FO /4/ FNFOOTCDSS 02Y00213S–0Y–0M–30Y–0Y	ICARDA
G5	PLATA_6/GREEN_17//SNITAN/4/YAZI_1/AKAKI_4//SOMAT_3/3/AUK/GUIL// GREENCDSS02Y00369S–0Y–0M–16Y–0Y	ICARDA
G6	TOPDY_18/FOCHA_1//ALTAR 84/3/AJAIA_12/F3 LOCAL(SEL.ETHIO .135 .85)//PLATA_13/4/SOMAT_3/ GREEN _22 CDSS02Y00394S–0Y–0M–13Y–0Y	ICARDA
G7	RASCON_33/TISOMA_2/3/CANELO_8//SORA/2*PLATA_12/4/SOMAT_4/ INTER_8CDSS02Y00802T–0TOPB–0Y–0M–19Y–0Y	ICARDA
G8	RISSA/GAN//POHO_1/3/PLATA_3//CREX/ALLA/4/STOT// ALTAR 84/ALD/5/ ARMENT//SRN_3 /NIGRIS_4/3/ CANELO_9.1CDSS02Y01145T–0TOPB–0Y–0M–10Y–0Y	ICARDA
G9	SORA/2*PLATA_12//SOMAT_3/3/STORLOM/4/BICHENA/ AKAKI_7CDSS02Y01279T–0TOPB–0Y–0M–28Y–0Y	ICARDA
G10	SOOTY_9/RASCON_37//STORLOMCGSS02Y00006S–2F1–12Y–0B–3Y–0B–2Y–0B	ICARDA
G11	CHEN_1/TEZ/3/GUIL//CIT71/CII/4/SORA/PLATA_12/5/STOT//ALTAR 84/ALD/9/ USDA595/3/D67.3/ RABI//CRA/4/ ALO/5/ HUI/YAV_1/6/ ARDEN TE/7/HUI/ YAV79/8/ POD_9CDSS02B 00022S–0Y–0M–41Y–4M–04Y–0B	ICARDA
G12	ADAMAR_15//ALBIA_1/ALTAR 84/3/SNITAN /4/SOMAT _4/INTER _8CDSS02B00296S–0Y–0M–17Y–2M–04Y–0B	ICARDA
G13	1A.1D 5+10–6/2*WB881//1A.1D 5+10–6/3*MOJO/3/SOOTY _9/RASCON_37/9/ USDA595 /3/D67.3/RABI//CRA/4/ALO/5/ HUI/YAV_1/6/ARD ENTE/7/HUI/ YAV79/8/POD_9CDSS 02B00650S–0Y–0M–3Y–2M–04Y–0B	ICARDA
G14	1A.1D 5+10–6/2*WB881//1A.1D 5+10–6/3*MOJO /3/SOOTY _9/RASCON_37/9/ USDA595/3/ D67.3/RABI//CRA/4/ALO/5/ HUI/YAV_1/6/ ARDENTE/7/HUI/ YAV79/8/POD_9 CDSS02B00650S–0Y–0M–7Y–3M–04Y–0B	ICARDA

Drought Indices

The stress susceptibility index (SSI) of Fischer and Maurer (1978) was calculated as:

$$SSI = [1-(Ys / Yp)] / [1-(\bar{Y}s / \bar{Y}p)] \quad \text{------- (1)}$$

where Ys is the yield performance in stress conditions, Yp is the yield performance in non-stress conditions, $\bar{Y}s$ is the average of yield performance of all genotypes in stress conditions, and $\bar{Y}p$ is the average of yield performance of all genotypes in non-stress conditions.

The superiority index (PI) of Lin and Binns (1988) was computed as:

$$PI = \sum_{j=1}^{n} \frac{(X_{ij} - M_j)^2}{2n} \quad \text{------- (2)}$$

where n is the number of conditions, X_{ij} is the seed yield of i^{th} genotype in the j^{th} condition, and M_j is the yield of the genotype with the maximum yield at condition j.

The mean productivity (MP) and tolerance (TOL) of Rosielle and Hamblin (1981) were calculated as:

$$MP = (Ys + Yp) / 2 \quad \text{------- (3)}$$
$$TOL = (Yp - Ys) \quad \text{------- (4)}$$

The yield stability index (YSI) of Bouslama and Schapaugh Jr. (1984) was computed as:

$$YSI = Ys / Yp \quad \text{------- (5)}$$

The stress tolerance index (STI), geometric mean productivity (GMP), and harmonic mean (HM) of Fernandez (1992) were computed as:

$$STI = (Yp \times Ys) / Yp^2 \quad \text{------- (6)}$$

$$GMP = \sqrt{(Ys + Yp)} \quad \text{------- (7)}$$

$$HM = [2(Yp \times Ys)] / (Yp + Ys) \quad \text{------- (8)}$$

The yield index (YI) was calculated according to Gavuzzi *et al.* (1997):

$$YI = Ys / \bar{Y}s \quad \text{------- (9)}$$

The STI-based indices in non-stress (K_1STI) and stress conditions (K_2STI) were assessed as Naderi *et al.* (2000):

$$K_1STI = [(Yp)^2 / (\bar{Y}p)^2] \times STI \quad \text{------- (10)}$$
$$K_2STI = [(Ys)^2 / (\bar{Y}s)^2] \times STI \quad \text{------- (11)}$$

The relative reduction (RR) was computed based on the formula of Sadiki (2006):

$$RR = (Yp - Ys) / Yp \quad \text{------- (12)}$$

Statistical Analysis

The dataset was firstly tested for normality by the Anderson and Darling normality test using Minitab 14 software (Minitab, 2005). Data from each trial were subjected to analysis of variance (ANOVA) using appropriate model (RCBD) as y = Block + Genotype + Error, where y is the measured trait's value, Block is the block effect and it is representing replication, Genotype is the main effect of each genotype, and Error is the residual of the model. Dataset was analyzed using the SAS version 6.12 (SAS, 1996). The least significant differences (LSD) method was used for mean comparison for each pair of genotypes.

Phenotypic correlation coefficients were calculated for all comparisons of drought tolerance indices using Pearson's correlation coefficient. The general divergence among genotypes was estimated using principal component (PC) analysis based on a correlation matrix to define the patterns of variation according to drought stress indices using Minitab 14 (2005). Drought stress indices were used for clustering of genotypes based on squared Euclidean distance and Ward's minimum variance cluster analysis was used to group the tested accessions in the experiment.

RESULTS AND DISCUSSION

Analysis of variance for both yield performances in non-stress (YP) and stress conditions (YS) indicated highly significant ($P < 0.01$) differences among durum wheat genotypes (Table 2). Accordingly, highly significant differences were observed for durum wheat genotypes regarding most drought tolerance indices including MP, STI, GMP, HM, YI, PI, and K_2STI ($P < 0.01$) while significant differences were recorded for SSI, TOL, YSI, RR, and K_1STI ($P < 0.05$) drought tolerance indices in the durum wheat genotypes (Table 2).

Genotypes G3 and G4 had the highest yield in non-stress conditions with 4,032 ± 448 and 4,025 ± 444 kg ha^{-1} grain yield performance, respectively, while genotype G8 displayed the highest yield performance (2,702 ± 336 kg ha^{-1}) under stress conditions. The low yield performance genotype was G7 (3,028 kg ha^{-1}) under non-stress conditions and was G2 (2,089 kg ha^{-1}) under stress conditions (Table 3). Interestingly, some genotypes including G1, G3, G6, G8, and G14 had high performances in both stress and non-stress conditions and their differences with the best genotypes of both conditions are not significant statistically. Also, the other durum wheat genotypes were identified as semi-tolerance or semi-sensitive to drought stress. It is rare that a special genotype shows good performance in two different conditions and finding such a genotype is a good chance for plant breeder. Therefore, genotypes G1, G3, G6, G8, and G14 are good candidates for commercial recommendations to farmers in the future in both rain-fed and irrigated regions.

Based on SSI, genotype G7 displayed the lowest amount of SSI (0.63 ± 0.10) while according to MP, genotypes G3 (3,302 ± 331 kg ha^{-1}) and G8 (3,238 ± 327 kg ha^{-1}) were drought tolerance genotypes (Table 3). According to TOL, genotype G4 was identified as the most drought tolerance genotype as well as genotypes G3 and G8 when STI was considered (Table 3). Based on SSI, genotype G7 displayed the lowest amount of SSI while according to GMP, genotypes G3 (3,212 ± 350 kg ha^{-1}) and G8 (3,191 ± 327 kg ha^{-1}) were drought tolerance genotypes while genotypes G2 and G7 were drought sensitive genotypes (Table 3). Regarding yield performances in non-stress and stress conditions and SSI, STI, MP, TOL, and STI indices, genotypes G1, G3, G6, and G13 were the favorable genotypes. The other remained genotypes were detected as semi-tolerance or semi-sensitive to drought stress. Genotypes G3 and G8 were identified as the most favorable and tolerant genotypes based on HM and YI while genotypes G2 and G7 were found as the most tolerant genotypes based on PI (Table 3). Akçura and Çeri (2011) indicated that genotypes with high STI values usually have a high difference in yield in two different humidity conditions and also, reported relatively similar ranks for the genotypes by GMP and MP as well as STI index, which suggests that these indices are equal for screening drought tolerant genotypes. According to YSI, RR, K_1STI, and K_2STI indices, genotypes G3 and G14 were the most tolerant genotypes (Table 3). Ilker *et al.* (2011) and Sabaghnia and Janmohammadi (2014) reported that STI-related indices (K_1STI and K_2STI) are convenient parameters for selecting high-yielding genotypes in both stress and non-stress conditions whereas relative decrease is observed in yield performance.

The simple correlation coefficients between YP, YS, and several drought tolerance indices of the durum wheat genotypes are given in Table 4. The YP showed a significant positive correlation with YS (0.53) and all of the drought tolerance indices except PI (-0.37) and YSI (-0.69) while YS had a significant positive correlation only with MP (0.81), STI (0.80), GMP (0.84), HM (0.87), YI (0.99), K_1STI (0.63), and K_2STI (0.98) indices. Similar correlations among MP, GMP, and YP indices (Toorchi *et al.*, 2012) and correlations among GMP, MP, and STI indices (Dehghani *et al.*, 2009) were reported in canola. Also, a positive correlation of YP with STI, GMP, and PI, and a positive correlation of YS with HM and YI were reported by Sabaghnia and Janmohammadi (2014) in chickpea.

Table 2 Analysis of variance for yield performances of durum wheat genotypes in non-stress and stress conditions and twelve drought tolerance indices

SOV	df	YP	YS	SSI	MP	TOL	STI	GMP
Block	3	219,377.6^{ns}	1,459,948.5**	0.9526*	492,182.0*	1,390,757.4*	1.56×10^{-9}*	561,681.7**
Genotype	13	1,161,457.3**	460,749.5**	0.5848*	597,839.5**	853,588.9*	1.89×10^{-9}**	573,547.1**
Error	39	337,337.3	165,045.6	0.2952	143,472.1	430,777.4	4.54×10^{-10}	135,747.7
CV (%)		9.7	8.5	54.3	7.1	54.3	7.1	6.9
SOV	**df**	**HM**	**YI**	**PI**	**YSI**	**RR**	**K_1STI**	**K_2STI**
Block	3	636,653.9**	0.0645**	1.18×10^{12}**	0.0420**	0.0421**	6.12×10^{-9}^{ns}	4.03×10^{-8}**
Genotype	13	554,443.1**	0.0203**	1.51×10^{12}**	0.0170*	0.0171*	2.18×10^{-9}*	1.72×10^{-8}**
Error	39	131,628.6	0.0072	2.42×10^{11}	0.0095	0.0095	6.96×10^{-10}	6.08×10^{-9}
CV (%)		6.8	8.5	33.9	12.1	50.5	26.7	25.1

Note: SOV = source of variation, df = degrees of freedom, Error = the residual of analysis of variance, CV = coefficient of variation, YP = yield performance in non-stress conditions, YS = yield performance in stress conditions, SSI = stress susceptibility index, MP = mean productivity, TOL = tolerance, STI = stress tolerance index, GMP = geometric mean productivity, HM = harmonic mean, YI = yield index, PI = superiority index, YSI = yield stability index, RR = relative reduction, K_1STI = STI–based indices in non-stress conditions, K_2STI = STI–based indices in non-stress conditions. ** Significant at P < 0.01, * significant at P < 0.05, ns = not significant

Table 3 Mean comparison for yield performances in non-stress and stress conditions as well as twelve drought tolerance indices for fourteen durum wheat genotypes

Code	YP (kg ha^{-1})	YS (kg ha^{-1})	SSI	MP (kg ha^{-1})	TOL (kg ha^{-1})	STI	GMP (kg ha^{-1})
G1	3,838 ± 400^{abc}	2,413 ± 302^{abcd}	1.19 ± 0.18^{ab}	3,125 ± 310^{ab}	1,426 ± 184^{ab}	0.00049 ± 0.00006^{ab}	3,042 ± 319^{ab}
G2	3,090 ± 325^{e}	2,089 ± 213^{e}	0.83 ± 0.13^{bcd}	2,589 ± 247^{f}	1,001 ± 134^{bcd}	0.00040 ± 0.00005^{f}	2,538 ± 251^{e}
G3	4,032 ± 448^{a}	2,573 ± 335^{ab}	1.22 ± 0.19^{ab}	3,302 ± 331^{a}	1,460 ± 193^{ab}	0.00052 ± 0.00007^{a}	3,212 ± 350^{a}
G4	4,025 ± 444^{a}	2,327 ± 224^{bcde}	1.42 ± 0.21^{a}	3,176 ± 294^{ab}	1,698 ± 195^{a}	0.00050 ± 0.00006^{ab}	3,056 ± 308^{ab}
G5	3,154 ± 427de	2,356 ± 268^{bcde}	0.67 ± 0.15^{cd}	2,755 ± 274^{def}	799 ± 128^{cd}	0.00043 ± 0.00005^{def}	2,720 ± 306^{cde}
G6	3,835 ± 351^{abc}	2,428 ± 248^{abcd}	1.17 ± 0.15^{ab}	3,131 ± 297^{ab}	1,407 ± 176^{ab}	0.00049 ± 0.00006^{ab}	3,051 ± 286^{ab}
G7	3,028 ± 298^{e}	2,268 ± 350^{cde}	0.63 ± 0.10^{d}	2,648 ± 286f^{e}	760 ± 134^{d}	0.00041 ± 0.00006^{ef}	2,612 ± 288^{e}
G8	3,773 ± 376^{abc}	2,702 ± 336^{a}	0.89 ± 0.14^{bcd}	3,238 ± 327^{a}	1,071 ± 163^{bcd}	0.00051 ± 0.00006^{a}	3,191 ± 327^{a}
G9	3,531 ± 407^{bcd}	2,212 ± 243de	1.10 ± 0.18^{abc}	2,872 ± 276^{bcdef}	1,320 ± 165^{abc}	0.00045 ± 0.00005^{bcdef}	2,790 ± 294^{bcde}
G10	3,502 ± 406^{cde}	2,514 ± 240^{abc}	0.82 ± 0.15^{bcd}	3,008 ± 286^{abcd}	988 ± 142^{bcd}	0.00047 ± 0.00006^{abcd}	2,964 ± 299^{abc}
G11	3,475 ± 380^{cde}	2,347 ± 295^{bcde}	0.94 ± 0.15^{bcd}	2,911 ± 292^{bcde}	1,128 ± 158^{bcd}	0.00045 ± 0.00006^{bcde}	2,849 ± 304^{bcd}
G12	3,509 ± 424^{cde}	2,142 ± 255de	1.14 ± 0.19^{ab}	2,826 ± 276^{cdef}	1,367 ± 170^{ab}	0.00044 ± 0.00006^{cdef}	2,732 ± 301^{cde}
G13	3,768 ± 430^{abc}	2,392 ± 217^{bcd}	1.15 ± 0.19^{ab}	3,080 ± 285^{abc}	1,376 ± 169^{ab}	0.00048 ± 0.00006^{abc}	3,000 ± 300^{abc}
G14	3,538 ± 376^{abcd}	2,539 ± 288^{abc}	0.83 ± 0.14^{bcd}	3,038 ± 300^{abcd}	999 ± 149^{bcd}	0.00047 ± 0.00006^{abcd}	2,989 ± 305^{abc}

Note: YP = yield performance in non-stress conditions, YS = yield performance in stress conditions, SSI = stress susceptibility index, MP = mean productivity, TOL = tolerance, STI = stress tolerance index, GMP = geometric mean productivity. Mean values of the same category followed by different letters are significant at $P < 0.05$

Table 3 Continue.

Code	HM (kg ha^{-1})	YI	PI (kg^2 ha^{-1})	YSI	RR	K_1STI	K_2STI
G1	2,961 ± 324^{ab}	1.01 ± 0.13^{abcd}	283,543 ± 33,998^{ab}	0.63 ± 0.08^{cd}	0.37 ± 0.04^{cd}	0.03569 ± 0.00357^{abc}	0.00049 ± 0.00005^{abcd}
G2	2,488 ± 267^{e}	0.88 ± 0.11^{e}	787,584 ± 55,450^{bcd}	0.68 ± 0.06^{abcd}	0.32 ± 0.03^{abcd}	0.02964 ± 0.00296^{e}	0.00035 ± 0.00004^{e}
G3	3,125 ± 353^{a}	1.08 ± 0.15^{ab}	189,563 ± 31,638^{bcd}	0.64 ± 0.08^{abcd}	0.36 ± 0.04^{abcd}	0.03606 ± 0.00361^{a}	0.00057 ± 0.00006^{ab}
G4	2,941 ± 343^{ab}	0.98 ± 0.15^{bcde}	275,117 ± 35,729^{cde}	0.58 ± 0.08^{d}	0.42 ± 0.04^{d}	0.03718 ± 0.00372^{ab}	0.00050 ± 0.00005^{bcde}
G5	2,685 ± 323^{cde}	0.99 ± 0.12^{bcde}	642,243 ± 53,232^{cde}	0.76 ± 0.08^{a}	0.24 ± 0.02^{a}	0.02960 ± 0.00296^{de}	0.00047 ± 0.00005^{cde}
G6	2,973 ± 301^{ab}	1.02 ± 0.12^{abcd}	260,954 ± 30,423^{cde}	0.63 ± 0.07^{cd}	0.37 ± 0.04^{cd}	0.03423 ± 0.00342^{abc}	0.00046 ± 0.00005^{abcd}
G7	2,576 ± 258de	0.95 ± 0.10^{cde}	751,499 ± 52,337^{a}	0.75 ± 0.07^{ab}	0.25 ± 0.02^{ab}	0.02698 ± 0.00270^{e}	0.00037 ± 0.00005^{de}
G8	3,146 ± 321^{a}	1.14 ± 0.12^{a}	200,681 ± 28,662^{e}	0.72 ± 0.07^{abc}	0.28 ± 0.03^{abc}	0.03038 ± 0.00304^{abc}	0.00056 ± 0.00006^{a}
G9	2,712 ± 316^{bcde}	0.93 ± 0.13^{de}	491,318 ± 44,730^{cde}	0.63 ± 0.08^{cd}	0.37 ± 0.04^{cd}	0.03581 ± 0.00358^{cde}	0.00044 ± 0.00004^{de}
G10	2,920 ± 325^{abc}	1.06 ± 0.13^{abc}	367,944 ± 38,513^{ab}	0.72 ± 0.08^{abc}	0.28 ± 0.03^{abc}	0.03082 ± 0.00308^{bcde}	0.00051 ± 0.00005^{abcd}
G11	2,789 ± 307^{bcd}	0.99 ± 0.12^{bcde}	451,162 ± 41,384^{de}	0.68 ± 0.08^{abcd}	0.32 ± 0.03^{abcd}	0.03253 ± 0.00325^{cde}	0.00045 ± 0.00005^{bcde}
G12	2,643 ± 320^{cde}	0.90 ± 0.14^{de}	546,804 ± 48,336^{a}	0.62 ± 0.08^{cd}	0.38 ± 0.04^{cd}	0.03689 ± 0.00369^{cde}	0.00043 ± 0.00005^{de}
G13	2,923 ± 336^{abc}	1.01 ± 0.14^{bcd}	313,541 ± 36,967^{e}	0.64 ± 0.07^{bcd}	0.36 ± 0.04^{bcd}	0.03376 ± 0.00338^{abc}	0.00050 ± 0.00004^{bcd}
G14	2,941 ± 312^{abc}	1.07 ± 0.12^{abc}	458,934 ± 41,579^{bc}	0.72 ± 0.07^{abc}	0.28 ± 0.03^{abc}	0.03030 ± 0.00303^{abcd}	0.00053 ± 0.00005^{abc}

Note: HM = harmonic mean, YI = yield index, PI = superiority index, YSI = yield stability index, RR = relative reduction, K_1STI = STI–based indices in non-stress conditions, K_2STI = STI–based indices in non-stress conditions. Mean values of the same category followed by different letters are significant at $P < 0.05$

Table 4 Correlation coefficients of yield performances in non-stress and stress conditions as well as twelve drought resistance indices for fourteen durum wheat genotypes

	YP	YS	SSI	MP	TOL	STI	GMP	HM	YI	PI	YSI	RR	K_1STI
YS	0.53^{*}												
SSI	0.78^{**}	-0.12^{ns}											
MP	0.93^{**}	0.81^{**}	0.49^{ns}										
TOL	0.78^{**}	-0.12^{ns}	0.99^{**}	0.49^{ns}									
STI	0.93^{**}	0.80^{**}	0.49^{ns}	1.00^{**}	0.49^{ns}								
GMP	0.90^{**}	0.84^{**}	0.44^{ns}	1.00^{**}	0.44^{ns}	0.99^{**}							
HM	0.88^{**}	0.87^{**}	0.38^{ns}	0.99^{**}	0.38^{ns}	0.99^{**}	0.99^{**}						
YI	0.53^{*}	0.99^{**}	-0.12^{ns}	0.81^{**}	-0.12^{ns}	0.81^{**}	0.84^{**}	0.87^{**}					
PI	-0.37^{ns}	-0.29^{ns}	-0.21^{ns}	-0.38^{ns}	-0.21^{ns}	-0.39^{ns}	-0.39^{ns}	-0.39^{ns}	-0.30^{ns}				
YSI	-0.69^{**}	0.25^{ns}	-0.99^{**}	-0.37^{ns}	-0.99^{**}	-0.37^{ns}	-0.31^{ns}	-0.26^{ns}	0.25^{ns}	0.18^{ns}			
RR	0.69^{**}	-0.25^{ns}	0.99^{**}	0.37^{ns}	0.99^{**}	0.37^{ns}	0.31^{ns}	0.26^{ns}	-0.25^{ns}	-0.18^{ns}	-0.99^{**}		
K_1STI	0.99^{**}	0.63^{**}	0.69^{**}	0.96^{**}	0.69^{**}	0.96^{**}	0.95^{**}	0.93^{**}	0.63^{*}	-0.36^{ns}	-0.58^{*}	0.58^{*}	
K_2STI	0.65^{*}	0.98^{**}	0.03^{ns}	0.88^{**}	0.03^{ns}	0.88^{**}	0.90^{**}	0.92^{**}	0.98^{**}	-0.31^{ns}	0.09^{ns}	-0.09^{ns}	0.74^{**}

Note: YP = yield performance in non-stress conditions, YS = yield performance in stress conditions, SSI = stress susceptibility index, MP = mean productivity, TOL = tolerance, STI = stress tolerance index, GMP = geometric mean productivity, HM = harmonic mean, YI = yield index, PI = superiority index, YSI = yield stability index, RR = relative reduction, K_1STI = STI–based indices in non-stress conditions, K_2STI = STI–based indices in non-stress conditions. ** $P < 0.01$, * $P < 0.05$, ns = not significant

The SSI had a positive association with TOL (0.99), RR (0.99), and K_1STI (0.69) ($P < 0.01$) but had a negative correlation with YSI (-0.99; $P < 0.01$) while MP index showed a positive correlation with STI (1.00), GMP (1.00), HM (0.99), YI (0.81), K_1STI (0.96), and K_2STI (0.88) ($P < 0.01$) (Table 4). Similarly, Mohammadi and Abdulahi (2017) found no correlation between SSI and yield under non-stress conditions and Ayed *et al.* (2021) reported a positive correlation between MP with STI, GMP, and HM in durum wheat.

The TOL index had a positive correlation with RR and K_1STI ($P < 0.01$) but had a negative correlation with YSI ($P < 0.01$) while the STI had a positive correlation with GMP, HM, YI, K_1STI, and K_2STI ($P < 0.01$) (Table 4). Similarly, Toorchi *et al.* (2012) found a positive association between STI with GMP and HM indices in canola. In this study, GMP had a positive correlation with HM, YI, K_1STI, and K_2STI ($P < 0.01$) and the HM indicated a positive correlation with YI, K_1STI, and K_2STI indices ($P < 0.01$) (Table 4). The significant positive associations between GMP and HM and YI were also reported by Dehghani *et al.* (2009). The YI indicated a positive correlation with K_1STI (0.63; $P < 0.05$) and K_2STI (0.98; $P < 0.01$) while the PI did not show any positive correlation with all drought tolerant indices (Table 4). The YSI had a negative correlation with K_1STI (-0.58; $P < 0.05$) and RR (-0.99; $P < 0.01$) while there was a significant positive correlation between RR and K_1STI (0.58; $P < 0.05$) and between K_1STI and K_2STI (0.74; $P < 0.01$). In general, the observed relationships in our durum wheat genotypes were consistent with those reported by Mohammadi and Abdulahi (2017) in durum wheat and Khalili *et al.* (2012) in canola.

The associations among different drought tolerance indices are graphically indicated in a plot of two first principal components (PC1 and PC2) of the principal component analysis (Figure 1). The first and second components justified 93.6% of the variations among criteria (58.4% for PC1 and 35.2% for PC2). The PC1 mainly distinguishes the PI and YSI indices from the other indices and the PC2 distinguishes the RR, SSI, YP, K_1STI, and TOL indices from the indices which related to each other based on the PC1 scores (Figure 1). One of the interesting interpretations of this plot is that the cosine of the angle between the vectors of indices approximates the simple correlation coefficient between them. The cosine of the angles does relatively translate into correlation coefficients since the plot of principal components analysis does explain most of the variation in a dataset.

Therefore, it could be concluded that the GMP, MP, STI, K_1STI, YP, and HM indices were positively associated with each other as group 1 and had no or weakly positive association with group 2 (RR, SSI, and TOL) as well as group 3 (YI, YS, and K_2STI). The association of group 2 with group 3 was relatively near zero (Figure 1). Also, negative associations were seen between group 1 with PI and between group 2 with YSI.

Clustering of durum wheat genotypes based on YP, YS, and drought tolerant indices indicated four classes: class-A including genotypes G7 and G12, class-B including genotypes G8 and G13, class-C including genotypes G4, G5, G6, G9, and G11, and class-D including genotypes G1, G2, G3, G10, and G14 (Figure 2).

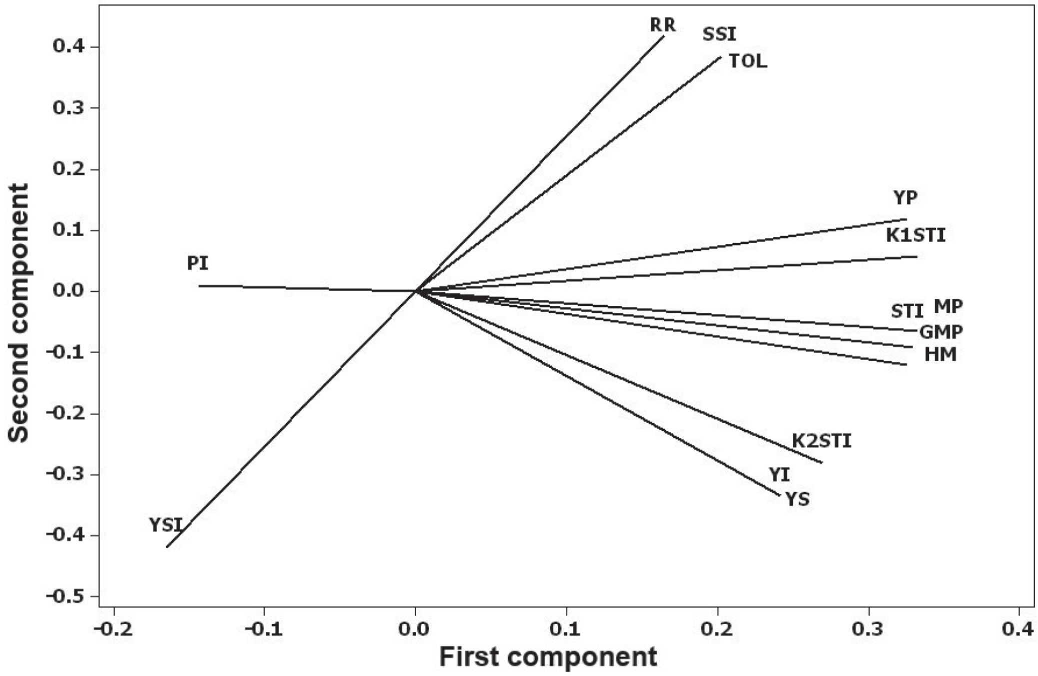

Figure 1 Two-way plot based on first two principal component axes (PC1 and PC2) for drought tolerance indices in durum wheat genotypes. YP = yield performance in non-stress conditions, YS = yield performance in stress conditions, SSI = stress susceptibility index, PI = superiority index, MP = mean productivity, TOL = tolerance, YSI = yield stability index, STI = stress tolerance index, GMP = geometric mean productivity, HM = harmonic mean, YI = yield index, RR = relative reduction, K_1STI = STI–based indices in non-stress conditions, K_2STI = STI–based indices in non-stress conditions.

The genotypes of class-A had relatively low yield in both stress and non-stress conditions but the genotypes of class-B had relatively high yield in both stress and non-stress conditions. Also, the genotypes of class-C and class-D were not identified as the lowest or highest yielding genotypes in one or both conditions. Therefore, it seems that the clustering method could not distinguish the performances of genotypes in stress and non-stress conditions.

There is general agreement that new improved high-yielding genotypes are more adapted to favorable growing conditions, while old cultivars have more stable performance under different stress conditions such as drought stress. It was interesting to note the positive correlation between STI-based indices and specially K_1STI and YP, indicating that K_1STI was positively correlated with non-stressed yield. This finding suggested that some traits that contribute to yield potential may act to increase tolerance to stress and that selection for both K_1STI and YP may counteract each other. Some studies showed that GMP and STI indices are preferred in late drought conditions for selecting the most favorable genotypes (Blum, 1996; Akçura *et al.,* 2011) while some other investigation indicated that PI and MP indices are preferred for selecting the most tolerant genotypes (Sio-Se Mardeh *et al.,* 2006; Khalili *et al.,* 2012).

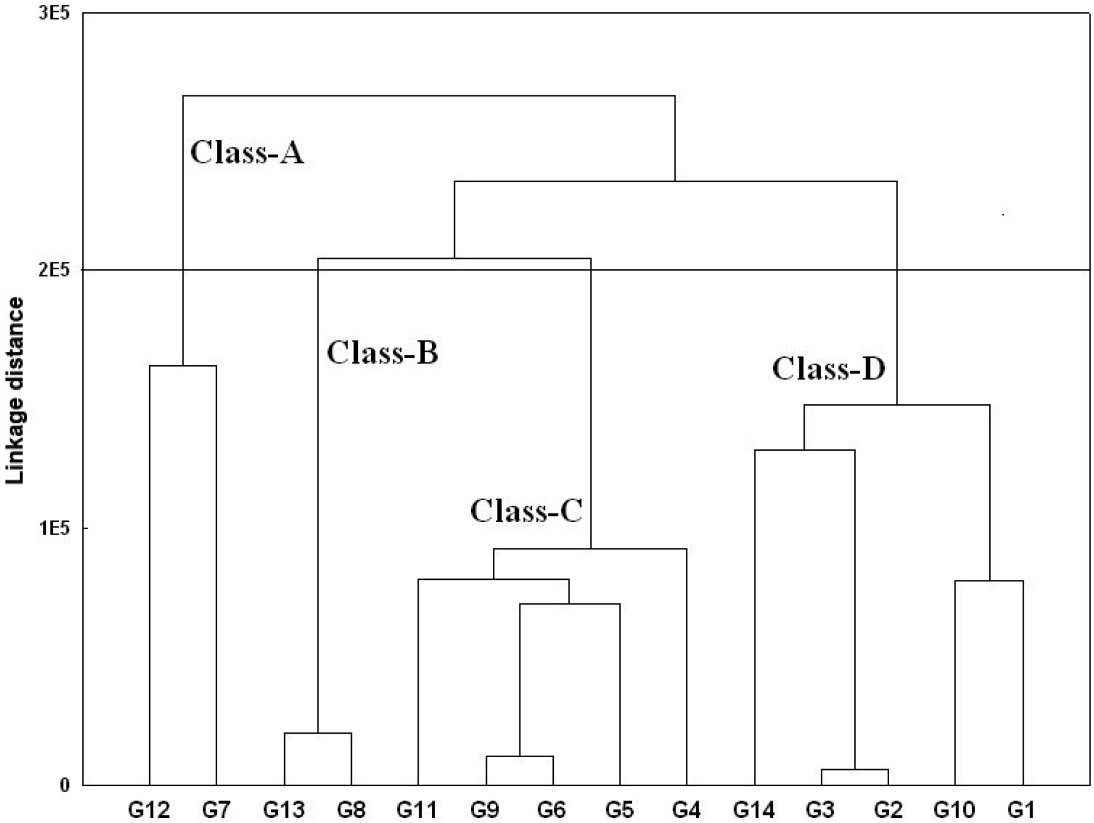

Figure 2 Dendrogram of cluster analysis for grouping durum wheat genotypes based on drought tolerance indices

Also, we found that K_2STI and YS were correlated to each other and would be preferred for selecting the most tolerant genotypes in drought stress conditions. Relatively, such a similar conclusion was reported by Fernandez (1992), Mohammadi *et al.* (2010), and Sabaghnia and Janmohammadi (2014), which mentioned the priority of STI and K_2STI parameters under the level of high to moderate stress. Akçura *et al.* (2011) reported that STI was able to differentiate genotypes that belonged to genotypes with high yield performance in both conditions, from the others.

Some studies conducted for measuring drought response of improved genotypes indicated that SSI and TOL indices were not efficient to be used in selecting genotypes with high yield capacity in either stress or non-stress conditions, but in contrast, STI was identified as an efficient index (Saba *et al.,* 2001; Naghavi *et al.,* 2013). Akçura *et al.* (2011) mentioned when the stress was severe, SSI was a more useful index for determining tolerant genotypes, although most of the indices could identify genotypes with high yield under both stress and non-stress conditions. The SSI and TOL indices only assess the plasticities of the genotypes, while a genotype may rank first in both conditions but still have higher values for these indices than other genotypes. The use of landraces has been neglected in plant breeding programs because they have low-yield potential under irrigated conditions while they have out-yielded the exotic material under low input conditions (Ceccarelli *et al.,* 1998; Dencic *et al.,* 2000). But it seems that the most effective way to improve the yield performance in stress conditions is to use locally adapted landraces and select them for target areas. The drought conditions are predominant over the years and wet years are infrequent in the most arid and semi-arid areas and so, selection should be based on the grain yield in the target regions. If the main purpose of the breeding program is to improve yield in small stress or non-stress conditions, it may be possible to describe local adaptation to increase grain yield from selection (Sio-Se Mardeh *et al.,* 2006; Akçura *et al.,* 2011).

CONCLUSIONS

The genotype G3 (4,032 ± 448 kg ha^{-1} in non-stress and 2,573 ± 335 kg ha^{-1} in stress conditions) and genotype G8 (3,773 ± 376 kg ha^{-1} in non-stress and 2,702 ± 336 kg ha^{-1} in stress conditions) were found to be the most favorable genotypes and are thus recommended for future recommendation in arid and semi-arid areas of Iran. Clustering of genotypes indicated four classes: class-A with low yield in both stress and non-stress conditions, class-B with high yield in both conditions, class-C and class-D with moderate yield in one or both conditions. According to PC analysis, GMP, MP, STI, K_1STI, YP, and HM could introduce high YP, while only K_2STI had the same property regarding YS, therefore, STI-based indices (STI, K_1STI, and K_2STI) can discriminate drought tolerant genotypes with high grain yield under both non-stress and stress conditions.

ACKNOWLEDGEMENT

The authors thank the Iranian Dryland Agricultural Research Institute (DARI) for making available the plant materials.

REFERENCES

Akçura, M., F. Partigoç and Y. Kaya. 2011. Evaluating of drought stress tolerance based on selection indices in Turkish bread wheat landraces. J. Anim. Plant Sci. 21(4): 700–709.

Akçura, M. and S. Çeri. 2011. Evaluation of drought tolerance indices for selection of Turkish oat (*Avena sativa* L.) landraces under various environmental conditions. Zemdirbyster. 98(2): 157–166.

Ayed, S., A. Othmani, I. Bouhaouel and J.A. Teixeira da Silva. 2021. Multi-environment screening of durum wheat genotypes for drought tolerance in changing climatic events. Agronomy. 11(5): 875.

Barati, V., E. Bijanzadeh and Z. Zinati. 2020. Nitrogen source and deficit irrigation influence on yield and nitrogen translocation of triticale in an arid Mediterranean agroecosystem. J. Agric. Sci. Technol. 22(5): 1295–1311.

Blum, A. 1996. Crop responses to drought and the interpretation of adaptation. Plant Growth Regul. 20: 135–148.

Bouslama, M. and W.T. Schapaugh Jr. 1984. Stress tolerance in soybean. I. Evaluation of three screening techniques for heat and drought tolerance. Crop Sci. 24(5): 933–937.

Ceccarelli, S., S. Grando and A. Impiglia. 1998. Choice of selection strategy in breeding barley for stress environments. Euphytica. 103: 307–318.

Dehghani, G.H., F. Malekshhi and B. Alizadeh. 2009. A study of drought tolerance indices in canola (*Brassica napus* L.) genotypes. J. Sci. Technol. Agric. Nat. Resour. 13(48): 77–90.

Dencic, S., R. Kastori, B. Kobiljski and B. Duggan. 2000. Evaluation of grain yield and its components in wheat cultivars and landraces under near optimal and drought conditions. Euphytica. 113: 43–52.

Fernandez, G.C.J. 1992. Effective selection criteria for assessing stress tolerance, pp.257–270. *In*: C.G. Kuo, (Ed), Proceedings of the International Symposium on Adaptation of Vegetables and Other Food Crops in Temperature and Water Stress, Tainan, Taiwan.

Fischer, R.A. and R. Maurer. 1978. Drought resistance in spring wheat cultivars. I. Grain yield response. Aust. J. Agric. Res. 29(5): 897–912.

Gavuzzi, P., F. Rizza, M. Palumbo, R.G. Campaline, G.L. Ricciardi and B. Borghi. 1997. Evaluation of field and laboratory predictors of drought and heat tolerance in winter cereals. Can. J. Plant Sci. 77: 523–531.

Ilker, E., O. Tatar, F. Aykut-Tonk and M. Tosun. 2011. Determination of tolerance level of some wheat genotypes to post-anthesis drought. Turk. J. Field Crops 16(1): 59–63.

Karimizadeh, R., M. Mohammadi, M. Armion, M.K. Shefazadeh and H. Chalajour. 2012. Determining heritability, reliability and stability of grain yield and yield-related components in durum wheat (*Triticum durum* L.). Bulg. J. Agric. Sci. 18(4): 595–607.

Khalili, M., M.R. Naghavi, A. Pour-Aboughadareh and S.J. Talebzadeh. 2012. Evaluating of drought stress tolerance based on selection indices in spring canola cultivars (*Brassica napus* L.). J. Agric. Sci. 4(11): 78–85.

Lin, C.S. and M.R. Binns. 1988. A superiority measure of cultivar performance for cultivar × location data. Can. J. Plant Sci. 68: 193–198.

Minitab. 2005. Minitab User's Guide. Version 14. Minitab Inc, Harrisburg, Pennsylvania, USA.

Mohammadi, R. and A. Abdulahi. 2017. Evaluation of durum wheat genotypes based on drought tolerance indices under different levels of drought stress. J. Agric. Sci. 62(1): 1–14.

Mohammadi, R., M. Armion, D. Kahrizi and A. Amri. 2010. Efficiency of screening techniques for evaluating durum wheat genotypes under mild drought conditions. Int. J. Plant Prod. 4(1): 11–24.

Naderi, A., A. Hashemi-dezfuli, A. Rezai, E.M. Heravan and G.N. Mohamadi. 2000. Study on correlation of traits and components affecting grain weight and determination of effect of some physiological parameters on grain yield in spring wheat genotypes under optimum and drought stress conditions. Seed Plant. 16(3): 374–386.

Naghavi, M.R., A. Pour-Aboughadareh and M. Khalili. 2013. Evaluation of drought tolerance indices for screening some of corn (*Zea mays* L.) cultivars under environmental conditions. Not. Sci. Biol. 5(3): 388–393.

Rawtiya, A.K. and Y.G. Kasal. 2021. Drought stress and wheat (*Triticum aestivum* L.) yield: a review. Pharma Innov. J. 10(5): 1007–1012.

Rosielle, A.A. and J. Hamblin. 1981. Theoretical aspects of selection for yield in stress and non-stress environments. Crop Sci. 21(6): 943–946.

Saba, J., M. Moghaddam, K. Ghassemi and M.R. Nishabouri. 2001. Genetic properties of drought resistance indices. J. Agric. Sci. Technol. 3: 43–49.

Sabaghnia, N. and M. Janmohammadi. 2014. Evaluation of selection indices for drought tolerance in some chickpea (*Cicer arietinum* L.) genotypes. Acta Technol. Agric. 12: 6–12.

Sadiki, M. 2006. Diversity of Moroccan local faba bean landraces for reaction to drought stress, pp. 11–17. *In*: D. Jarvis, I. Mar and L. Sears, (Eds), Enhancing the Use of Crop Genetic Diversity to Manage Abiotic Stress in Agricultural Production Systems. International Plant Genetic Resources Institute, Rome, Italy.

SAS. 1996. SAS/STAT User's Guide. Version 6.12. SAS Institute Inc, Cary, NC, USA.

Sio-Se Mardeh, A., A. Ahmadi, K. Poustini and V. Mohammadi. 2006. Evaluation of drought resistance indices under various environmental conditions. Field Crops Res. 98(2–3): 222–229.

Thumjamras, S., H. de Jong and S. Iamtham. 2019. Assessment of some physiological and biochemical parameters of three Thai sugarcane cultivars under salt- and drought-stress. Thai J. Agric. Sci. 52(4): 220–231.

Toorchi, M., R. Naderi, A. Kanbar and M.R. Shakiba. 2012. Response of spring canola cultivars to sodium chloride stress. Ann. Biol. Res. 2(5): 312–322.