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# SCREENING IRANIAN BREAD WHEAT LINES UNDER DIFFERENT WATER REGIMES USING YIELD BASED DROUGHT TOLERANCE INDICES

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## SUMMARY

Drought stress is the most limiting factor affecting growth and productivity of crop plants including bread wheat. The objective of this study was to evaluate the power and ability of several drought tolerance indices to be used in screening 47 bread wheat lines under different water regimes. Stress tolerance index (STI), geometric mean productivity (GMP), mean productivity (MP), tolerance index (TOL), stress susceptibility index (SSI), yield stability index (YSI), yield index (YI), harmonic mean (HM), drought resistance index (DRI) and sensitivity drought index (SDI) were calculated from grain yield under drought stressed and irrigated conditions. Combined ANOVA on grain yield, thousand grain weight and test weight data revealed significant effects ($P \leq 0.01$) for water regime, genotype and genotype × water regime interaction. Mean comparison of drought tolerance indices and grain yield validated the significant influences of drought stress on yield as well as significant differences among lines. Results of calculated Pearson's correlation coefficients and multivariate analyses showed that GMP, MP and STI indices were able to discriminate drought sensitive and tolerant genotypes. Cluster analysis using the drought tolerance indices divided the 16 genotypes into tolerant and susceptible groups. High broad-sense heritability was obtained for grain yield (45.1%), thousand grain weight (70.1%) and test weight (52.8%). There were positive and highly significant correlations between drought tolerance indices such as MP, GMP, STI and HM with yield in drought and irrigated conditions. Results of the principal components analysis (PCA) revealed that the first component (PC1) explained 61.0% of the total yield variation and exhibited a positive correlation with Ys, Yp, STI, GMP, MP, YI and HM. The PC2 explained 38.2% of the total yield variation and had a higher positive correlation with SSI, TOL and STI. Cluster analysis using the drought tolerance indices divided the 47 genotypes into tolerant and susceptible groups.

**Key words:** Bread wheat, drought tolerance indices, cluster analysis, principal components analysis

**Key findings:** This study consisted of 47 bread wheat lines varying in levels of drought tolerance. The results of the present study, the STI, GMP and MP indices could be efficiently used not only to screening of lines for drought tolerant but also to identify superior lines under different water regimes in field conditions for bread wheat.

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## INTRODUCTION

Hexaploid bread wheat (*Triticum aestivum* L.) is one of the most important cereal crops grown in arid and semi-arid regions where drought stress significantly affects grain yield, yield components and some growth indices (Ceccarelli *et al.,* 2007). Iran is one of the primary centers of diversity for wheat and its relatives and cultivated wheat includes diploid (2n = 14), tetraploid (2n = 28), and hexaploid (2n = 42) species, are extensively distributed in various parts of Iran (Salimi *et al.,* 2002). In 2013 bread wheat was planted on more than 290 million hectares worldwide, which is more land than any other crop (FAOSTAT, 2013). Drought affects an estimated of 65 million hectares of wheat grown area worldwide and in these water limited environments, wheat yields are commonly reduced to 50% or less of the irrigated yield potential (Byerlee and Morris, 1993). However drought stress tolerance is an important aim in crops breeding programs (Ludlow and Muchow, 1990), the response to this stress differs in various plant species with dwindling water supplies and increasing drought intensity, yield loss is a great concern to breeders in these areas is water limited (Mitra, 2001).

Drought tolerance is a complex quantitative trait with low heritability. It has a high level of genotype by environment (G × E) interaction and traits such as phenology and plant height can confound plant responses to it (Fleury *et al.,* 2010). According to Trethowan and Reynolds (2007), a selection technique that may be beneficial for improving both maximum yield potential and drought tolerance is alternating the selection environment between stressed and ideal conditions. To differentiate drought tolerance genotypes, several selection indices have been suggested on the basis of a mathematical relationship between normal and stress conditions (Clarke *et al.,* 1984; Huang, 2000). Tolerance (TOL) (McCaig and Clarke, 1982; Clarke *et al.,* 1992), mean productivity (MP) (McCaig and Clarke, 1982), stress susceptibility index (SSI) (Fischer and Maurer, 1978), geometric mean productivity (GMP) and stress tolerance index (STI) (Fernandez, 1992) have all been employed under various conditions. Fischer and Maurer (1978) explained that genotypes with an SSI of less than a unit are drought tolerance, since their yield reduction in drought condition is lower than the mean yield reduction of all genotypes.

Relative yield performance of genotypes in drought stressed and non-stressed environments can be used as an indicator of drought tolerance in breeding programs for drought-prone environments. According to their comparative yield performance in stress and non-stress environments genotypes have been classified in four groups by Fernandez (1992) as genotypes with relatively uniform yield in both stress and non-stress conditions (group A), genotypes with high yield in non-stress conditions (group B), genotypes with high yield in stress conditions (group C) and genotypes with low yield in both stress and non-stress conditions (group D). Several yield-based drought tolerance indices, based on mathematical relationships between yield under irrigated and drought stress conditions, have been used in many crops like cotton (Zangi 2005; Dahab *et al.,* 2012; Singh *et al.,* 2016), Safflower (Bahrami *et al.*, 2014), Durum wheat (Talebi *et al.,* 2009; Mohammadi, 2016), Bean (Ramirez-Vallejo, 1998; Habibi 2011), Sorghum (Singh *et al.,* 2011; Menezes *et al.*, 2014), Potato (Cabello *et al.*, 2013), Maize (Mhike *et al.*, 2012; Kumar *et al.*, 2015) and Barley (Nazari and Pakniyat, 2010; Khokhar *et al.,* 2012). The efficiency of yield indices for bread wheat lines selection has been evaluated under salinity (Sardouie-Nasab *et al.*, 2013) and drought (Sio-Se Mardeh *et al.*, 2006; Drikvand *et al.,* 2012; Dorostkar *et al.*, 2014; Hassan *et al.*, 2016) conditions.

Different approaches have been proposed to improve the efficiency of plant breeding for increased yield potential in crops under drought stress conditions. Improving for drought tolerant crops largely depends on the availability of the genetic resources germplasm for tolerance, reliable method for the screening, identification of genetic components of drought tolerance, successful genetic change of the desired genetic backgrounds, and ultimate development of drought tolerant cultivars with favorable agronomic and quality related characters (Bahrami *et al.,* 2014). Therefore, the objective of the present study was to identify drought tolerant lines based on tolerance indices that could be used in wheat breeding and genetics program in Iran.

## MATERIALS AND METHODS

### Experimental design and trial management

The plant materials used in this study consisted of 47 bread wheat lines (selected from 180 local bread wheat genotypes obtained from different wheat breeding programs of the Seed and Plant Improvement Institute of Iran) varying in levels of drought tolerance. The field experimental design was a randomized complete block Latinized row-column design under two irrigation regimes (100% field capacity until harvest and no irrigation after anthesis) conducted in 2013/14 growing season at the research farm of Shahed University located at Shahr-e-Rey, Tehran, Iran (15 km south west of Tehran, 35°34´N, 51°8´E, 1130 MASL). Minimum and maximum temperatures ranged from -15 to 41 °C. The average long-term annual precipitation was 224 mm. Daily precipitation and temperature during cropping season is presented in Figure 1. Each plot was four rows with 2 m long and 25 cm distance between rows. Fertilizer was applied at 50 kg N ha$^{-1}$ and 50 kg $P_2O_5$ ha$^{-1}$. Weeds were manually controlled during the growing season. After removing the borders, the plot grain yields were calculated as productivity per hectare (kg ha$^{-1}$).

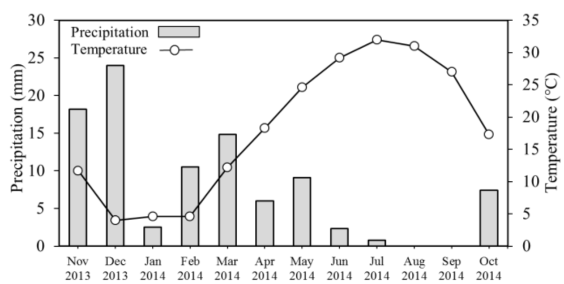


**Figure 1.** Mean precipitation and temperature between November 2013 and October 2014 during cropping season at Tehran.

For each genotype, several drought selection indices were calculated based on grain yield, under drought stress condition (Ys) and irrigated condition (Yp). Based on the mean grain yield across trials under non-stress, conventional drought tolerance indices, namely, the stress tolerance index and geometric mean productivity (Fernandez, 1992), mean productivity (Rosielle and Hamblin, 1981), tolerance index (Hossain *et al.*, 1990), stress susceptibility index (Fischer and Maurer, 1978), yield stability index (Bouslama and Schapaugh, 1984), yield index (Gavuzzi *et al.*, 1997), drought resistance index (Lan, 1998), harmonic mean (Jafari *et al.*, 2009) and sensitivity drought index (Farshadfar *et al.*, 2011) were calculated for each genotype using the below formula:

$$\text{Stress tolerance index (STI)} = \frac{(Y_s)(Y_p)}{(\bar{Y}_p)^2} \quad (1)$$

$$\text{Geometric mean productivity (GMP)} = \sqrt{(Y_s)(Y_p)} \quad (2)$$

$$\text{Mean productivity (MP)} = \frac{(Y_s+Y_p)}{2} \quad (3)$$

$$\text{Tolerance index (TOL)} = (Y_s - Y_p) \quad (4)$$

$$\text{Stress susceptibility index (SSI)} = \frac{[1-(Y_s/Y_p)]}{1\text{-SI}}, \quad (5)$$

$$\text{SI} = 1-(\bar{Y}_s/\bar{Y}_p)$$

$$\text{Yield stability index (YSI)} = Y_s/Y_p \quad (6)$$

$$\text{Yield index (YI)} = Y_s / \bar{Y}_p \quad (7)$$

$$\text{Harmonic mean (HM)} = \frac{2\,(Y_s \times Y_p)}{Y_s + Y_p}, \quad (8)$$

$$\text{Drought resistance index (DI)} = \frac{[Y_s \times (Y_s/Y_p)]}{\bar{Y}_s}, \quad (9)$$

Where Ys: drought stressed yield, Yp: non-stressed yield, Ȳp: overall mean of non-stressed yield, SI: stress intensity and Ȳs: overall mean of stressed yield.

**Statistical analysis**

A combined analysis of variance (ANOVA) was performed for grain yield (GY) thousand grain weight (TGW) and test weight (TW) using the GLM procedure of SAS version 9.1 (SAS Institute, 2004). The genotypic means of GY, TGW and TW were compared using LSD test at 5%. The ANOVA indicated only slight gains in efficiency using a randomized complete block design for the majority of the traits studied. Broad-sense heritability ($h^2_b$) was computed based on (i) single environments and (ii) over the trials. For all traits, plot mean heritability ($h_b^2$) was calculated from variance components obtained by a PROC GLM procedure:

$$(h^2_b) = \sigma^2_G / [(\sigma^2 + r\sigma^2_{GE} + rn\sigma^2_G)/rn]$$

Where $\sigma^2_G$ is the amount of genetic variance, $\sigma^2_{GE}$ is the amount of genotype by environment variance, $\sigma^2$ is the error variance, "*r*" is the number of replicates and n is the number of environments. GE interaction and error effects were calculated from the expected mean squares of the ANOVA, respectively. In order to screening drought tolerant genotypes, three dimensional scatter plots were used. In this method, grain yield under drought stress and irrigated condition and stress tolerance index (STI) are evaluated, simultaneously (Fernandez, 1992; Bahrami *et al.*, 2014; Dorostkar *et al.*, 2014). Then, principal components analysis (PCA) based on the correlation matrix were used to construct a biplot of genotypes and yield-based drought tolerance indices including MP, GMP, STI, TOL, SSI, YSI, YI, HM, DRI and SDI and yield in drought stressed (Ys) and irrigated (Yp) conditions. This statistical method is used for visualizing multivariate data and presenting them, interpretably. Based on these indices and PCA, superior genotypes for drought tolerance were identified. Correlations between these indices and with grain yield under drought stress and irrigated conditions were evaluated using the CORR procedure of SAS. The means of the genotypes for each environment were standardized to unit variance prior to pattern analysis. A cluster analysis was conducted for both wheat lines and drought indices, using squared Euclidean distance as the proximity measure and Ward's method as the grouping strategy.

## RESULTS AND DISCUSSION

**Effect of genotype, water regime and genotype × water regime interaction**

Combined ANOVA on grain yield, thousand grain weight and test weight data revealed significant effects ($P \leq 0.01$) for water regime, genotype and genotype × water interaction (Table 1). The relative value of different sources of variation varies greatly, as indicated by the variance components expressed as the percentages of total variation. The ANOVA on grain yield showed that 55.2% and 19.2% of the total variation in grain yield was related to the differences between water regime and the differences among genotypes, respectively. Only 11.1% of the total variance was referred to genotype × water regime interaction and the remaining variation (16.4%) was attributed to error (Table 1).

**Broad-sense heritability estimates**

Grain yield varied widely between water regime and genotypes. The $h^2_b$ for grain yield was 60.2% in the irrigated condition and 54.2% under drought stress condition (Table 2). Decrease in heritability ($h^2_b$) for grain yield under drought condition corresponded to the decrease in mean grain yields, a relationship that has been previously finding which was observed. (Bolaños and Edmeades, 1996). Also, the $h^2_b$ for thousand grain weight and test weight was higher in the irrigated experiments than in the drought stress experiments (Table 2). Clearly, traits with high heritability are easier to improve than those with lower heritability (Saba *et al.*, 2001) and estimation of heritability of a trait and its association with yield is useful in formulating appropriate breeding program and reliable index for genetic improvement mainly under stress conditions. Therefore, traits with high heritability could be used as indirect selection criteria to improve grain yield in water stress environments.

**Table 1.** Combined analysis for grain yield, thousand grain weight and test weight under drought stress and irrigated conditions from 2013-2014.

| Source of variation | df | Mean square | | | Expected mean square | % TTS |
|---|---|---|---|---|---|---|
| | | GY | TGW | TW | | GY |
| Env (E) | 1 | 525432959** | 7361.2** | 625703** | $\sigma^2 + r\sigma^2_{GE} + t\sigma^2_{R(E)} + rt\sigma^2_E$ | 58.61 |
| Block (Env) | 2 | 953985 | 2.5 | 33838 | $\sigma^2 + r\sigma^2_{R(E)}$ | 0.21 |
| Genotype (G) | 46 | 4010247** | 87.7** | 17697** | $\sigma^2 + r\sigma^2_{GE} + rn\sigma^2_G$ | 20.58 |
| G × E | 46 | 2199393** | 25.8** | 15424** | $\sigma^2 + r\sigma^2_{GE}$ | 11.28 |
| Error | 92 | 786223 | 8.1 | 1878 | $\sigma^2$ | 9.29 |
| CV (%) | | 18.14 | 10.32 | 8.25 | | |

GY grain yield, TGW Thousand grain weight, TW test weight; % TSS percentage relative to total sum of squares.
* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.

**Table 2.** Trait means, genetic variance ($V_G$), and broad-sense heritability ($h^2_b$) among 47 bread wheat lines in control and drought experiments in 2013-2014.

| Trait | Control | | | Drought | | | Combined ANOVA | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean ± S.E | $V_G$ | $h^2_b$ (%) | Mean ± S.E | $V_G$ | $h^2_b$ (%) | Difference | $V_G$ | $h^2_b$ (%) |
| GY | 6531 ± 206 | 711652 | 60.2 | 3270 ± 131.0 | 1725530 | 54.2 | 3261** | 1810854 | 45.15 |
| TGW | 40.2 ± 0.90 | 37.2 | 39.11 | 28.4 ± 0.56 | 12.8 | 34.9 | 11.8** | 61.9 | 70.58 |
| TW | 77.6 ± 6.1 | 1487 | 33.54 | 66.4 ± 8.32 | 13721 | 42.67 | 11.2** | 2273 | 52.84 |

** Significant at the 0.01 probability level.

**Response of genotypes to different water regime**

Mean traits of the 47 bread wheat genotypes under drought stressed and irrigated conditions are given in Table 3. Significant differences were observed among genotypes in each water regime for all traits. Compared to water stressed conditions, mean increasing yield equal to 49.9% was observed in irrigated conditions (Table 3). The six highest yielding genotypes under well watered conditions (overall mean 8695 kg ha$^{-1}$) were lines G8, G33, G41, G34, G14 and G37, whereas the six lowest yielding genotypes were lines G47, G30, G4, G1, G3 and G15 with an overall mean yield of 4407 kg ha$^{-1}$. Under drought stressed conditions with an overall mean yield of 4823 kg ha$^{-1}$, lines G21, G26, G8, G11, G25 and G6 were the highest yielding genotypes, whereas lines G19, G31, G15, G18, G5, and G32 were the six lowest yielding genotypes responded to water stressed conditions (overall mean yield of 1836 kg ha$^{-1}$). Under irrigated condition, thousand kernel weight and test weight were significantly affected by water stress (Tables 1 and 2). The highest thousand kernel weight was recorded for line G21 (51 g), and the lowest thousand kernel weight for line G32 (27.8 g) with an overall mean of 41.2 g. Thousand kernel weight ranged from 21.7 g (line G23) to 38.1 g (line G26) with an overall mean of 28.4 g under stress conditions

**Table 3.** Mean yields (kg ha$^{-1}$) of 47 bread wheat lines under drought stress and irrigated conditions.

| Genotype | Grain yield (kg ha$^{-1}$) | | | Thousand grain weight (g) | | | Test weight (kg hL$^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Irrigated | Drought | Reduced (%)† | Irrigated | Drought | Reduced (%) | Irrigated | Drought | Reduced (%) |
| G1 | 4474 | 3902 | 24.7 | 51.0 | 37.4 | 26.7 | 71.00 | 66.70 | 6.1 |
| G2 | 5227 | 2836 | 45.7 | 40.0 | 24.7 | 38.3 | 67.70 | 54.60 | 19.4 |
| G3 | 4282 | 2577 | 39.8 | 44.5 | 30.3 | 31.9 | 80.70 | 70.50 | 12.6 |
| G4 | 4625 | 2364 | 48.9 | 30.8 | 24.0 | 22.1 | 75.70 | 63.20 | 16.5 |
| G5 | 7257 | 1845 | 74.6 | 41.9 | 27.9 | 33.4 | 81.10 | 76.40 | 5.8 |
| G6 | 7497 | 4409 | 41.2 | 46.5 | 30.1 | 35.3 | 77.70 | 67.40 | 13.3 |
| G7 | 5446 | 3091 | 43.2 | 39.8 | 28.5 | 28.4 | 78.30 | 67.90 | 13.3 |
| G8 | 9722 | 4891 | 49.7 | 48.9 | 35.0 | 28.4 | 83.80 | 70.00 | 16.5 |
| G9 | 6686 | 3771 | 43.6 | 36.0 | 25.4 | 29.4 | 84.00 | 75.10 | 10.6 |
| G10 | 7336 | 3665 | 50.0 | 43.8 | 30.3 | 30.8 | 81.80 | 71.30 | 12.8 |
| G11 | 7373 | 4848 | 34.2 | 34.1 | 23.0 | 32.6 | 77.40 | 70.60 | 8.8 |
| G12 | 5222 | 2391 | 54.2 | 40.8 | 28.0 | 31.4 | 80.90 | 62.80 | 22.4 |
| G13 | 5309 | 4000 | 24.7 | 42.0 | 33.7 | 19.8 | 75.10 | 66.90 | 10.9 |
| G14 | 8195 | 2805 | 65.8 | 35.1 | 23.8 | 32.2 | 77.50 | 69.50 | 10.3 |
| G15 | 3521 | 1967 | 44.1 | 28.5 | 24.0 | 15.8 | 67.20 | 51.70 | 23.1 |
| G16 | 5818 | 3709 | 36.2 | 40.7 | 32.3 | 20.6 | 80.20 | 68.00 | 15.2 |
| G17 | 6955 | 3920 | 43.6 | 42.0 | 28.9 | 31.2 | 78.90 | 62.40 | 20.9 |
| G18 | 5062 | 1855 | 63.4 | 47.9 | 28.5 | 40.5 | 76.50 | 67.70 | 11.5 |
| G19 | 7700 | 2082 | 73.0 | 33.4 | 24.9 | 25.4 | 75.10 | 53.00 | 29.4 |
| G20 | 5944 | 4264 | 28.3 | 44.4 | 29.9 | 32.7 | 71.80 | 62.30 | 13.2 |
| G21 | 8082 | 5227 | 35.3 | 46.8 | 31.0 | 33.8 | 81.90 | 66.30 | 19.0 |
| G22 | 4978 | 3000 | 39.7 | 45.8 | 29.8 | 34.9 | 79.60 | 69.40 | 12.8 |
| G23 | 7731 | 2891 | 62.6 | 34.1 | 21.7 | 36.4 | 78.40 | 58.70 | 25.1 |
| G24 | 7902 | 2900 | 63.3 | 44.1 | 28.1 | 36.3 | 80.80 | 65.10 | 19.4 |
| G25 | 6313 | 4591 | 27.3 | 40.4 | 31.8 | 21.3 | 75.20 | 61.00 | 18.9 |
| G26 | 6407 | 4973 | 22.4 | 48.9 | 38.1 | 22.1 | 79.10 | 72.50 | 8.3 |
| G27 | 7191 | 3327 | 53.7 | 47.7 | 30.8 | 35.4 | 79.20 | 65.30 | 17.6 |
| G28 | 7963 | 2302 | 71.1 | 32.3 | 23.1 | 28.5 | 77.40 | 56.90 | 26.5 |
| G29 | 5241 | 3336 | 36.3 | 38.8 | 30.3 | 21.9 | 78.80 | 70.40 | 10.7 |
| G30 | 4673 | 2707 | 42.1 | 29.6 | 25.3 | 14.5 | 76.00 | 60.00 | 21.1 |
| G31 | 7335 | 1986 | 72.9 | 31.2 | 28.2 | 10.6 | 75.60 | 60.30 | 20.2 |
| G32 | 6327 | 1282 | 79.7 | 45.4 | 29.0 | 36.1 | 77.00 | 57.50 | 25.3 |
| G33 | 9442 | 3200 | 66.1 | 47.9 | 27.8 | 42.0 | 75.30 | 65.60 | 12.9 |
| G34 | 8255 | 3970 | 51.9 | 46.8 | 27.3 | 41.7 | 78.70 | 61.10 | 22.4 |
| G35 | 5258 | 3091 | 41.2 | 31.8 | 25.1 | 21.1 | 68.10 | 60.50 | 11.2 |
| G36 | 7162 | 3727 | 48.0 | 38.0 | 25.9 | 31.8 | 71.00 | 57.60 | 18.9 |
| G37 | 8132 | 2345 | 71.2 | 38.2 | 24.2 | 36.6 | 76.30 | 67.20 | 11.9 |
| G38 | 8127 | 3536 | 56.5 | 42.1 | 26.1 | 38.0 | 79.30 | 61.40 | 22.6 |
| G39 | 6239 | 3427 | 45.1 | 39.6 | 24.5 | 38.1 | 77.00 | 63.00 | 18.2 |
| G40 | 7078 | 3709 | 47.6 | 44.3 | 31.6 | 28.7 | 82.70 | 64.40 | 22.1 |
| G41 | 8429 | 4291 | 49.1 | 39.5 | 36.2 | 8.4 | 81.80 | 71.00 | 13.2 |
| G42 | 6955 | 3729 | 46.4 | 44.7 | 30.0 | 32.9 | 81.10 | 65.40 | 19.4 |
| G43 | 6609 | 3151 | 52.3 | 39.2 | 26.9 | 31.4 | 80.00 | 59.50 | 25.6 |
| G44 | 5083 | 2938 | 42.2 | 46.5 | 24.6 | 47.1 | 84.30 | 58.30 | 30.8 |
| G45 | 5136 | 3045 | 40.7 | 27.8 | 23.2 | 16.5 | 72.50 | 67.80 | 6.5 |
| G46 | 6412 | 2791 | 56.5 | 33.7 | 25.1 | 25.5 | 79.60 | 56.10 | 29.5 |
| G47 | 4752 | 3517 | 26.0 | 44.1 | 29.0 | 34.2 | 85.00 | 70.80 | 16.7 |
| Mean | 6531 | 3270 | 49.9 | 40.2 | 28.4 | 29.4 | 77.60 | 66.40 | 14.4 |
| LSD 5% | 2184 | 1123 | - | 6.44 | 4.63 | - | 5.40 | 9.70 | - |

†Values in the parentheses are the percentage of reduction compared to the irrigated condition.

(Table 3). Mean test weight varied from 85.1 kg $hL^{-1}$ for lines G8 and G44 to 67 kg $hL^{-1}$ for lines G2 and G15 under irrigated condition with an overall mean of 77.6 kg $hL^{-1}$. Under stress condition test weight ranged from 51.7 kg $hL^{-1}$ for line G15 and 76.4 kg $hL^{-1}$ for line G5 with an overall mean of 66.4 kg $hL^{-1}$ (Table 3). Also, the mean thousand kernel weight and test weight reduction due to water stress was 11.8 g (28.4%) and 11.2 kg $hL^{-1}$ (14.4%), respectively.

**Variation in yield-based selection indices**

Mean values of drought indices for different genotypes under different levels of drought stress were presented in Table 4. As shown the greater the TOL and SSI value, the larger yield reduction under drought stress conditions and the higher drought sensitivity. According to Rizza *et al.* (2004) study, reducing levels of minimum yield-based selection under stress conditions was unsuccessful to identify the most tolerant genotypes in comparison with no-stress conditions (TOL). Rosielle and Hamblin (1981) suggested that selection based on the tolerance index often leads to selecting genotypes which have low yield performance under irrigated conditions. Among the 47 bread wheat lines used in this study, lines G1, G13, G26 and G47 had the lowest values of SSI and TOL as well as the highest values of YSI and were suggested as the most drought tolerant genotypes under drought stress conditions (Table 4). This data indicated that SSI, TOL, and YSI indices were reliable for identifying genotypes with higher yields under drought stress rather than under irrigated conditions. The tolerance indices (STI, GMP, HM and MP) measure the higher stress tolerance and yield potential. The highest values of STI, GMP, HM and MP were recorded for G8, G21, G11 and G41 lines. Hence, they were introduced as the most stable and productive genotypes among the cultivated genotypes under both environmental conditions.

**Correlation of the drought tolerance indices**

Pearson's correlations among the drought indices at each level of water regimes were given in Table 5. The STI, GMP, MP and HM had a positive highly significant correlation with grain yield under both environmental conditions; the significant correlation between Ys and SSI, TOL and SDI indices was negative (Table 5). Also, there was a negative highly significant correlation between Yp and YSI. The correlation among the indices of STI, GMP, MP, YSI, HM and DI was positive highly significant, showing high similarity among these indices for ranking the lines. Stress tolerance index, GMP, MP and YI were the better predictors of grain yield than other indices under both water and stress conditions. Similar results were observed by Nazari *et al.* (2010), Bahrami *et al.* (2014) and Sardouie-Nasab *et al.* (2015) so that GMP, MP and STI were significantly and positively correlated with stress yield. A recent study by Dorostkar *et al.* (2014) showed that MP, GMP and STI values are suitable indices to select high yielding wheat genotypes in both stress and non-stress conditions. The study such as that conducted by Jafari *et al.* (2009) indicated that STI, GMP and MP indices which showed the highest correlation with yield under both normal and stress conditions, can be used as the effective indices for breeding programs to introduce drought tolerant genotypes.

**Principal component analysis (PCA)**

A PCA was conducted using the yield-based drought tolerance indices, and the 47 bread wheat lines were then subjected to biplot analysis to obtain the relationships among the indices (Table 6; Figure 2). Results of the PCA showed that the first component (PC1) explained 61% of the total yield variation and exhibited a positive correlation with Ys, Yp, STI, GMP, MP, YI and HM. Therefore, PC1 was related to yield potential and drought tolerance. The genotypes which have a high value of first component (PC1) are expected to have a high yield under both stress and irrigated conditions. The PC2 explained 38.2% of the total yield variation and had a higher positive correlation with SSI, TOL and STI. Therefore, PC1 and PC2 were named grain yield potential and drought stress susceptibility, respectively. Based on this criterion, stable genotypes possessed greater PC1 but lower PC2 values and contrariwise (Kaya *et al.,* 2006). The results of a PCA biplot drawn based on the PC1 and PC2

**Table 4.** Mean yields (kg ha$^{-1}$) and yield-based drought tolerance indices of 47 bread wheat lines under drought stress and irrigated conditions.

| Line | Yp | Ys | STI | GMP | MP | TOL | SSI | YSI | YI | HM | SDI | DI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| G1 | 4474 | 3902 | 0.37 | 3982 | 4022 | 1135 | 0.49 | 0.75 | 0.53 | 3942 | 0.25 | 1.04 |
| G2 | 5227 | 2836 | 0.35 | 3851 | 4032 | 2391 | 0.91 | 0.54 | 0.43 | 3677 | 0.46 | 0.47 |
| G3 | 4282 | 2577 | 0.26 | 3322 | 3429 | 1705 | 0.80 | 0.60 | 0.39 | 3218 | 0.40 | 0.47 |
| G4 | 4625 | 2364 | 0.26 | 3306 | 3494 | 2261 | 0.98 | 0.51 | 0.36 | 3128 | 0.49 | 0.37 |
| G5 | 7257 | 1845 | 0.31 | 3660 | 4551 | 5412 | 1.49 | 0.25 | 0.28 | 2943 | 0.75 | 0.14 |
| G6 | 7497 | 4409 | 0.77 | 5749 | 5953 | 3088 | 0.82 | 0.59 | 0.68 | 5553 | 0.41 | 0.79 |
| G7 | 5446 | 3091 | 0.39 | 4103 | 4269 | 2356 | 0.86 | 0.57 | 0.47 | 3944 | 0.43 | 0.54 |
| G8 | 9722 | 4891 | 1.11 | 6896 | 7306 | 4831 | 0.99 | 0.50 | 0.75 | 6508 | 0.50 | 0.75 |
| G9 | 6686 | 3771 | 0.59 | 5021 | 5228 | 2915 | 0.87 | 0.56 | 0.58 | 4822 | 0.44 | 0.65 |
| G10 | 7336 | 3665 | 0.63 | 5185 | 5501 | 3671 | 1.00 | 0.50 | 0.56 | 4888 | 0.50 | 0.56 |
| G11 | 7373 | 4848 | 0.84 | 5979 | 6110 | 2525 | 0.68 | 0.66 | 0.74 | 5850 | 0.34 | 0.97 |
| G12 | 5222 | 2391 | 0.29 | 3533 | 3807 | 2831 | 1.08 | 0.46 | 0.37 | 3280 | 0.54 | 0.33 |
| G13 | 5309 | 4000 | 0.50 | 4608 | 4655 | 1309 | 0.49 | 0.75 | 0.61 | 4562 | 0.25 | 0.92 |
| G14 | 8195 | 2805 | 0.54 | 4794 | 5500 | 5390 | 1.31 | 0.34 | 0.43 | 4179 | 0.66 | 0.29 |
| G15 | 3521 | 1967 | 0.16 | 2632 | 2744 | 1554 | 0.88 | 0.56 | 0.30 | 2524 | 0.44 | 0.34 |
| G16 | 5818 | 3709 | 0.51 | 4645 | 4764 | 2109 | 0.72 | 0.64 | 0.57 | 4530 | 0.36 | 0.72 |
| G17 | 6955 | 3920 | 0.64 | 5221 | 5437 | 3035 | 0.87 | 0.56 | 0.60 | 5014 | 0.44 | 0.68 |
| G18 | 5062 | 1855 | 0.22 | 3065 | 3459 | 3207 | 1.27 | 0.37 | 0.28 | 2715 | 0.63 | 0.21 |
| G19 | 7700 | 2082 | 0.38 | 4004 | 4891 | 5618 | 1.46 | 0.27 | 0.32 | 3278 | 0.73 | 0.17 |
| G20 | 5944 | 4264 | 0.59 | 5034 | 5104 | 1680 | 0.56 | 0.72 | 0.65 | 4965 | 0.28 | 0.94 |
| G21 | 8082 | 5227 | 0.99 | 6500 | 6655 | 2855 | 0.71 | 0.65 | 0.80 | 6348 | 0.35 | 1.03 |
| G22 | 4978 | 3000 | 0.35 | 3865 | 3989 | 1978 | 0.79 | 0.60 | 0.46 | 3744 | 0.40 | 0.55 |
| G23 | 7731 | 2891 | 0.52 | 4727 | 5311 | 4840 | 1.25 | 0.37 | 0.44 | 4208 | 0.63 | 0.33 |
| G24 | 7902 | 2900 | 0.54 | 4787 | 5401 | 5002 | 1.26 | 0.37 | 0.44 | 4243 | 0.63 | 0.33 |
| G25 | 6313 | 4591 | 0.68 | 5383 | 5452 | 1722 | 0.54 | 0.73 | 0.70 | 5316 | 0.27 | 1.02 |
| G26 | 6407 | 4973 | 0.75 | 5645 | 5690 | 1434 | 0.45 | 0.78 | 0.76 | 5600 | 0.22 | 1.18 |
| G27 | 7191 | 3327 | 0.56 | 4891 | 5259 | 3864 | 1.07 | 0.46 | 0.51 | 4549 | 0.54 | 0.47 |
| G28 | 7963 | 2302 | 0.43 | 4282 | 5133 | 5661 | 1.42 | 0.29 | 0.35 | 3572 | 0.71 | 0.20 |
| G29 | 5241 | 3336 | 0.41 | 4182 | 4289 | 1905 | 0.73 | 0.64 | 0.51 | 4077 | 0.36 | 0.65 |
| G30 | 4673 | 2707 | 0.30 | 3556 | 3690 | 1966 | 0.84 | 0.58 | 0.41 | 3428 | 0.42 | 0.48 |
| G31 | 7335 | 1986 | 0.34 | 3817 | 4661 | 5349 | 1.46 | 0.27 | 0.30 | 3126 | 0.73 | 0.16 |
| G32 | 6327 | 1282 | 0.19 | 2848 | 3805 | 5045 | 1.59 | 0.20 | 0.20 | 2132 | 0.80 | 0.08 |
| G33 | 9442 | 3200 | 0.71 | 5497 | 6321 | 6242 | 1.32 | 0.34 | 0.49 | 4780 | 0.66 | 0.33 |
| G34 | 8255 | 3970 | 0.77 | 5724 | 6112 | 4285 | 1.04 | 0.48 | 0.61 | 5361 | 0.52 | 0.58 |
| G35 | 5258 | 3091 | 0.38 | 4031 | 4174 | 2167 | 0.82 | 0.59 | 0.47 | 3893 | 0.41 | 0.56 |
| G36 | 7162 | 3727 | 0.63 | 5167 | 5445 | 3435 | 0.96 | 0.52 | 0.57 | 4903 | 0.48 | 0.59 |
| G37 | 8132 | 2345 | 0.45 | 4367 | 5239 | 5786 | 1.42 | 0.29 | 0.36 | 3641 | 0.71 | 0.21 |
| G38 | 8127 | 3536 | 0.67 | 5361 | 5832 | 4591 | 1.13 | 0.44 | 0.54 | 4928 | 0.56 | 0.47 |
| G39 | 6239 | 3427 | 0.50 | 4624 | 4833 | 2812 | 0.90 | 0.55 | 0.52 | 4424 | 0.45 | 0.58 |
| G40 | 7078 | 3709 | 0.62 | 5124 | 5394 | 3369 | 0.95 | 0.52 | 0.57 | 4868 | 0.48 | 0.59 |
| G41 | 8429 | 4291 | 0.85 | 6014 | 6360 | 4138 | 0.98 | 0.51 | 0.66 | 5687 | 0.49 | 0.67 |
| G42 | 6955 | 3729 | 0.61 | 5093 | 5342 | 3225 | 0.93 | 0.54 | 0.57 | 4855 | 0.46 | 0.61 |
| G43 | 6609 | 3151 | 0.49 | 4563 | 4880 | 3458 | 1.04 | 0.48 | 0.48 | 4267 | 0.52 | 0.46 |
| G44 | 5083 | 2938 | 0.35 | 3864 | 4010 | 2144 | 0.84 | 0.58 | 0.45 | 3724 | 0.42 | 0.52 |
| G45 | 5136 | 3045 | 0.37 | 3955 | 4091 | 2091 | 0.81 | 0.59 | 0.47 | 3824 | 0.41 | 0.55 |
| G46 | 6412 | 2791 | 0.42 | 4230 | 4601 | 3621 | 1.13 | 0.44 | 0.43 | 3889 | 0.56 | 0.37 |
| G47 | 4752 | 3517 | 0.39 | 4088 | 4135 | 1235 | 0.52 | 0.74 | 0.54 | 4042 | 0.26 | 0.80 |

**Table 5.** Pearson correlation coefficients between grain yield of wheat lines under irrigated (Yp, kg ha$^{-1}$), drought stress (Ys, kg ha$^{-1}$) conditions and arrays of yield-based drought tolerance indices.

| Parameter | Yp | Ys | STI | GMP | MP | TOL | SSI | YSI | YI | HM | SDI |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ys | $0.29^{ns}$ | | | | | | | | | | |
| STI | $0.72^{**}$ | $0.85^{**}$ | | | | | | | | | |
| GMP | $0.73^{**}$ | $0.86^{**}$ | $0.99^{**}$ | | | | | | | | |
| MP | $0.89^{**}$ | $0.69^{**}$ | $0.95^{**}$ | $0.95^{**}$ | | | | | | | |
| TOL | $0.80^{**}$ | $-0.34^{**}$ | $0.17^{ns}$ | $0.18^{ns}$ | $0.44^{**}$ | | | | | | |
| SSI | $0.48^{**}$ | $-0.69^{**}$ | $-0.23^{ns}$ | $-0.23^{ns}$ | $0.04^{ns}$ | $0.90^{**}$ | | | | | |
| YSI | $-0.48^{**}$ | $0.69^{**}$ | $0.23^{ns}$ | $0.23^{ns}$ | $-0.04^{ns}$ | $-0.90^{**}$ | $-1.00^{**}$ | | | | |
| YI | $0.30^{*}$ | $0.99^{**}$ | $0.86^{**}$ | $0.87^{**}$ | $0.70^{**}$ | $-0.33^{**}$ | $-0.68^{**}$ | $0.68^{**}$ | | | |
| HM | $0.56^{*}$ | $0.95^{**}$ | $0.96^{**}$ | $0.97^{**}$ | $0.87^{**}$ | $-0.05^{ns}$ | $-0.44^{**}$ | $0.44^{**}$ | $0.96^{**}$ | | |
| SDI | $0.48^{**}$ | $-0.69^{**}$ | $-0.23^{ns}$ | $-0.24^{ns}$ | $0.04^{ns}$ | $0.90^{**}$ | $1.00^{**}$ | $-1.00^{**}$ | $-0.68^{**}$ | $-0.44^{**}$ | |
| DI | $-0.09^{ns}$ | $0.91^{**}$ | $0.57^{**}$ | $0.57^{**}$ | $0.35^{**}$ | $-0.65^{**}$ | $-0.89^{**}$ | $0.89^{**}$ | $0.89^{**}$ | $0.72^{**}$ | $-0.89^{**}$ |

$Y_p$ yield under irrigated conditions, $Y_s$ yield under drought stress conditions, STI stress tolerance index, GMP geometric mean productivity, MP mean productivity, TOL tolerance index, SSI stress susceptible index, YSI yield stability index, YI yield index.

* Significant at the 0.05 probability level; ns, not significant.

** Significant at the 0.01 probability level.

**Table 6.** Results of principal component analysis for grain yield of wheat lines under drought and irrigated conditions and arrays of yield-based drought tolerance indices.

| F | Ys | Yp | STI | GMP | MP | TOL | SSI | YSI | YI | HM | SDI | DI | Eigen value | Variability (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PC1 | 0.81 | 0.79 | 0.99 | 1.0 | 0.98 | 0.27 | -0.15 | 0.15 | 0.82 | 0.95 | -0.15 | 0.51 | 7.3 | 61.0 |
| PC2 | -0.58 | 0.61 | -0.09 | -0.09 | 0.18 | 0.96 | 0.99 | -0.99 | -0.57 | -0.31 | 0.99 | -0.83 | 4.6 | 38.2 |

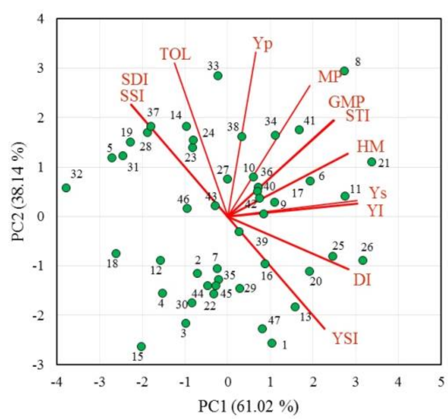


**Figure 2.** Two dimensional PCA plot based on the first two components for Yp, Ys and 12 yield-based drought tolerance indices of 47 Iranian bread wheat lines.

data for the 47 genotypes showed the five genotypes G8, G21, G25, G20, and G26 closely located to the best drought tolerance indices with high PC1 but low PC2 values. On the other hand, the majority of genotypes with low PC1 and high PC2 values were identified as susceptible genotypes. These lines including G32, G5, G31, G19, G28 and G37 (Figure 2). The results of the present study were similar to those reported in Kaya *et al.* (2006) study, wheat genotypes with higher PC1 and lower PC2 values had high grain yields (stable genotypes) and genotypes with lower PC1 and higher PC2 scores had low grain yield (unstable genotypes).

**Three dimensional scatter plots**

Considering the high positive correlation between the stress tolerance index (STI) and seed yield under drought stress and irrigated conditions, three dimensional scatter plots based on STI were drawn to categorize the 47 bread wheat genotypes according to their yield performance (Figure 3). These plots divided the genotypes into four groups that each of which represents one combination of the genotypes with high yields under both conditions (Group A), high yield in a irrigated condition (Group B), high yield in a drought stress condition (Group C), and low yield under both conditions (Group D). Three dimensional scatter plots showed that line numbers G8, G21, G41, G11, G34 and G6 were placed on group A. These lines showed firstly superior performance in stressed and irrigated conditions and were secondly superior for quantitative tolerance indices than others. Therefore, they were recommended as candidate genotypes for tolerance to drought. In spite of having high yield in stressed conditions, G20, G25 and G26 yield (yield potential) were low in irrigated condition, thus, they were placed on group C. Conversely, yield potential in genotype numbers G33, G37, G28, G19 and G24 were high but their yields in stressed conditions were poor. Consequently, these lines were classified as drought susceptible genotypes and they are only recommended for humid environments or regions with adequate water. Also, Fernandez (1992) and Bahrami *et al.* (2014) used the same approach to classify the genotypes into four groups, based on their performance under stress and irrigated conditions.

Three dimensional plots and biplot derived from principal component analysis showed that lines G8 and G21 had the best performance in stress conditions (Group A) and a lower sensitivity among the lines (Figures 2 and 3). Therefore, these lines seem to be sensitive to the access to irrigation water in irrigated plots and to have the ability of adaptation under stressful environments.

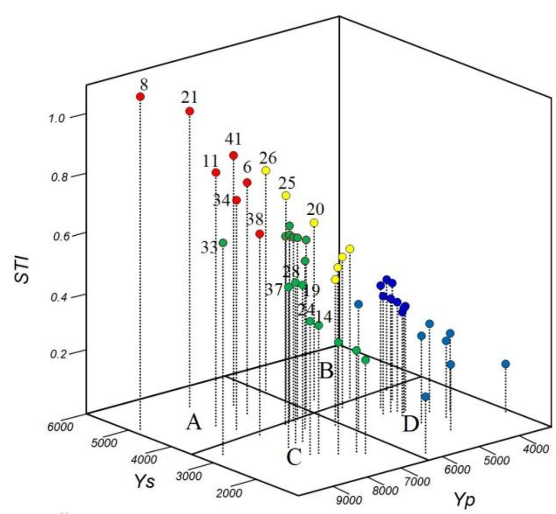


**Figure 3.** Three dimensional plot for identifying drought tolerant lines based on grain yield under drought stress, irrigated conditions and the stress tolerance index (STI). The lines with high grain yields under both conditions (Group A), high yield in irrigated condition (Group B), high grain yield in drought stress condition (Group C), and low grain yield under both conditions (Group D).

**Cluster analysis**

Cluster analysis was performed on the basis of Yp, Ys, MP, GMP, STI, TOL, SSI, YSI, YI, HM and DRI indices to classify the genotypes into four groups (Figure 4). The means of the drought indices and grain yield of genotypes under drought stress condition and irrigated condition, obtained from cluster analysis were presented in Table 4. The clustering results of the genotypes were consistent with the PCA results. Out of the 47 genotypes, 12 with low productivity under both environmental conditions were located in the group 4 (Ys = 2655 kg $ha^{-1}$ and Yp = 4876 kg $ha^{-1}$), whereas the group 3 included genotypes possessing the highest yield potential and yield components under both drought and irrigated conditions with mean yield of 4453 and 8212 kg $ha^{-1}$, respectively. Thus, the genotypes in groups 1 and 3 were identified as drought susceptible and tolerant genotypes, respectively. The ability of drought tolerance indices to identify genotypes with high performance under both drought stress and irrigated conditions has also been evaluated using both multivariate statistical analysis and the correlations of the indices with yield in other crop species such as bread wheat (Hassan *et al.*, 2014; Dorostkar *et al.*, 2016), durum wheat (Mohammadi *et al.*, 2016), barley (Nazari and Pakniyat, 2010), safflower (Bahrami *et al.*, 2011) and Iranian chickpea (Ganjeali *et al.*, 2011).

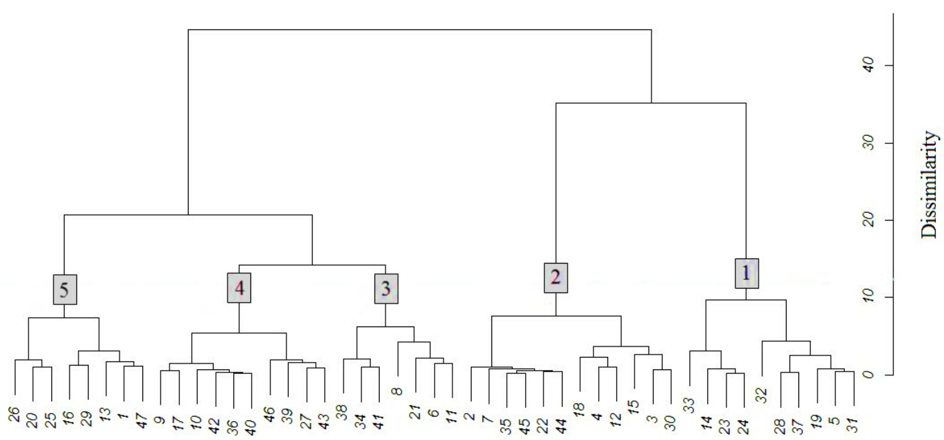


**Figure 4.** Dendrogram generated for 47 Iranian bread wheat lines based on grain yield under drought stress, irrigated conditions and ten yield-based drought tolerance indices using Ward's method.

**CONCLUSION**

In this study, positive significant correlations obtained in yield under drought stress condition and irrigated condition with STI, MP, GMP, HM and YI leads to the conclusion that these indices are the best predictors of yield under drought stress and non-stressed environments. YSI was also found to be useful indices in discriminating drought tolerant/susceptible lines which were stable in different conditions and produced high yield under water stressed conditions. The lines with high values of TOL, SSI and SDI were able to produce high yield only in the irrigated condition. It was also considered that drought stress significantly reduced the yield of some lines, while, some were tolerant to drought, indicating genetic diversity for drought tolerance among bread wheat lines. Therefore, breeders can select suitable lines under water-stressed conditions and compare their yield performance under irrigated conditions using STI, GMP and MP indices as a means to decide on performance under drought stress and irrigated conditions.

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