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Exploring of durum wheat genetic resources under early drought stress and selection of useful drought-responsive indices

Sourour Ayed [1,a,*], Afef Othmani [1,a], Imen Bouhaouel [2] and Jaime A. Teixeira da Silva [3]

[1] *University of Carthage, National Agricultural Research Institute of Tunisia, LR20-INRAT-02, Field Crops Laboratory, 2049 Ariana, Tunisia*
[2] *University of Carthage, National Agronomic Institute of Tunisia, LR14AGR01, Genetics and Cereal Breeding Laboratory, 1082 Tunis, Tunisia*
[3] *Independent researcher, P. O. Box 7, Ikenobe 3011-2, Kagawa-ken 761-0799, Japan;*
[a] *These authors equally contributed, joint first authors.*
* *Correspondence: ayedsourour@yahoo.fr*

Abstract:
Background*: In the literature, little information is available on the effect of drought stress on durum wheat cultivars at the seedling stage and on the best drought-responsive indices.*
Materials and Methods*: Five Tunisian landraces (Biskri, Mahmoudi, Agili, Chili, and Jeneh Khotifa) and three modern varieties (Karim, Nasr, and Rezzak) of durum wheat were evaluated under stressed (10% soil water capacity) and irrigated conditions (50% soil water capacity) in a pot trial. Eleven parameters were measured in seedlings including tiller number, leaf number, fresh root length, fresh shoot length, root fresh weight, root dry weight, shoot fresh weight, shoot dry weight, chlorophyll index, leaf area, and grain yield.*
Results*: Drought stress affected differently the growth of all genotypes. Scatter plots showing the relationship between seedling traits under both conditions indicated that landraces showed higher values than modern varieties. Based on grain yield under irrigated and control conditions, drought tolerance indices (geometric mean productivity, mean productivity, stress susceptibility index, stress tolerance index, stress tolerance, and yield stability index), revealed that Chili and Jeneh Khotifa were the most tolerant genotypes to limited water. Principal component analysis explained 73.90% of the total variation in the Tunisian germplasm and showed that root fresh weight, root dry weight, shoot fresh weight, shoot dry weight, and fresh root length were suitable traits for selecting drought-tolerant durum wheat at the seedling stage. Based on these traits, a large adaptation at an early growth stage distinguished three landraces, Mahmoudi, Jeneh Khotifa, and Biskri. Correlation analysis showed that fresh root length was significantly and positively correlated with root fresh weight (r = 0.68), fresh shoot length (r = 0.79), shoot fresh weight (r = 0.63), shoot dry weight (r = 0.63), and leaf area (r = 0.82) revealing that selection for this trait at the seedling stage is an effective strategy in a future wheat breeding program under rainfed conditions.*
Conclusion: *Root traits could be useful drought-tolerant traits for future use at early stage in breeding program.*
Keywords: *Adaptability; drought stress; genetic variability; landraces; seedling traits*

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I. Introduction

Durum wheat (*Triticum turgidum* subsp. *durum* Desf.) is a widely cultivated cereal crop in the Mediterranean region in irrigated and rainfed environments, especially in semi-arid areas with varying rainfall [1,2]. Durum wheat production is largely influenced by environmental stresses, including drought, heat, nutrient deficiency, ion toxicity, and others, although drought is the main factor limiting productivity [3–6]. The effects of drought on crop yield depend on its severity and on the stages of plant growth during which it occurs [7,8]. Increasing the efficiency of breeding drought-tolerant wheat varieties by targeting physio-morphological traits requires an understanding of the impact of drought at specific critical growth stages, such as germination and seedling, tillering, stem elongation, heading, anthesis, and grain-filling stages [8,9]. One common feature of the Mediterranean climate in North Africa is the uncertainty of rainfall immediately after wheat emerges and few studies have been performed to compare the drought tolerance of durum wheat cultivars under early-season drought stress, namely at the seedling stage. Improving tolerance to drought stress at the seedling stage is becoming a much more important target for durum wheat breeders due to an increase in the frequency and severity of drought occurrences at this stage. Seed germination, vigor and coleoptile length are fundamental aspects for the effective establishment of crop plants and the degree of seedling establishment is an extremely important factor that determines the timing of maturity and yield [10–12]. Root and shoot length, as well as fresh shoot and root weight are morpho-physiological traits that have been shown to influence the adaptive response of durum wheat to drought, and thus considered as potentially useful traits for breeding purposes [13–16]. However, only a few studies have reported a positive association between seedling traits and grain yield [17, 18]. Those studies highlighted the importance of seedling drought tolerance in durum wheat on performance. In this context, Man et al. [19] and Sallam et al. [12] noted that roots are important organs for absorption and metabolism, as well as important contributors to grain yield. The size, quantity, distribution, metabolism, and variation in activity of the root system directly influence the growth and development of above-ground tissues, and eventually grain yield [20]. Chen et al. [21] and Preethi et al. [22] reported that water stress at the seedling stage in wheat induced deeper roots and a larger root surface area at the detriment of shoot growth. Root traits play an important role in crop performance, particularly for durum wheat which is grown as a crop in drought-prone areas that are rainfed and tend to have low rainfall [14, 23, 24].

Increasing the genetic potential of yield under water deficit conditions is also a major objective and the principle selection index of durum wheat breeding programs in many countries that experience drought [25–27]. Several drought indices that are based on grain yield under drought and normal conditions have been studied to enhance selection efficiency under drought conditions [28]. Geometric mean productivity (GMP) was suggested by Fernandez [29] to select genotypes based on their performance in non-stressed and stressed conditions. According to Rosielle and Hamblin [30], stress tolerance (TOL) was defined as the difference in grain yield between stressed and irrigated environments and mean productivity (MP) as the average grain yield of genotypes under irrigated and drought environments. Fischer and Maurer [31] and Clarke et al. [32] proposed stress susceptibility index (SSI) as a measurement of yield stability in variable environments. Gavuzzi et al. [33] defined yield index (YI) as the stability determination of a genotype in both non-stressed and stressed conditions. Furthermore, Fernandez [29] suggested stress tolerance index (STI) as a useful key for identifying genotypes that produce high grain yield under both non-stressed and stressed environments. In addition, correlation analysis between grain yield and drought tolerance indices can be a reliable criterion for screening the best genotypes and indices utilized [34, 35]. Bennani et al. [36] outlined that the most appropriate index for selecting drought-tolerant genotypes is an index that is highly correlated with grain yield under non-stressed and stressed conditions. Mohammadi [37] and Grzesiak et al. [38] reported that selection for drought tolerance in wheat could be conducted for high MP, GMP, and STI under both conditions. The selection of different genotypes under stressed conditions is one of the main tasks of plant breeders whose genetic variations must be considered to improve drought tolerance [1, 26,39].

In the present study, the objectives were i) to assess the response of durum wheat genotypes to drought stress imposed at the seedling stage in order to identify tolerant genotypes, adaptive traits, and their association with grain yield, and ii) to determine useful drought-tolerant indices for future use in a durum wheat breeding program.

II. Material And Methods

Plant Material, Trial Preparation, and Experimental Conditions

Five Tunisian landraces (Biskri, Mahmoudi, Agili, Chili, and Jeneh Khotifa) and three modern varieties (Karim, Nasr, and Rezzak) of durum wheat (*Triticum turgidum* subsp. *durum* Desf.), characterized by contrasting agronomic traits, were selected for this study.

Six seeds from each genotype were sown in pots (21 cm diameter and 25 cm depth), filled with 2.50 kg of compost soil and sand (1:1, v/v). Pots were placed in a controlled growth chamber of the Agricultural School of Kef with a 16-h photoperiod, 25°C/20°C day/night temperatures, and 65-70% relative air humidity.

Drought stress treatment was applied from germination to harvest. Two irrigation levels were used: (i) control with 10% soil water capacity (i.e., stressed conditions) and (ii) supplemental irrigation with 50% soil water capacity, usually applied to durum wheat genotypes (i.e., non-stressed conditions). The statistical design was a completely randomized block with three replicates per treatment.

Measured Traits

Ten seedling growth traits at the Z21 stage [40] were measured for each genotype under non-stressed and stressed conditions: tiller number plant^{-1}, leaf number plant^{-1}, fresh root length (cm), fresh shoot length (cm), root fresh weight (g), root dry weight (g), shoot fresh weight (g), shoot dry weight (g), chlorophyll index (Chlorophyll meter SPAD 502, Konnica Minolta, Osaka, Japan), and leaf area (mm^2) (Electronic planimetre

AM300, Soil Mesures, France). After harvesting, grain yield (g pot^{-1}) was recorded. On the basis of these data, six drought tolerance indices were calculated, as shown in Table 1.

Table no 1. Drought tolerant indices measured on the basis of grain yield under non-stressed and stressed conditions.

Indices	Formula	Unit
Mean productivity (MP)	$MP = \frac{Ys + Yp}{2}$ [30]	g pot^{-1}
Geometric mean productivity (GMP)	$GMP = \sqrt{(Ys) \times (Yp)}$ [29]	g pot^{-1}
Stress susceptibility index (SSI)	$SSI = \frac{1 - \left(\frac{Ys}{Yp}\right)}{1 - \left(\frac{\overline{Ys}}{\overline{Yp}}\right)}$ [31]	-
Stress tolerance index (STI)	$STI = \frac{(Ys) \times (Yp)}{(\overline{Yp})^2}$ [29]	-
Stress tolerance (TOL)	$TOL = Yp - Ys$ [30]	g pot^{-1}
Yield stability index (YSI)	$YSI = \frac{Ys}{Yp}$ [41]	-

Yp: mean yield of the genotype under non-stressed conditions, Ys: mean yield of the genotype under stress conditions, $\overline{Yp}$: mean yield of all genotypes under non-stressed conditions, $\overline{Ys}$: mean yield of all genotypes under stressed conditions.

Data Analysis

Data obtained were subjected to analysis of variance (ANOVA) and Duncan's multiple range test [42] was employed to compare treatment means. Simple correlation coefficients were calculated between seedling traits. All data were analyzed using R software version 4.0 (The R Foundation for Statistical Computing). In order to better classify the eight genotypes, principal component analysis (PCA) was carried out on the correlation matrix, calculated on the mean data of three replicates.

III. Result

Variance Analysis and Means Comparison

ANOVA was performed on 11 traits during the seedling stage in two contrasting environments (irrigated and drought-stressed) as a prerequisite for measuring the effect of early drought stress and genetic diversity on seedling growth. Differences among genotypes and water regimes were highly significant ($p < 0.001$) for all traits (Table 2), indicating notable genetic variability among the durum wheat genotypes and a positive effect of irrigation compared to the control treatment (Table 3).

Table no 2. Variance analysis of the 11 traits measured for eight durum wheat genotypes under two water regimes (irrigated and control).

	Treatments (T)	Genotypes (G)	G x T	R^2
df	1	7	7	
TN	152.35***	18.49***	1.44^{ns}	0.44
LN	106.79***	4.97***	1.91^{ns}	0.29
FRL	82.01***	7.17***	1.12^{ns}	0.27
FSL	604.05***	26.39***	5.50***	0.69
RFW	142.74***	38.84***	1.95^{ns}	0.53
RDW	122.55***	24.16***	1.82^{ns}	0.45
SFW	206.19***	19.91***	3.70**	0.50
SDW	196.45***	20.39***	0.99^{ns}	0.48
Chl index	238.12***	14.63***	2.17*	0.49
LA	342.64***	50.61***	13.54***	0.68
GY	2.99***	0.15***	0.02^{ns}	0.56

TN: tiller number, LN: leaf number, FRL: fresh root length (cm), FSL: fresh shoot length (cm), RFW: root fresh weight (g), RDW: root dry weight (g), SFW: shoot fresh weight (g), SDW: shoot dry weight (g), Chl index: chlorophyll index, LA: leaf area (mm^2), GY: grain yield (g), df: degrees of freedom, R^2 = multiple correlation coefficient. Level of significance: $p > 0.05$ = ns, $p \leq 0.05$ = *, $p < 0.01$ = **, $p < 0.001$ = ***.

Mean comparisons indicated that water deficit significantly affected all traits; it reduced shoot fresh weight, root dry weight, root fresh weight, and shoot dry weight by 19.01%, 18.18%, 16.67%, and 16.30%, respectively (Table 3). At the seedling stage, landraces and modern genotypes responded differently to drought stress. The results showed that among all studied genotypes, Agili and Chili had significantly highest values of tiller number $plant^{-1}$ (6.66 and 6.90), root fresh weight (0.93 g and 0.88 g), root dry weight (0.13 g and 0.11 g), and chlorophyll index (52.05 and 52.41) (Table 3). This suggests that the magnitude of differences between or among genotypes was sufficient to provide some scope for selecting genotypes to improve drought tolerance. In this study, root characters were reliable markers for identifying different categories of genotypes tested and could be used as a preliminary screening technique for detecting early drought tolerance.

Table no 3. Mean of seedling traits measured for eight durum wheat genotypes grown in two contrasting environments (irrigated and control).

Traits	TN	LN	FRL	FSL	RFW	RDW	SFW	SDW	Chl index	LA	GY
Water regime											
Irrigated	6.44a	3.26a	9.55a	31.99a	0.84a	0.11a	9.47a	1.35a	52.27a	2585.29a	1.32b
Control	5.72b	3.08b	9.06b	27.12b	0.70b	0.09b	7.67b	1.13b	47.78b	2206.28b	1.61a
Mean	6.20	3.20	9.39	30.36	0.80	0.10	8.87	1.28	50.77	2458.62	1.47
% decrease	11.18	5.52	5.13	15.22	16.67	18.18	19.01	16.30	8.59	14.66	18.01
Genotypes											
Biskri	6.13c	3.40a	9.68b	30.15c	0.88b	0.10c	9.60b	1.36bc	50.32bc	2717.96b	1.44bcd
Mahmoudi	5.73d	3.15cd	10.31a	32.98a	0.89b	0.10d	8.89c	1.36bc	52.17a	2890.44a	1.48abcd
Agili	6.66b	3.14cd	9.30c	28.41d	0.93a	0.13a	9.10c	1.47a	52.05a	2603.94c	1.38cd
Chili	6.90a	3.30ab	9.23c	31.29b	0.88b	0.11b	9.10c	1.30c	52.41a	2150.77g	1.45bcd
Jeneh Khotifa	6.04c	3.18c	9.76b	32.77a	0.89b	0.11b	10.07a	1.42ab	51.96a	2442.85d	1.34d
Karim	5.42e	3.20bc	8.86d	28.46d	0.50d	0.06e	8.12de	0.92f	49.18c	2206.65fg	1.55ab
Nasr	6.19c	3.04d	8.99cd	28.80d	0.70c	0.09d	8.23d	1.15[e]	46.71d	2373.63de	1.52abc
Rezzak	6.52b	3.17c	8.97cd	30.00c	0.70c	0.10d	7.84 e	1.24d	51.36ab	2285.79ef	1.61a

TN: tiller number, LN: leaf number, FRL: fresh root length (cm), FSL: fresh shoot length (cm), RFW: root fresh weight (g), RDW: root dry weight (g), SFW: shoot fresh weight (g), SDW: shoot dry weight (g), Chl index: chlorophyll index, LA: leaf area (mm^2), GY: grain yield (g). For each trait, different letters indicate significant differences according to Duncan's multiple range test ($p \leq 0.05$).

Scatter Plots and Correlation Analysis

Scatter plots, showing the relationship between seedling traits under non-stressed and stressed conditions, indicate significant correlations between the two treatments for tiller number (r = 0.86), fresh root length (r = 0.73), root fresh weight (r = 0.90), and root dry weight (r = 0.87) (all $p < 0.05$) (Figure 1). For tiller number, root fresh weight, and root dry weight, Agili, Chili, and Jeneh Khotifa showed the best results in stressed and irrigated treatments. On the other hand, Jeneh Khotifa, and Mahmoudi recorded the highest values for fresh root length and fresh shoot length for the two environments. Overall, landraces showed the best values in most seedling traits compared to modern varieties under stressed and non-stressed conditions.

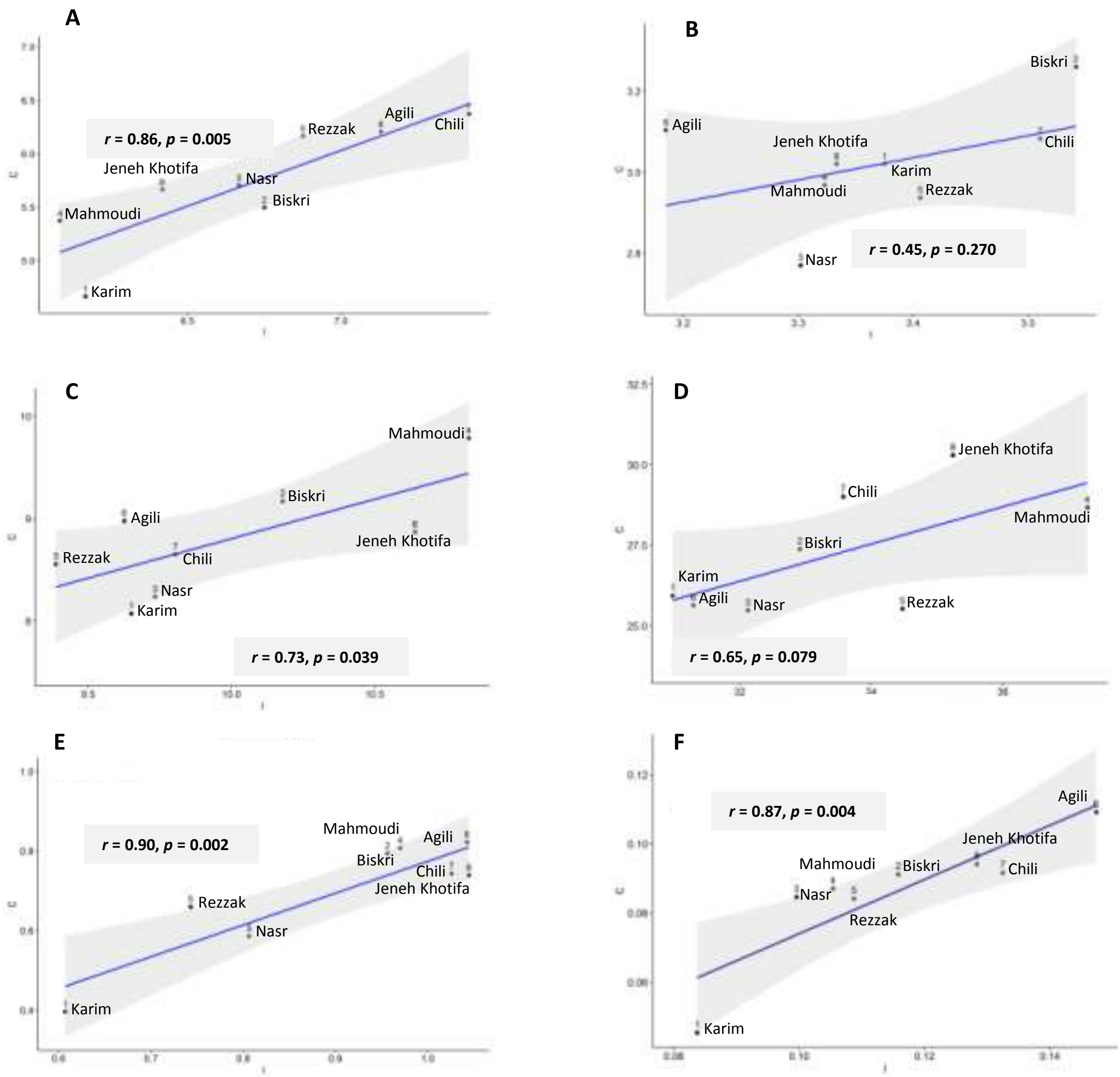

Figure 1. Scatter plots showing the relationship between seedling traits under irrigated (I) and control (C) conditions. **A**: tiller number, **B**: leaf number; **C**: fresh root length; **D**: fresh shoot length; **E**: root fresh weight; **F**: root dry weight. Level of significance: $p > 0.05$ = ns, $p \leq 0.05$ = *, $p < 0.01$ = **, $p < 0.001$ = ***.

For all treatments, correlations among all phenotypic seedling traits were calculated (Figure 2). Fresh root length was significantly and positively correlated (all $p < 0.05$) with root fresh weight ($r = 0.68$), fresh shoot length ($r = 0.79$), shoot fresh weight ($r = 0.63$), shoot dry weight ($r = 0.63$), and leaf area ($r = 0.82$). These results indicate that an increase in fresh root length may cause a simultaneous increase in other traits. The different parameters could be useful for screening wheat genotypes at the seedling stage and eventually lead to the development of drought-tolerant durum wheat varieties. Indeed, grain yield showed a negative correlation with root fresh weight ($r = -0.87$, $p < 0.01$), root dry weight ($r = -0.80$, $p < 0.05$), shoot fresh weight ($r = -0.90$, $p < 0.01$), and shoot dry weight ($r = -0.82$, $p < 0.05$). These findings indicate that landraces generally showed the greatest adaptation of traits, except to a lesser extent grain yield, compared to high-yielding modern varieties.

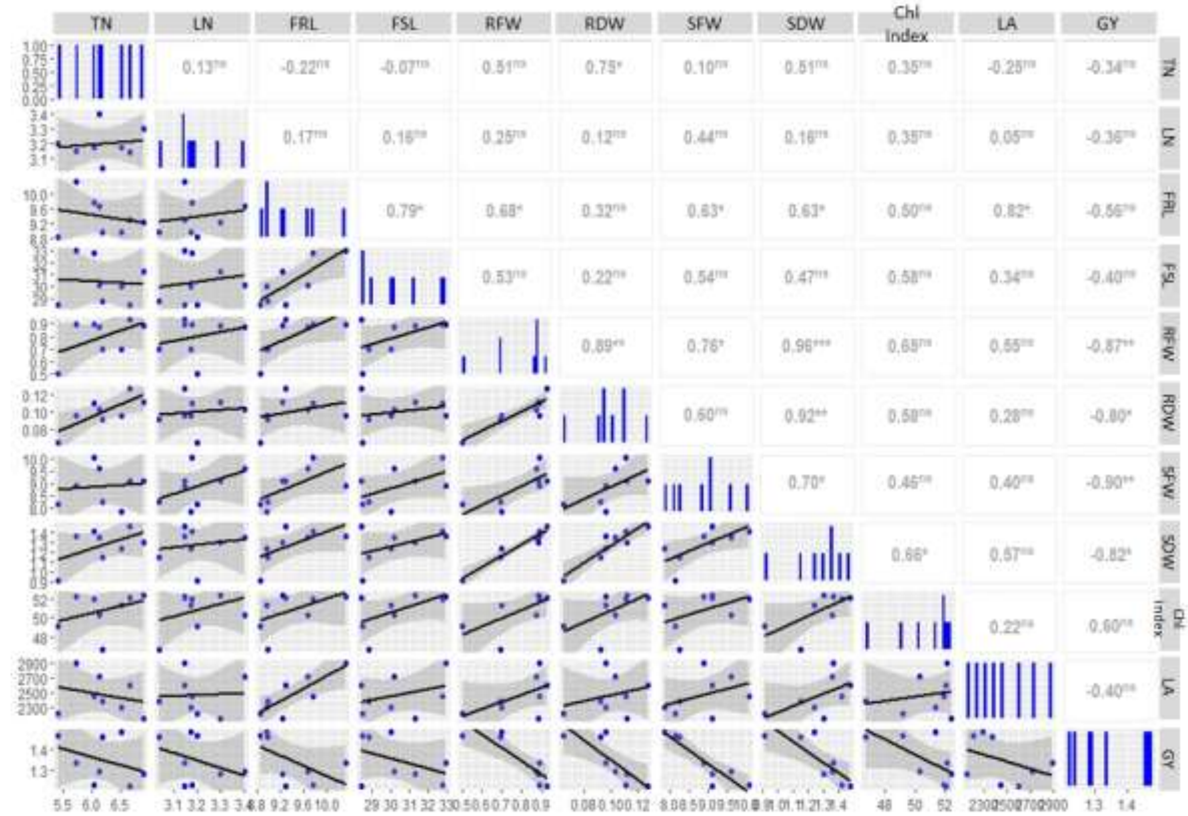

Figure 2. Scattter plot and Pearson's correlation coefficient matrix between seedling traits among eight durum wheat genotypes in two contrasting environments (non-stressed and stressed conditions). TN: tiller number, LN: leaf number, FRL: fresh root length, FSL: fresh shoot length, RFW: root fresh weight, RDW: root dry weight, SFW: shoot fresh weight, SDW: shoot dry weight, Chl index: chlorophyll index, LA: leaf area, GY: grain yield. Level of significance: $p > 0.05$ = ns, $p \leq 0.05$ = *, $p < 0.01$ = **, $p < 0.001$ = ***.

Drought Resistance Indices and their Relationship with Grain Yield

Based on grain yield under irrigated and control conditions, drought tolerance indices (GMP, MP, SSI, STI, TOL, and YSI) were calculated (Figure 3). Rezzak (1.61, 1.62, and 0.99), Karim (1.54, 1.55, and 0.91), and Nasr (1.51, 1.52, and 0.87) showed, the highest GMP, MP, and STI, respectively. However, Jeneh Khotifa recorded the lowest values (1.34, 1.34, and 0.68). All genotypes showed similar ranks for SSI, TOL, and YSI. Chili and Jeneh Khotifa exhibited the lowest SSI (0.71 and 0.81) and the highest YSI (0.87 and 0.86). Nasr and Karim had the highest TOL (0.42 and 0.33) values, indicating a large decrease in grain yield under drought conditions and thus higher drought sensitivity. However, the low TOL index values (0.20 and 0.21) recorded for Chili and Jeneh Khotifa revealed that these genotypes were the most tolerant to drought.

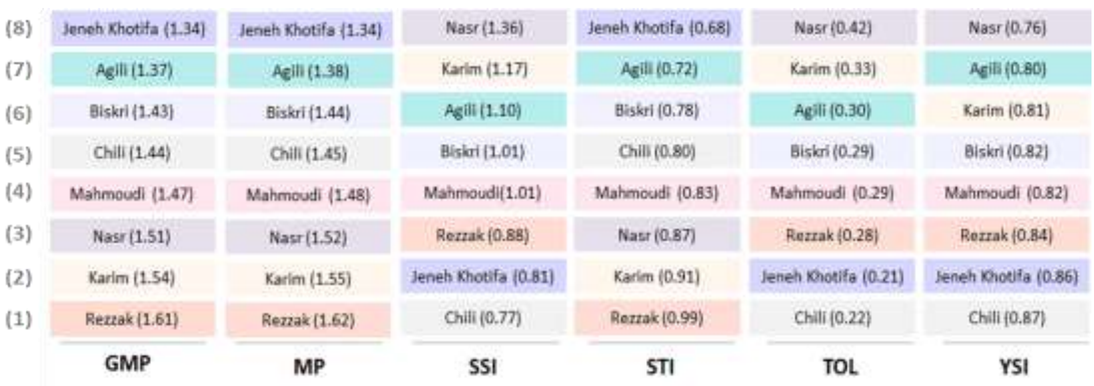

Figure 3. Drought tolerance and susceptibility indices for the eight durum wheat genotypes grown in two contrasting environments (irrigated and control). GMP: geometric mean productivity (g pot^{-1}), MP: mean productivity (g pot^{-1}), SSI: stress susceptibility index, STI: stress tolerance index, TOL: stress tolerance (g pot^{-1}), YSI: yield stability index. Each color indicate one genotype.

Correlation analysis between all indices showed that GMP was highly significantly correlated with MP ($r = 0.99$, $p < 0.001$) and STI ($r = 0.99$, $p < 0.001$) (Figure 4). Our findings also show positive and significant correlations among Ys and GMP, MP and STI, and between Yp and GMP, MP and STI. These results demonstrate that these indices could be suitable for screening drought-tolerant wheat genotypes.

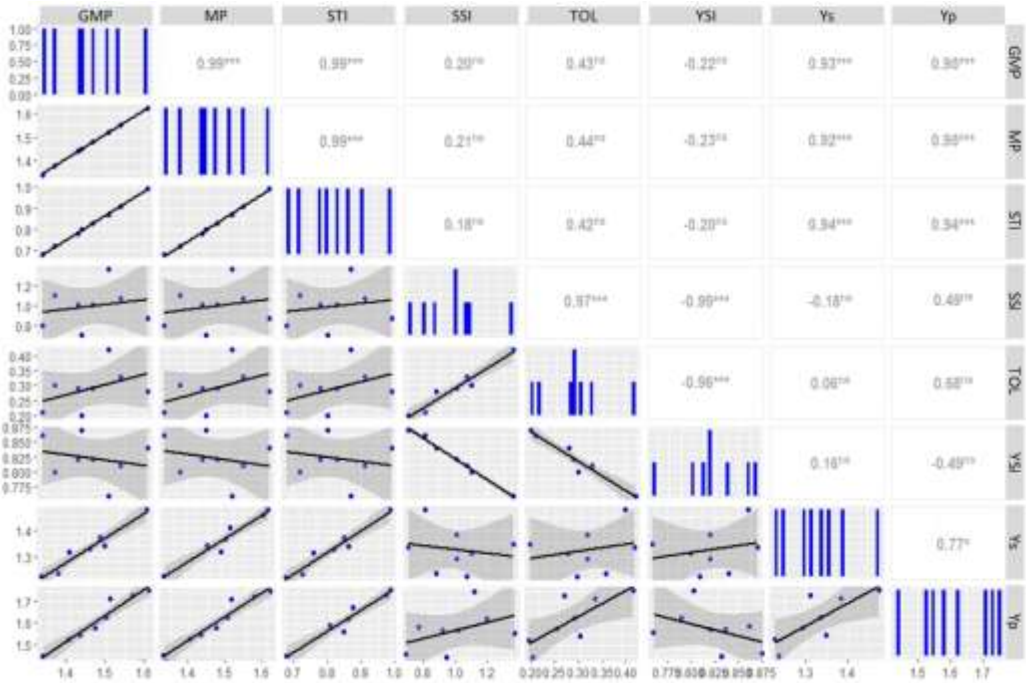

Figure 4. Scattter plot and Pearson's correlation coefficient matrix among drought tolerance indices for eight durum wheat genotypes under irrigated and stressed conditions. GMP: geometric mean productivity, MP: mean productivity, SSI: stress susceptibility index, STI: stress tolerance index, TOL: stress tolerance, YSI: yield stability index, Ys: yield under stressed conditions, Yp: yield under irrigated conditions. Level of significance: $p > 0.05$ = ns, $p \leq 0.05$ = *, $p < 0.01$ = **, $p < 0.001$ = ***.

Principal Component Analysis (PCA)

PCA explained 73.90% of total variation under irrigated and stressed treatments (Figure 5). The first axis (PC1) explained 53.70% of total variability and the most associated traits were root fresh and dry weight, shoot fresh and dry weight, fresh shoot and root length. The second PCA axis (PC2) explained 20.20% of total variability and was mostly related to the number of tillers plant^{-1}. In this study, the collection of eight durum wheat genotypes was characterized by large diversity over the two PC axes. Seedlings' traits varied among the eight Tunisian durum wheat genotypes under irrigated and stressed conditions. PCA could further classify the eight durum wheat genotypes into three groups. The first group formed by Mahmoudi, Jeneh Khotifa, and Biskri is characterized by high leaf area, fresh root and shoot length, and shoot fresh weight, suggesting a higher stress tolerance. The second group contained Agili and Chili with high root dry weight, shoot dry weight, and tiller number. The third group included Nasr, Karim, and Rezzak.

Traits	Factors	
	PC1	PC2
TN	0.37	0.89
LN	0.33	0.03
FRL	0.77	-0.60
FSL	0.66	-0.43
RFW	0.97	0.52
RDW	0.81	0.52
SFW	0.80	-0.11
SDW	0.94	0.18
Chl index	0.74	0.11
LA	0.59	-0.54

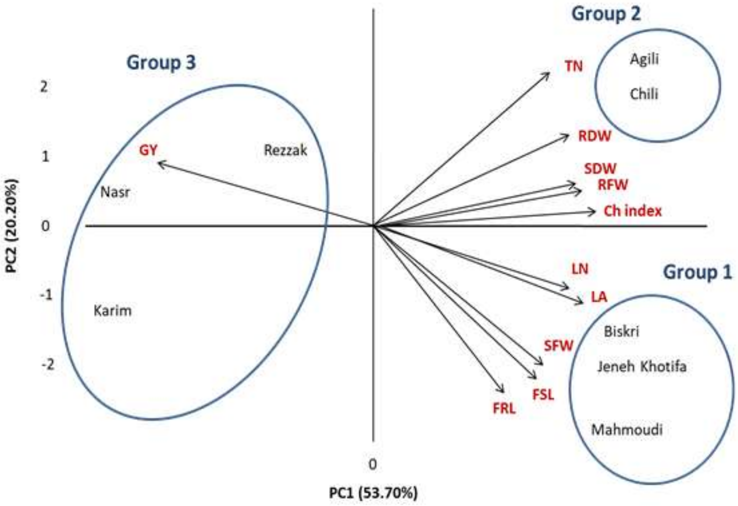

Figure 5. Principal component analysis showing the distribution of seedling traits and the eight durum wheat genotypes, grown in non-stressed and stressed conditions. TN: tiller number, LN: leaf number, FRL: fresh root length, FSL: fresh shoot length, RFW: root fresh weight, RDW: root dry weight, SFW: shoot fresh weight, SDW: shoot dry weight, Chl index: chlorophyll index, LA: leaf area.

IV. Discussion

Seedling Traits, an Important Indicator of Drought Tolerance

Notable genetic variability among eight durum wheat genotypes was observed in this study for most traits. In fact, the potential number of tillers, one of the five developmental processes in durum wheat, varies from genotype to genotype and depends on environmental conditions, mainly on water availability [43, 44]. Grain yield depends on the number of tillers that survive up to maturity [45]. In agreement with previous studies, water deficit stress decreased leaf area and chlorophyll index for all tested genotypes. Leaf area index is the main physiological determinant of crop yield [45,46]. Drought mostly affects the growth of leaves and roots, photosynthesis, and dry matter accumulation [47–49]. An average of 15% of the leaf area decreased in rain-fed wheat varieties compared to a 36% decline in irrigated varieties under water stress [50]. One of the initial responses of plants to water stress is a decrease in leaf elongation [51,52] and the closing of stomata [53–55] in order to reduce water loss *via* transpiration.

Our results showed that root traits were reliable markers for identifying differences between genotypes. According to Vincent [56] and Reynolds et al. [57], long roots are an important organ to aid a crop's adaptation to water limitations. Also, as reported by Botwright et al. [58], screening for quicker root growth and depth can be used to identify appropriate genotypes with increased root exploration which allow removing more subsoil water and taking up more nutrients, thus sustaining crop growth and improving crop performance in water-limited environments. In general, drought-tolerant wheat genotypes have more roots, a highly absorptive surface area, and long roots compared to susceptible genotypes, when screened for drought tolerance [59,60]. In addition, seedlings of drought-tolerant wheat cultivars can compensate for decreased root absorption area and retain higher root water uptake ability by enhancing root vitality, maintaining higher root biomass, and retaining higher leaf photosynthetic area and net photosynthetic rate to mitigate the inhibition of growth by drought [15,61,62]. While breeders have occasionally selected, consciously or subconsciously, for extensive rooting, a systematic breeding program for a desirable root system will undoubtedly contribute to higher yields under water stress. Moreover, screening root characteristics at early stages of plant development may serve as proxy traits at mature stages, although verification is needed because characters are associated with improved crop productivity under drought [63,64].

Correlations between Seedling Traits Can Reveal Drought Tolerance

The results of our correlation analyses indicate that shoot and root traits (length and weight) were positively correlated. A similar finding was observed by Hossein et al. [43], who reported that wheat root length was significantly and positively correlated with root fresh weight (r = 0.34, p < 0.001), root dry weight (r = 0.28, p < 0.05), shoot fresh weight (r = 0.38, p < 0.001), and shoot dry weight (r = 0.45, p < 0.001). These results are also supported by the findings of Rauf et al. [65] and Xu et al. [66], who found that root length was positively and significantly correlated with fresh shoot weight, dry shoot weight, fresh root weight, and dry root weight. According to Junjittakarn et al. [67], root traits should be considered in a breeding program for the improvement of other traits. More profuse (higher root length density) and deeper root systems are often viewed as desirable traits for wheat's adaptation to drought [68,69]. Our results are consistent with these findings and indicate that an increase in root fresh weight may cause a simultaneous increase in other traits. The different parameters studied in the present study could be useful for screening durum wheat genotypes at the seedling stage and eventually lead to the development of drought-tolerant varieties. In fact, Hossein et al. [43] reported that the capacity of seeds to germinate at low osmotic potential is related to some extent to its capacity to absorb water.

Genotypes Performances Based on Drought Indices

The yield performance of genotypes under drought stress and more favorable environments seems to be a common starting point in the selection of genotypes in wheat breeding programs [32]. Drought indices, based on yield loss under stressed conditions in comparison to normal conditions, have been used for screening drought-tolerant genotypes [28]. These indices are either based on drought resistance or susceptibility of genotypes [29]. Our results showed that GMP, MP, and STI indices are suitable for screening genotypes under both non-stressed and stressed conditions. These findings are in agreement with the conclusions drawn by Grzesiak et al. [38] in 20 wheat genotypes assessed for their drought response. Mevlut and Sait [70] indicated that genotypes with high STI usually have large differences in yield in two different conditions. These authors also reported that similar ranks for genotypes were noticed when employing GMP, MP and STI indices, suggesting that these three indices are equally powerful for screening genotypes under drought stress conditions. In addition, GMP, MP, and STI had the highest correlation with durum wheat grain yield under non-stressed and stressed conditions, similar to previous research in wheat [71] and in two other cereal crops, barley [72] and millet [73]. Several studies [1,34,35,74,75] highlighted the effectiveness of these indices for the selection of drought tolerance. Lowest SSI and highest YSI were observed in two landraces, Chili (0.77 and 0.87, respectively) and Jeneh Khotifa (0.81 and 0.86, respectively), which seem to be drought-tolerant and had stable grain yield under a semi-arid environment. Durum wheat production tends to employ modern cultivars, and landraces are only cultivated by conservator farmers in a very limited area [76,77]. Nowadays, landraces are important genetic resources characterized by their adaptation to their original agro-ecological zones, so their preservation is important for avoiding genetic erosion [78]. The focus on landraces led to the rediscovery and reutilization of durum wheat landraces in new breeding programs [79]. Wheat landraces are generally tolerant to biotic and abiotic stresses and have been grown under low-input or sustainable farming conditions where they produce reasonable yield [80]. However, unlike landraces, Del Pozoa et al. [81] and Nakhforoosh et al. [82] showed that modern genotypes exhibit higher grain yield, harvest index, number of grains per ear, and higher grain yield.

V. Conclusion

In general, root traits may be of importance for explaining drought tolerance. Moreover, screening root characteristics at early stages in plant development could serve as proxy traits at mature stages but verification is needed because characters are associated to improved crop productivity under drought.

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