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Variations of Grain Yield and Agro-morphological Traits of Some Promising Durum Wheat Lines (*Triticum turgidum* L. var. *durum*) at Zinc Sufficient and Deficient Conditions

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Abstract

Successful production and development of stable and adaptable genotypes only depend on the positive results achieved from the interaction between genotype and environment that consequently has a significant impact on breeding strategies. In this regard, we conducted an experiment to study genotypic differences of 16 lines durum wheat under both zinc sufficient and deficient stress during 2014-2015 growing seasons in University of Maragheh, Iran. Our results showed that Zn stress significantly ($P < 0.001$) affected all studied traits among the lines. The interaction between zinc stress conditions (C) and lines (L) was significant for peduncle length and plant height. Our findings indicated that zinc-deficient stress significantly reduced spike length (6.8%), spike dry weights (19.1%), plant height (12.0%), peduncle length (15.2%) and peduncle dry weights (26.7%). Zinc deficient stress also decreased the number of grains per spike, number of fertile spikelet per spike, thousand grain weight, biological yield, grain yield, and harvest index by 29.2, 15.5, 5.1, 24.1, 32.5, and 10.5%, respectively. The results showed that line numbers of 2 (G2, 4025) and 5 (G5, 46202) produced the lowest and highest spike length (SL) and spike weight (SW), number of grains per spike (NGS), and number of fertile spikelet (NFT), respectively; while line numbers of 10 (G10, 45704) and 14 (G14, 45415) produced the highest and line numbers of 1 (G1, 4017), 11 (G11, 45667), and 12 (G12, 45632) produced the lowest grain yield (GY), and harvest index (HI), respectively. Under non-zinc deficient stress and zinc deficient stress, GY was positively associated ($P < 0.001$) with STI, GMP, MP, and HARM as well as negatively correlated ($P < 0.001$) with SSI under zinc-deficient stress. Accordingly, indices of STI, GMP, MP, and HARM were the best indices for identification of high yielding lines in both conditions (zinc deficient tolerant lines). In total, results showed that G14 (45415) and G10 (45704) lines relatively identified as zinc tolerant and G1 (4017), G2 (4025), and G11 (45667) lines identified as susceptible lines.

Key words: Genetic diversity; Durum wheat; Agro-morphological traits; Zinc deficient resistance indices

Introduction

Wheat is the first and the most important grain in the world. Meanwhile, durum wheat (*Triticum turgidum* L. var. *durum*) as one of the major cereal crops, is the only tetraploid (AABB, 2n = 4x = 28) species of commercial wheat that is widely cultivated in Mediterranean climates (Pour Siahbid *et al*., 2013; Etminan *et al*., 2016). Compared to other cereal species (such as rye, triticale, barley, and bread), durum wheat genotypes possess high sensitivity to Zn deficiency (Cakmak *et al*., 1998; Cakmak, 2008).

Zinc (Zn) deficiency is a common micronutrient deficiency in wheat-growing areas of the world, particularly in arid and semi-arid regions (Graham and Welch, 1996). Zinc deficiency in soil is a significant limiting factor for agricultural productivity and generally inhibits plant growth and yield in crop plants through reduction of water absorption, photosynthesis rate, photosynthetic metabolism processes, nutrient uptake, and etc (Kalayci *et al*., 1999; Wissuwa *et al*., 2006; Cakmak, 2008; Cakmak *et al*., 2010; Esfandiari *et al*., 2016). Plant zinc deficient tolerance is a highly complex trait that involves multiple genetic, morphological, physiological, and biochemical mechanisms (Cakmak *et al*., 2010; Esfandiari *et al*., 2016). Grain yield is a complex of component traits and is greatly affected by many environmental conditions, particularly the conditions of zinc deficiency and drought stress. In general, characteristics such as morphological traits, plant height, number of grain per spike, 1000-grain weight, biological yield and harvest index are the most important traits in cereals especially wheat (Abdoli and Saeidi, 2012; Pour Siahbidi *et al*., 2013).

Indeed, evaluation of genetic diversity of germplasm is one of main tasks in breeding programmes, because it may help selection of cultivars and lines with higher diversity and better performance under specific conditions (Etminan *et al*., 2016). Generally, indices such as SSI (Fischer and Maurer, 1978), TOL (Rosielle and Hamblin, 1981; Naghavi *et al*., 2013), STI and GMP (Fernandez, 1992; Khalili *et al*., 2014; Khalili *et al*., 2016), and HARM (Kristin *et al*., 1997; Saeidi *et al*., 2016) have been reported for selection of tolerant genotypes to environmental stresses. Also, one type of method for studying genotypes is to allocate genotypes into qualitatively homogeneous stability subsets through cluster analysis (Lin *et al*., 1986).

For improving zinc-tolerant crop lines and varieties by plant breeding, it is necessary to identify tolerant genotypes to zinc stress during all growth stages. The present study was conducted (i) to study the associations between yield and agro-morphological traits under both zinc deficient stress and non-stress conditions in order to find a suitable trait that could be used to improve yield under the both conditions, and also (ii) to evaluate the performance of sixteen promising durum wheat lines and identification desirable lines to use for further breeding programs.

Materials and Methods

Experimental site and soil characters

In order to identify Zn stress susceptible and tolerance in durum wheat, sixteen lines were evaluated under zinc sufficient and deficient stress conditions during 2014-2015 growing seasons at University of Maragheh (46º, 16'/E; 37º, 22'/ N, altitude 1542 m above sea level) located in the East Azerbaijan province at northwest of Iran. This region is characterized by a semi-arid cool climate, with an annual mean temperature of 13.2°C and mean precipitation of 309 mm for the past 30 year. The soil of experimental site had a clay loam texture (39% clay, 45% silt, and 16% sand) with pH (H_2O) of 7.2, $CaCO_3$ of 20% and organic matter of 0.4%. Available N, P and K were 0.092%, 6.1 and 360 mg/kg soil, respectively. The concentration of DTPA-extractable Zn was 0.4 mg/kg soil (Lindsay and Norvell, 1978), which is lower than the widely accepted critical Zn amount of 0.5 mg/kg (Sims and Johnson, 1991). Pursuant to soil test and before planting, the soil was mixed homogeneously with a basal fertilizers of 200 mg N [as $Ca(NO_3)_2.4H_2O$]/kg soil and 100 mg P [as KH_2PO_4]/kg soil.

Experimental design and treatments

The pot experiment was carried out in a factorial design in the randomized complete block design (RCBD) with 32 treatments (2 Zn conditions, and 16 durum wheat lines) in three replications. The first factor was two condition of Zn were (1) zinc deficient stress (non-Zn supply; -Zn), and (2) normal Zn supply (combination of soil application with 5 mg Zn/kg soil at planting + foliar application with 0.44 g Zn/liter water at stem elongation and grain filling stages; +Zn), and also the second factor was sixteen durum wheat lines including ‘4017’, ‘4025’, ‘4303’, ‘4341’, ‘46202’, ‘46046’, ‘46020’, ‘45868’, ‘45717’, ‘45704’, ‘45667’, ‘45632’, ‘45620’, ‘45415’, ‘45430’, and ‘45558’. These sixteen durum wheat lines were chosen owing to they were new lines with unknown morphological and agronomical traits.

Plant material and growth conditions

The seeds of durum wheat lines were obtained by Dryland Agricultural Research Institute (DARI) of Iran. The names, code, agronomic traits and growth characteristics of durum wheat lines used in this experiment are given in Table 1. Seeds were sowed on 12th March 2014 in plastic pots (PVC; 20×30 cm diameter and height, respectively) which were filled with 3.5 kg of soil. Fourteen seeds were sown in each pot and daily watered by deionized water, and the seedlings were thinned to seven seedlings per pot at 3 to 4-leaf stage. Irrigation of plant in the pots (FC = 90 ± 5%) and crop management practices such as pests and weeds were controlled from pots close to maturity of plants.

Table 1. List of durum wheat lines used in this experiment and their agronomical and morphological traits.

No.	Line	Code	GH	DHE	DMA	PH	TKW (g)	GY (kg/ha)
1	4017	G1	SF	167	197	65	36	607
2	4025	G2	SF	165	185	73	39	1673
3	4303	G3	S	158	191	57	45	1093
4	4341	G4	SF	158	185	44	28	1333
5	46202	G5	S	164	195	44	37	420
6	46046	G6	SF	156	185	46	41	1853
7	46020	G7	S	154	185	58	39	1760
8	45868	G8	S	155	191	52	45	793
9	45717	G9	SF	155	183	52	36	1713
10	45704	G10	S	160	187	50	38	1733
11	45667	G11	S	162	191	65	34	820
12	45632	G12	SF	163	191	65	34	533
13	45620	G13	S	156	187	54	39	1787
14	45415	G14	S	161	191	38	42	1173
15	45430	G15	S	159	187	60	42	1807
16	45558	G16	S	156	185	52	36	1800

Growth habit (GH), days to heading (DHE), days to maturity (DMA), plant height (PH), thousand grain weight (TKW), and grain yield (GY). Source: Dryland Agricultural Research Institute, Agricultural Research, Education and Extension Organization (AREEO), Maragheh, Iran. S: spring, SF: spring-fall (interstitial).

Agronomic traits and morphological characteristics measurements

The following agro-morphological characteristics were recorded: spike length (SL), peduncle length (PedL), plant height (PH), spike weight (SW), peduncle weight (PedW), number of grains per spike (NGS), number of fertile spikelet (NFT), thousand grain weight (TKW), biological yield (BY), grain yield (GY), and harvest index (HI). At the maturity period, five randomly chosen plants from each pot were used for recording data on agro-morphological characters. Plant height was measured from ground to the tip of the main spike at maturity. In addition, main spike length was measured excluding awns. Moreover, the total above ground dry weight was measured as biological yield.

Table 2. List of zinc stress tolerance indices used in this experiment.

No.	Index	Formula	Reference
1	Stress Susceptibility Index	$SSI = [1 - (Ys/Yp)]/SI$	Fischer and Maurer (1978)
2	Stress Index	$SI = \left(1 - \frac{\bar{Y}s}{\bar{Y}p}\right)$	
3	Stress Tolerance Index	$STI = \frac{Yp}{\bar{Y}p} \times \frac{Ys}{\bar{Y}s} \times \frac{\bar{Y}s}{\bar{Y}p} = \frac{Yp \times Ys}{(\bar{Y}p)^2}$	Fernandez (1992)
4	Geometric Mean Productivity	$GMP = \sqrt{Ys \times Yp}$	Fernandez (1992)
5	Stress Tolerance	$TOL = Yp - Ys$	Rosielle and Hamblin (1981)
6	Mean Productivity	$MP = \frac{Ys + YP}{2}$	Rosielle and Hamblin (1981)
7	Harmonic Mean	$HARM = \frac{2(Yp \times Ys)}{Yp + Ys}$	Kristin *et al*. (1997)

Yp and Ys: Grain yield of each line under non-stress and zinc deficient stress conditions, respectively.
$\bar{Y}p$ and $\bar{Y}s$: Mean grain yield of all lines under non-stress and zinc deficient stress conditions, respectively.

Zinc deficient resistance indices determination

In order to estimates the tolerance and sensitivity indices under Zn deficit stress in various durum wheat lines, the relationships that proposed by Fischer and Maurer (1978) for SSI, Fernandez (1992) for STI and GMP, Rosielle and Hamblin (1981) for TOL and MP, and Kristin *et al*. (1997) for HARM were used. All used indices in this experiment are shown in Table 2.

Statistical analysis

The obtained data were subjected to analysis of variance (ANOVA) using SAS software version 8.0 (SAS Institute Inc., Cary, NC, USA) and MSTAT-C software version 2.10 for DOS (MSTATC, 1989). Mean comparison was conducted using Duncan's multiple range test (DMRT) at $P < 0.05$ (Duncan, 1955). The data were analyzed using SPSS software version 16.0 (SAS Institute, 1987) for cluster analysis of durum wheat lines based on Square Euclidean distance and Ward method.

Results

Grain yield and agronomic traits

The analysis of variance revealed highly significant difference among lines for all traits studied except of biological yield (Table 3). Also, results showed the significant difference among two different conditions of Zn element for all studied traits (Table 3). On the other hand, interaction effect of line × conditions (L × C) was significant on peduncle length (PedL) and plant height (PH) at $P < 0.001$ and $P < 0.05$, respectively (Table 3).
The results showed that there was variation among lines for spike length (SL) and spike weight (SW) (Table 3). So that G5 (46202) with 4.7 cm had the highest and G2 (4025), G6 (46046), and G16 (45558) with 3.3 cm had the lowest spike length of wheat (Table 5). Also, G5 (46202) with 323 mg had the highest and G2 (4025) with 166 mg had the lowest weight of spike (Table 5). Means of agro-morphological characteristics under zinc-deficient stress and non-stress conditions and also reduction percent of these characteristics due to zinc-deficient stress are shown in Table 4. The results showed that the mean of spike length and spike weight decreased 6.8 and 19.1% under zinc-deficient stress conditions, respectively (Table 4).
Greater variation was observed among lines for peduncle dry weight (PedW) under zinc-deficient stress and non-zinc deficient stress conditions (Table 5). The line of G11 (45667) followed by 170 mg had the highest dry weight of peduncle internode, and lines of G4 (4341), G1 (4017), and G2 (4025) by 37, 99, and 102 mg, individually, had the lowest dry weight of peduncle internode (Table 5). Zinc-deficient stress reduced dry weight of peduncle internode by 26.7% (Table 4).
Number of grains per spike (NGS) ranged from 18.2 grain (highest) for G5 line to 8.7 grain (lowest) for G2 line (Table 5). Similarly, the highest and lowest number of fertile spikelet (NFT) were occurred in G5 (46202) and G2 (4025) lines with 9.6 and 5.2 fertile spikelet's per spike, respectively (Table 5). Zinc-deficient stress decreased number of grains per spike (NGS) and number of fertile spikelet (NFT) per spike by 29.2 and 15.5%, respectively (Table 4). The agronomical and morphological characters correlations for each condition (normal and zinc-deficient stress) are shown in Table 8. In the normal (non-zinc deficient stress) condition, a negative significant correlation was found between NGS with pedL ($R^2 = -0.59$, $P < 0.05$) and PH ($R^2 = -0.54$, $P < 0.05$), but under zinc-deficient stress condition, a positive significant correlation was found between NGS with SL ($R^2 = 0.53$, $P < 0.05$) and SW ($R^2 = 0.65$, $P < 0.001$) (Table 8).
Thousand grain weight (TKW) differed narrowly among durum wheat lines under zinc-deficient stress and non-zinc deficient stress conditions, with a mean value of 39.5 g and 37.5 g, respectively (Table 4). Considerable differences in TKW were observed among durum wheat lines at $P < 0.001$ (Table 3). So that, G7 (46020) with 53.4 g had the highest and G1 (4017) and G5 (46202) with 27.0 and 26.7 g had the lowest TKW of wheat (Table 5).
The mean grain yield (GY) of the 16 durum wheat lines was 0.567 g plant^{-1} under normal (non-stress) conditions and 0.383 g plant^{-1} under zinc-deficient stress conditions; mean grain yield was thus 32.5% lower under zinc-deficient stress than under non-zinc deficient stress (Table 4). Also, zinc-deficient stress reduced biological yield by 24.1% (Table 4).

The lines also showed GY ranging from 0.295 to 0.620 g plant^{-1} (Table 5). Accordingly, G7 (46020), G8 (45868), G10 (45704), G14 (45415), and G15 (45430) showed the highest GY values, whereas; G1 (4017), G2 (4025), G11 (45667), and G12 (45632) had significantly lower GY values than other lines (Table 5). Based on mean performance, these durum wheat lines were identified as the superior lines for these environmental conditions. In this experiment, grain yield showed positive correlation with TKW and BY in both environments and in zinc-deficient stress condition had positive correlation with SW ($R^2 = 0.54$, $P < 0.05$), NGS ($R^2 = 0.77$, $P < 0.001$), and NFT ($R^2 = 0.51$, $P < 0.05$) (Table 8).

The results of this study showed that G10 (45704) and G14 (45415) with 47.7 and 48.2% had the highest and G1 (4017), G11 (45667), and G12 (45632) with 25.6, 23.2, and 27.3% had the lowest harvest index (Table 5). Also, zinc-deficient stress decreased harvest index by 10.5% (Table 4).

Peduncle length measured for durum wheat lines ranged from 14.6 to 30.7 cm (G1 and G12, respectively), with an average value of 22.9 cm under zinc-deficient stress conditions, and also from 19.6 to 32.6 cm (G4 and G12, respectively), with an average value of 27 cm, under non-zinc deficient stress conditions (Table 6). So that, peduncle length was thus 15.2% lower under zinc-deficient stress than under non-zinc deficient stress (Table 4).

Among durum wheat lines, considerable variation was found for plant height under both zinc deficient and non-zinc deficient stress conditions (Table 3). Among durum wheat lines, plant height varied from 33.1 cm at G1 (4017 line) to 52.4 cm at G12 (45632 line), with an average of 42.5 cm under zinc-deficient stress, and from 38.1 cm at G4 (4341 line) to 57.7 cm at G11 (45667 line), with an average of 48.3 cm under non-zinc deficient stress (Table 6). In other words, mean plant height was 12% lower under zinc-deficient stress than under non-zinc deficient stress (Table 4).

Table 3. Analysis of variance for studied traits of durum wheat lines as the factorial experiment based on randomized complete block design.

Source of variation	df	Mean squares					
		SL	PedL	pH	SW	PedW	NGS
Replication	2	1.02*	18.7^{ns}	88.9*	15911*	2058^{ns}	64.9*
Conditions (C)	1	1.92*	18.7**	811.4**	66465**	36270**	425.0**
Line (L)	15	1.24**	400.9**	144.9**	11185*	2762*	38.1**
L × C	15	0.371^{ns}	71.0**	44.6*	4823^{ns}	2021^{ns}	15.9^{ns}
Error	62	0.317	9.53	24.3	4824	1355	14.3
CV (%)	-	14.2	12.3	10.8	27.8	29.1	30.7
Source of variation	**df**	**NFT**	**TKW**	**BY**	**GY**	**HI**	
Replication	2	7.44*	29.7^{ns}	0.463*	0.103*	49.2^{ns}	
Conditions (C)	1	28.7**	95.6*	2.64**	0.743**	447.6**	
Line (L)	15	5.72**	359.9**	0.156^{ns}	0.075**	337.5**	
L × C	15	1.08^{ns}	14.7^{ns}	0.109^{ns}	0.018^{ns}	41.7^{ns}	
Error	62	1.60	21.3	0.117	0.028	45.9	
CV (%)	-	19.3	12.0	28.5	35.4	17.4	

Degree of freedom (df), coefficient of variations (CV), spike length (SL), peduncle length (PedL), plant height (PH), spike weight (SW), peduncle weight (PedW), number of grains per spike (NGS), number of fertile spikelet (NFT), thousand grain weight (TKW), biological yield (BY), grain yield (GY), and harvest index (HI).
ns, * and ** indicate non-significant, significant in $P < 0.05$ and $P < 0.001$ respectively.

Table 4. The average values of the studies traits under normal and zinc deficient stress conditions, and the percentage change of each traits after the stress treatment in durum wheat.

Traits	Conditions		Percentage change (%)
	Normal (non-stress)	Zinc deficient stress	
Spike length (cm)	4.10 ^{a}	3.82 ^{b}	-6.8
Peduncle length (cm)	27.0 ^{a}	22.9 ^{b}	-15.2
Plant height (cm)	48.3 ^{a}	42.5 ^{b}	-12.0
Spike weight (mg)	276.0 ^{a}	223.4 ^{b}	-19.1
Peduncle weight (mg)	145.8 ^{a}	106.9 ^{b}	-26.7
Number of grains per spike	14.4 ^{a}	10.2 ^{b}	-29.2
Number of fertile spikelet	7.08 ^{a}	5.98 ^{b}	-15.5
Thousand grain weight (g)	39.5 ^{a}	37.5 ^{b}	-5.1
Biological yield (g/plant)	1.37 ^{a}	1.04 ^{b}	-24.1
Grain yield (g/plant)	0.567 ^{a}	0.383 ^{b}	-32.5
Harvest index (%)	41.0 ^{a}	36.7 ^{b}	-10.5

Conditions for each trait with the same letters are not significantly different from each other at $P < 0.05$.

Table 5. Mean comparison of different traits of studied durum wheat lines using Duncan's multiple range test (DMRT) method.

Lines code	SL (cm)	SW (mg)	PedW (mg)	NGS	NFT	TKW (g)	GY (g/plant)	HI (%)
G1	4.3 $^{a-c}$	255 $^{a-e}$	99 ^{c}	10.9 $^{b-c}$	6.4 ^{bc}	27.0 ^{h}	0.295 ^{b}	25.6 ^{c}
G2	3.3 ^{e}	166 ^{e}	102 ^{c}	8.7 ^{c}	5.2 ^{c}	37.1 ^{de}	0.333 ^{b}	38.9 ^{ab}
G3	3.8 $^{b-e}$	235 $^{a-e}$	108 ^{bc}	10.7 $^{b-c}$	5.7 ^{bc}	45.0 ^{bc}	0.487 ^{ab}	43.0 ^{ab}
G4	4.4 $^{a-c}$	282 $^{a-c}$	97 ^{c}	14.8 ^{ab}	7.1 ^{b}	33.9 $^{e-g}$	0.506 ^{ab}	43.0 ^{ab}
G5	4.7 ^{a}	323 ^{a}	111 ^{bc}	18.2 ^{a}	9.6 ^{a}	26.7 ^{h}	0.484 ^{ab}	35.6 ^{b}
G6	3.3 ^{e}	223 $^{b-e}$	128 $^{a-c}$	10.3 $^{b-c}$	6.0 ^{bc}	45.7 ^{bc}	0.486 ^{ab}	41.4 ^{ab}
G7	4.4 ^{ab}	304 ^{ab}	132 $^{a-c}$	10.9 $^{b-c}$	6.4 ^{bc}	53.4 ^{a}	0.583 ^{a}	40.9 ^{ab}
G8	4.2 $^{a-c}$	272 $^{a-d}$	124 $^{a-c}$	13.6 $^{a-c}$	6.9 ^{bc}	43.7 ^{bc}	0.614 ^{a}	42.2 ^{ab}
G9	3.6 $^{c-e}$	200 $^{c-e}$	133 $^{a-c}$	14.3 ^{ab}	6.3 ^{bc}	35.4 $^{e-g}$	0.511 ^{ab}	43.6 ^{ab}
G10	4.2 $^{a-c}$	266 $^{a-d}$	127 $^{a-}$c	14.5 ^{ab}	7.1 ^{b}	42.1 ^{cd}	0.620 ^{a}	47.7 ^{a}
G11	4.1 $^{a-d}$	286 $^{a-c}$	170 ^{a}	9.1 ^{c}	5.9 ^{bc}	36.5 $^{d-e}$	0.347 ^{b}	23.2 ^{c}
G12	4.2 $^{a-c}$	232 $^{a-e}$	154 ^{ab}	10.1 $^{b-c}$	6.1 ^{bc}	30.2 ^{gh}	0.303 ^{b}	27.3 ^{c}
G13	3.4 ^{de}	178 ^{de}	139 $^{a-c}$	11.7 $^{b-c}$	5.6 ^{bc}	36.8 $^{d-e}$	0.441 ^{ab}	41.2 ^{ab}
G14	4.1 $^{a-d}$	260 $^{a-d}$	105 ^{bc}	14.5 ^{ab}	6.8 ^{bc}	42.3 ^{cd}	0.615 ^{a}	48.2 ^{a}
G15	4.1 $^{a-d}$	270 $^{a-d}$	145 $^{a-c}$	11.9 $^{b-c}$	6.7 ^{bc}	48.2 ^{ab}	0.576 ^{a}	43.7 ^{ab}
G16	3.2 ^{e}	242 $^{a-e}$	148 $^{a-c}$	12.8 $^{b-c}$	6.7 ^{bc}	31.0 $^{f-h}$	0.401 ^{ab}	36.8 ^{b}

Spike length (SL), spike weight (SW), peduncle weight (PedW), number of grains per spike (NGS), number of fertile spikelet (NFT), thousand grain weight (TKW), grain yield (GY), and harvest index (HI). Similar letters of each trait within different lines show no significant differences between lines at $P < 0.05$.

Table 6. Comparison of the mean interactions of line × conditions (L × C) on peduncle length and plant height of sixteen durum wheat lines under non-stress and zinc deficient stress conditions.

Lines code	Peduncle length (cm)			Plant height (cm)		
	Normal (non-stress)	Zinc deficient stress	Mean	Normal (non-stress)	zinc deficient stress	Mean
G1	26.9 ± 2.8	14.6 ± 3.2	20.7 ^{gh}	51.4 ± 3.5	33.1 ± 7.4	42.3 $^{c-e}$
G2	31.6 ± 0.6	21.8 ± 4.7	26.7 $^{b-e}$	51.4 ± 1.8	38.5 ± 6.6	45.0 $^{c-e}$
G3	31.5 ± 3.5	22.7 ± 0.4	27.1 $^{b-d}$	51.8 ± 6.0	39.6 ± 5.9	45.7 $^{b-d}$
G4	19.6 ± 4.4	19.5 ± 2.0	19.5 ^{h}	38.1 ± 7.3	39.4 ± 4.9	38.8 ^{e}
G5	24.3 ± 1.3	19.7 ± 1.7	22.0 $^{f-h}$	43.6 ± 1.0	42.4 ± 2.7	43.0 $^{c-e}$
G6	23.5 ± 2.0	23.2 ± 2.9	23.4 $^{d-h}$	44.3 ± 2.9	39.6 ± 6.2	41.9 $^{c-e}$
G7	26.2 ± 0.8	22.7 ± 3.7	24.5 $^{c-g}$	46.3 ± 2.0	45.6 ± 4.3	45.9 ^{bc}
G8	25.9 ± 1.8	17.3 ± 4.8	21.6 $^{f-h}$	49.9 ± 1.9	39.0 ± 8.4	44.4 $^{c-e}$
G9	26.3 ± 4.5	19.2 ± 2.0	22.8 $^{e-h}$	43.6 ± 8.3	34.8 ± 1.9	39.2 ^{de}
G10	26.8 ± 0.7	23.5 ± 3.3	25.1 $^{c-f}$	49.4 ± 3.2	44.6 ± 5.1	47.0 ^{bc}
G11	30.7 ± 5.8	28.3 ± 3.6	29.5 ^{ab}	57.7 ± 5.7	52.2 ± 0.8	55.0 ^{a}
G12	32.6 ± 0.9	30.7 ± 1.6	31.7 ^{a}	57.3 ± 3.2	52.4 ± 4.7	54.9 ^{a}
G13	27.4 ± 2.2	27.1 ± 4.2	27.3 $^{b-d}$	45.8 ± 2.1	42.6 ± 3.6	44.2 $^{c-e}$
G14	23.1 ± 4.2	21.2 ± 3.5	22.1 $^{f-h}$	42.4 ± 6.7	38.4 ± 7.0	40.4 $^{c-e}$
G15	29.1 ± 1.4	26.1 ± 1.5	27.6 ^{bc}	53.5 ± 3.3	49.9 ± 4.7	51.7 ^{ab}
G16	26.9 ± 5.3	29.2 ± 1.5	28.1 $^{a-c}$	46.1 ± 9.7	47.4 ± 2.1	46.8 ^{bc}
Mean	27.0 a	22.9 b		48.3 a	42.5 b	

Similar letters of each trait within different lines show no significant differences between lines at $P < 0.05$. Mean ± standard deviation (SD).

Zinc resistance indices

Stress susceptibility index (SSI) was used as a selection criterion of zinc deficient tolerant in terms of minimization of yield reduction caused by zinc deficient stress as compared with non-stress conditions. Calculated SSI varied from 0.119 to 1.945 for lines (Table 7). G5 (46202) and G1 (4017) lines that had the lowest and highest value were found to be the most tolerant and susceptible durum wheat lines, respectively (Table 7).

The zinc tolerance indices for line based on grain yield in non-stress and zinc deficient stress conditions are presented in Table 7. Based on STI, GMP and HARM values, lines numbers of 14 (G14, 45415) and 10 (G10, 45704) were identified as zinc tolerant lines (Table 7).

According to TOL, lines number of 5 (G5, 46202) and 12 (G12, 45632) exhibited the lowest value and lines numbers of 9 (G9, 45717) and 8 (G8, 45868) exhibited the highest value (Table 7).

According to MP, lines number of 10 (G10, 45704), 14 (G14, 45415), and 8 (G8, 45868) exhibited the highest value and lines numbers of 1 (G1, 4017) and 12 (G12, 45632) exhibited the lowest value (Table 7).

The correlation coefficients among the various indexes are presented in Table 9. Under non-zinc deficient stress, GY was positively associated with STI (r = 0.89**), GMP (r = 0.88**), MP (r = 0.92, $P < 0.001$), and HARM (r = 0.84, $P < 0.001$). While, under zinc deficient stress, GY was positively associated with STI (r = 0.93, $P < 0.001$), GMP (r = 0.94, $P < 0.001$), MP (r = 0.91, $P < 0.001$), and HARM (r = 0.97, $P < 0.001$) and also negatively correlated with SSI (r = -0.69, $P < 0.001$) (Table 9).

Table 7. The amounts of yields in normal and zinc deficient conditions and zinc resistance indices in studied durum wheat lines.

Lines code	Yp	Ys	SSI	STI	GMP	TOL	MP	HARM
G1	0.431	0.159	**1.945**	0.213	0.262	0.272	0.295	0.232
G2	0.451	0.214	1.619	0.300	0.311	0.237	0.333	0.290
G3	0.586	0.389	1.036	0.709	0.477	0.197	0.488	0.468
G4	0.570	0.441	0.697	0.782	0.501	0.129	0.506	0.497
G5	0.493	0.474	0.119	0.727	0.483	0.019	0.484	0.483
G6	0.562	0.409	0.839	0.715	0.479	0.153	0.486	0.473
G7	0.652	0.513	0.657	1.040	0.578	0.139	0.583	0.574
G8	**0.782**	0.446	1.324	1.085	0.591	0.336	0.614	0.568
G9	0.685	0.338	1.561	0.720	0.481	**0.347**	0.512	0.453
G10	0.754	0.485	1.099	1.137	0.605	0.269	**0.620**	0.590
G11	0.481	0.212	1.723	0.317	0.319	0.269	0.347	0.294
G12	0.324	0.282	0.399	0.284	0.302	0.042	0.303	0.302
G13	0.505	0.376	0.787	0.591	0.436	0.129	0.441	0.431
G14	0.659	**0.571**	0.411	**1.170**	**0.613**	0.088	0.615	**0.612**
G15	0.664	0.487	0.821	1.006	0.569	0.177	0.576	0.562
G16	0.467	0.335	0.871	0.487	0.396	0.132	0.401	0.390
Max	0.782	0.571	1.945	1.170	0.613	0.347	0.620	0.612
Min	0.324	0.159	0.119	0.213	0.262	0.019	0.295	0.232
Mean	0.567	0.383	0.994	0.705	0.463	0.183	0.475	0.451

Grain yield of each line under non-stress conditions (Yp), grain yield of each line under zinc deficient stress conditions (Ys), stress susceptibility index (SSI), stress tolerance index (STI), geometric mean productivity (GMP), stress tolerance (TOL), mean productivity (MP), harmonic mean (HARM).

Table 8. Simple correlation coefficients between some agronomical and morphological characters in durum wheat lines under normal (above diameter) and zinc-deficient stress (down diameter) conditions.

Traits	SL	pedL	PH	SW	PedW	NGS	NFT	TKW	BY	GY	HI
SL	1	-0.12	0.16	0.78**	0.01	0.22	0.38	0.08	0.66**	0.22	-0.20
pedL	-0.10	1	0.89**	-0.20	0.70**	-0.59*	-0.55*	0.03	-0.03	-0.39	-0.49
PH	0.33	0.86**	1	0.14	0.78**	-0.54*	-0.39	0.05	0.28	-0.32	-0.61*
SW	0.86**	0.07	0.43	1	0.16	0.26	0.42	0.15	0.79**	0.31	-0.15
PedW	0.17	0.83**	0.81**	0.39	1	-0.39	-0.38	0.26	0.47	0.00	-0.34
NGS	0.53*	0.03	0.11	0.65**	0.25	1	0.78**	-0.33	0.24	0.46	0.42
NFT	0.80**	-0.16	0.14	0.86**	0.13	0.81**	1	-0.29	0.24	0.29	0.17
TKW	-0.07	-0.01	0.07	0.05	-0.08	-0.09	-0.23	1	0.41	0.66**	0.54*
BY	0.75**	0.24	0.54*	0.92**	0.55*	0.66**	0.71**	0.27	1	0.59*	0.06
GY	0.39	-0.04	0.07	0.54*	0.11	0.77**	0.51*	0.55*	0.69**	1	0.83**
HI	-0.18	-0.16	-0.29	-0.08	-0.27	0.46	0.04	0.52*	0.06	0.74**	1

Spike length (SL), peduncle length (PedL), plant height (PH), spike weight (SW), peduncle weight (PedW), number of grains per spike (NGS), number of fertile spikelet (NFT), thousand grain weight (TKW), biological yield (BY), grain yield (GY), and harvest index (HI).
* and ** indicate significancy at $P < 0.05$ and $P < 0.001$ respectively.

Table 9. Correlation coefficients between studied zinc resistance indices in durum wheat under non-stress and zinc deficient stress conditions.

Indices	Yp	Ys	SSI	STI	GMP	TOL	MP	HARM
Yp	1							
Ys	0.68**	1						
SSI	0.03	-0.69**	1					
STI	0.89**	0.93**	-0.40	1				
GMP	0.88**	0.94**	-0.43	0.99**	1			
TOL	0.46	-0.34	0.88**	0.01	-0.01	1		
MP	0.92**	0.91**	-0.35	0.99**	1.00**	0.08	1	
HARM	0.84**	0.97**	-0.50*	0.99**	1.00**	-0.09	0.98**	1

Grain yield of each line under non-stress conditions (Yp), grain yield of each line under zinc deficient stress conditions (Ys), stress susceptibility index (SSI), stress tolerance index (STI), geometric mean productivity (GMP), stress tolerance (TOL), mean productivity (MP), harmonic mean (HARM). * and ** indicate significancy at $P < 0.05$ and $P < 0.001$ respectively.

Cluster analysis

The aim of cluster analysis was to define the degree of relatedness in yielding ability under non-stress and zinc deficient stress conditions in durum wheat lines. The result of cluster analysis for studied durum wheat lines has been presented in Figure 1. The yielding cluster analysis divided the lines into three main groups at distance level of 5.

Five durum wheat lines (G7, G8, G10, G14, and G15) were placed in group I. These lines had high yields in the both environment and showed less reduction in yield in zinc deficient stress condition (Figure 1) and had high value of STI, GMP, MP, and HARM indices (Table 7). Group II consisted of highly sensitive durum wheat lines that have high yielding in optimum condition with significantly reduction showing low yields in zinc deficient stress condition. Group III (G1, G2, G11, and G12) comprised those lines which low yield under both non-stress and zinc deficient stress conditions and had low value of STI, GMP, MP, and HARM indices (Table 7). The results of cluster analysis showed that only simultaneous evaluation of germplasm under optimum and zinc deficient stress conditions could reveal the most valuable source for zinc deficient stress tolerance.

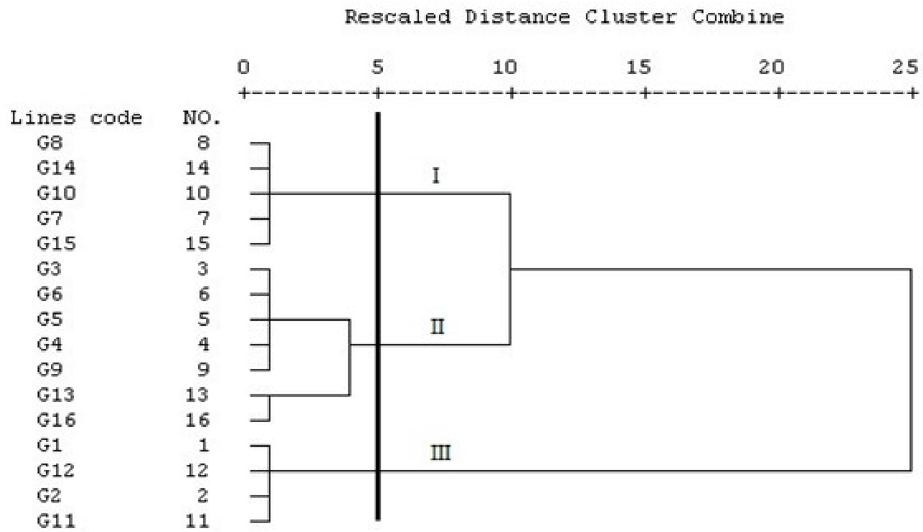

Fig. 1. Dendrogram of cluster analysis of durum wheat lines classified according to yield ability in non-stress and zinc deficient stress conditions using Ward method based on Euclidean distance. Numbers inside the figure are number of durum wheat lines.

Discussion

Zinc is a necessary component of several enzymes participating in the synthesis and degradation of carbohydrates, lipids, proteins, and nucleic acids as well as in the metabolism of other micronutrients, and plays an important role in the production of biomass (Cakmak, 2008). Therefore soil Zn deficiency can cause significant reductions in yield (Abdoli *e al*., 2016; Esfandiari *et al*., 2016) and induces changes in plant metabolic processes such as cell division, photosynthesis, and protein synthesis (Marschner, 1995).

Grain yield and its related traits are complex quantitative characters controlled by multiple genes and are highly influenced by environmental conditions (Shi *et al*., 2009; Khalili *et al*., 2016). According to the results of this research, zinc deficient stress decreased the spike length and dry weights, plant height, peduncle length and dry weights, number of grains per spike, number of fertile spikelet per spike, thousand grain weight, biological yield, grain yield, and harvest index by 6.8, 19.1, 12.0, 15.2, 26.7, 29.2, 15.5, 5.1, 24.1, 32.5, and 10.5%, respectively. Decrease in grain yield and agro-morphological traits under zinc-deficient stress for various crops including wheat (Kalayci *et al*., 1999), spring wheat (Velu *et al*., 2017), rice (Wissuwa *et al*., 2006), and bread and durum wheat (Abdoli *et al*., 2016; Abdoli and Esfandiari, 2017) have already been reported.

In this experiment, grain yield showed positive correlation with TKW and BY in both environments and under zinc-deficient stress condition had positive correlation with SW, NGS, and NFT. In addition, it could be suggested that some characters such as thousand grain weight, number of fertile spikelet and grains per plant should be increased in durum wheat lines in order to improve grain yield.

Considering to genetic variability, the genetic variability parameters provide information about the expected response of grain yield and other agronomic characters and can be used to select and develop optimum breeding procedures. In our study, statistical analysis for morphological traits showed significant differences among durum wheat lines (except biological yield). The variation among 16 durum wheat lines was effective for selection of promising tolerant lines based on 11 agro-morphological traits. Similarly, many studies indicated that morphological characters are very helpful in identification and evaluation of genetic diversity in wheat germplasms (Salimi *et al*., 2005; Naghavi *et al*., 2009; Talebi and Fayyaz, 2012; Zhang *et al*., 2015; Pour-Aboughadareh *et al*., 2017). On the basis of our result, lines of G14 (45415) and G8 (45868) located in first and second places related to grain yield, respectively.

Cluster analysis is a method for allocating genotypes into qualitatively homogeneous stability subsets (Lin *et al*., 1986). Based on cluster analysis, the sample studied was clustered into three main groups. So that, the lines of G7, G8, G10, G14, and G15 at group I had high yield in the both environments by, showed less reduction in yield under zinc-deficient stress condition and had high value of STI, GMP, MP, and HARM. It seems that the durum wheat lines studied are suitable for cultivation in marginal lands that constantly exposed to zinc deficit during the growing seasons. It is reported that resistant plants under nutrients stress conditions developed various morphological, physiological and biochemical responses to adaptive nature (Cakmak *et al*., 2010). These include changes of water use efficiency, pigment content, osmotic adjustment and photosynthetic activity. These mechanisms play a key role in preventing membrane disintegration and provide tolerance against stress and cellular dehydration. Also, tolerant genotypes may have lower Zn requirements or translocate relatively more Zn from roots to shoots under zinc deficit stress (Cayton *et al*., 1985).

Selection based on a combination of indices may provide a more useful criterion for improving zinc tolerance. Correlation analysis between grain yield and zinc tolerance indices can be a good criterion for screening the best genotypes and indices. Thus, a suitable index must significantly correlate with grain yield under both conditions (Mitra, 2001; Khalili *et al*., 2014). The correlation analysis between grain yields in both conditions with zinc tolerance indices showed that STI, GMP, MP, and HARM had positive and significant correlations with GY under non-stress and zinc deficient stress conditions. But, SSI had negative correlation with GY under zinc deficient stress conditions. Negative relationships between SSI and grain yield under explain which conditions indicated that selection on the basis of which index decreases grain yield under favorable conditions but increases it under stress conditions (Khalili *et al*., 2016).

Our finding showed selection of superior lines on the basis of each indicator difference. In agreement with these results, Khalili *et al*. (2012) reported that GMP, MP, and STI were significantly and positively correlated with grain yield in non-stress and stress conditions. The results obtained revealed that STI, GMP, MP, and HARM were the best indices for identifying high yielding lines in both conditions (zinc deficient tolerant lines). Accordingly, G14 (45415) and G10 (45704) lines relatively identified as zinc tolerant and G1 (4017), G2 (4025), and G11 (45667) lines identified as susceptible lines. The ability of the STI, MP and GMP indices to identify genotypes suitably under both conditions observed in this study is consistent with the results reported by Nouri *et al*. (2011) with durum wheat, Abdoli and Saeidi (2012) with bread wheat, Naghavi *et al*. (2013) with maize, Khalili *et al*. (2014) with safflower, Khalili *et al*. (2016) with barley, and Saeidi *et al*. (2016) with bread and durum wheat. Moreover, Khalili *et al*. (2016) reported that MP, GMP and STI indicators can be efficiently used to screen drought-tolerant lines and also to detect superior lines for both non-stress and stress field conditions among multiple environments.

Conclusions

In general, results of the present study indicated that zinc-deficient stress significantly decreased spike length and dry weights, plant height, peduncle length and dry weights, number of grains per spike, number of fertile spikelet per spike, thousand grain weight, biological yield, grain yield, and harvest index. Also, the results suggested that durum wheat lines should have the maximum thousand grain weight and biological yield for increase yield under non-stress conditions and also under stress conditions the durum wheat lines should have maximum number of fertile spikelet, number of grains per spike, thousand grain weight, and biological yield. In addition, under the two conditions, lines of 45704 and 45415 produced the highest and lines of 4017, 45667, and 45632 produced the lowest grain yield and harvest index, respectively. Correlation analysis between grain yields under the both conditions accompanied by calculation of zinc deficient resistance indices revealed that STI, GMP, MP, and HARM were the best indices for identifying high yielding lines (zinc deficient tolerant lines). Accordingly, 45415 and 45704 lines relatively identified as zinc tolerant and 4017, 4025, and 45667 lines identified as susceptible lines. The potential of these durum wheat lines offers further opportunities for analysis at the molecular and cellular levels to confront with zinc deficient stress through a physiological mechanism.

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