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Research paper

Agro-morphological and physiological traits affecting grain yield of durum wheat advanced generations under rainfed conditions

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Abstract
Durum wheat production in the Mediterranean climate is limited when water shortages occur during anthesis. Breeding programs try to increase crop yield under challenging weather conditions such as water shortage. The improvement in phenotyping with the purpose of selecting key plant traits is important for increasing the efficiency of the breeding program. In this study, 125 and 119 durum recombinant inbred lines (RILs) from F_7 and F_8 generations, respectively, derived from the cross between the Iranian landrace "Iran_249" and the Iranian variety "Zardak" were compared in the field over two successive years (2015 and 2016) in the temperate rainfed conditions with the Mediterranean climate. The results showed that the performance of RILs was influenced by the year. Harvest index, biomass, number of spikes per plant, number of tillers per plant, straw yield, spike weight, spike density, and weight of grains per spike were positively associated with the grain yield in two years. According to path analysis in the first year, number of spikes per plant and awn length had a positive and significant direct effect on the grain yield whilst, in the second year, the positive and significant direct effects on the grain yield belonged to the number of tillers per plant, grain filling rate, and plant height. In conclusion, based on the two-year data, the RILs with higher spike weight, the weight of grains per spike, number of tillers per plant, biomass, grain filling rate, higher plant height with longer peduncle length, and longer spikes with longer awn length may have higher yield under rainfed conditions. These traits are promising traits for the indirect selection of grain yield. RILs No. 2, 16, 29, 43, 66, 80, 100, and 118 had the highest rank in both years and were superior to their parents.

Keywords: agro-morphological traits; drought; durum wheat; recombinant inbred lines

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Introduction

Durum wheat (*Triticum turgidum* L. var. durum) is one of the nutritional resources for millions of people. Despite low cultivation area, durum wheat is an economically important crop due to its unique characteristics and products. The most important product of durum wheat is known as semolina and used all over the world in bread, pasta, and porridge (Cakmak *et al*. 2010). Durum wheat accounts for about 10% of global wheat production (Royo *et al*. 2009). It is usually allocated to lower yield environments (Mefleh *et al*. 2019).

Climate change is a major threat to most crops growing in the tropical and subtropical regions worldwide. Drought stress causes dramatic morphological, biochemical, physiological, and molecular changes in plants. All of these changes reduce plant growth and crop production (Sallam *et al*.

2019). It has been suggested that selection of genotypes using yield-related morphological and physiological traits under water-deficit stress is useful in selecting high-yielding genotypes for arid environments. Although grain yield breeding progress has been achieved for irrigated conditions, less gain has been obtained in rainfed environments. To increase the efficiency of selection in these areas, identification of traits related to drought tolerance would be useful (Ain *et al*. 2015). Grain yield in wheat is affected by agronomic and physiological traits. Therefore, for further grain yield improvement in wheat, indirect selection for the yield-related traits is recommended (Tshikunde *et al*. 2019). Path analysis is a useful tool for identifying the desirable yield-related characteristics (Nayak *et al*. 2018). González-Ribot *et al.* (2017) stated that seed size and weight, days to heading, and plant height could aid in the selection for the grain yield in durum wheat under water-shortage conditions. González - Ribot *et al.* (2012) identified flowering date, plant height, seed size, initial vigor, tillering, and isotopic discrimination of carbon 13 as influencing traits on durum wheat yield in the rainfed conditions.

This study aimed to investigate the relationships between grain yield and physiological and morphological traits in durum wheat recombinant inbred lines (RILs) under rainfed conditions with the purpose of selecting key traits affecting durum wheat yield.

Materials and Methods

Plant materials and experimental design

F_7 and F_8 generations derived from the cross between the Iranian durum cultivar “Zardak” and the Iranian durum landrace “Iran_249”, were studied at the experimental field of the Faculty of Agriculture, Razi University, Iran during two successive years (2015 and 2016) under rainfed conditions. Data on temperatures and rainfall were obtained from the meteorological station located about five km away from the experimental field. The geographic location and climate of the research station are shown in Table 1. Ambrothermic graphs of the experimental site during 2015-2017 are given in Figure 1. In the first year (2015-2016), F_7 generation including 125 RILs with their parents and six genotypes as checks were evaluated using the augmented randomized complete block design (Federer 1961) with five replications. Sowing was performed by hand. In each plot, three rows were planted with 22.5 cm spacing and 3 m in length. The experimental blocks were separated by 1 m walkways. Planting density was about 320 seeds/m^2. Harvesting was carried out on June 2016. In the second year (2016-2017), the F_8 generation which consisted of 119 RILs together with their parents were planted in a simple lattice (11 ×

11) design with two replications. Planting and cultivation operations were similar to the first year and harvesting was carried out on June 2017. The soil type was clay silty (pH= 8.2, electrical conductivity (ds.m^{-1}) = 1.4, organic carbon (%) = 1.2). A soil test was conducted as needed. Weed control was done manually.

Each year, the central rows of each plot were combine harvested after physiological maturity. At harvesting, 10 plants of each genotype were sampled to record the grain yield per plant and other agronomic traits. Physiological traits were measured 14 days after anthesis. The data for different crop growth stages such as days to heading and days to maturity were recorded for each experimental plot. The measured traits included grain filling period, grain filling rate, flag leaf length, flag leaf width, flag leaf area, plant height, peduncle length, spike length, awn length, grain length and width, grain yield per plant, biomass, straw yield, harvest index, number of spikes, number of tillers per plant, spike weight, number of seeds per spike, weight of grains per spike, and days to maturity.

Table 1. The geographic location and climate of the research field.

Longitude	47° 9′
Latitude	34° 21′
Altitude	1319 mm
The average annual rainfall	450-480 mm
Soil texture	Clay silty
Average annual temperature in the first year of the experiment (2015-2016)	15.9 °C
Average annual temperature in the second year of the experiment (2016-2017)	13.3 °C
Average rainfall in the first year of the experiment (2015-2016)	715 mm
Average rainfall in the second year of the experiment (2016-2017)	438 mm

Relative water content (RWC) was measured according to Barrs and Weatherly (1962). Five fresh fully expanded flag leaves were harvested from each RIL in each plot and weighted rapidly to record the fresh weight (FW) at the anthesis stage. They were then immersed in distilled water for four hours and weighed again to obtain a turgid weight (TW). After that, they were incubated at 70 ° C for 24 h to record the dry weight (DW). RWC was calculated using the following equation:

$$RWC = ((FW - DW)/(TW - DW)) \times 100.$$

To measure the rate of water loss (RWL), five completely expanded flag leaves were sampled from each plot. Leaf specimens were weighed (FW), dried for 4 h at 35 °C, reweighed (W4h) and oven dried for 72 h at 72 °C to obtain the dry weight (DW). RWL was calculated using the following formula:

$$RWL (\%)= [(FW - W4h)/(FW - DW)]/4 \times 100$$

(Clarke 1992).

Excised leaf water retention (ELWR) was calculated as follows:

ELWR (%) = [1- ((FW- W4h)/FW)] × 100 (Clarke and Townley-Smith 1986).

To measure the membrane stability, 0.5 g of the youngest leaves was stored for 24 hours in vials containing 10 ml of distilled water at room temperature. The electrical conductivity was then measured (EC1). Secondary leakage was measured by determining the electrical conductivity of the samples after heating them for one hour at 100 °C (EC2). The membrane stability was calculated from the following equation (Sairam and Srivastava 2002):

Membrane stability= 1- EC1/EC2

Statistical analysis

The data collected from the first and second years were subjected to analysis of variance according to augmented randomized complete block design and simple lattice design using SAS ver 9.1 and MSTAT-C software, respectively. In the augmented design, data adjustment was only performed on the traits that had a significant block effect in the analysis of variance of the check varieties and all subsequent statistical analyzes were performed on the adjusted data. Path analysis was done based on the results from the

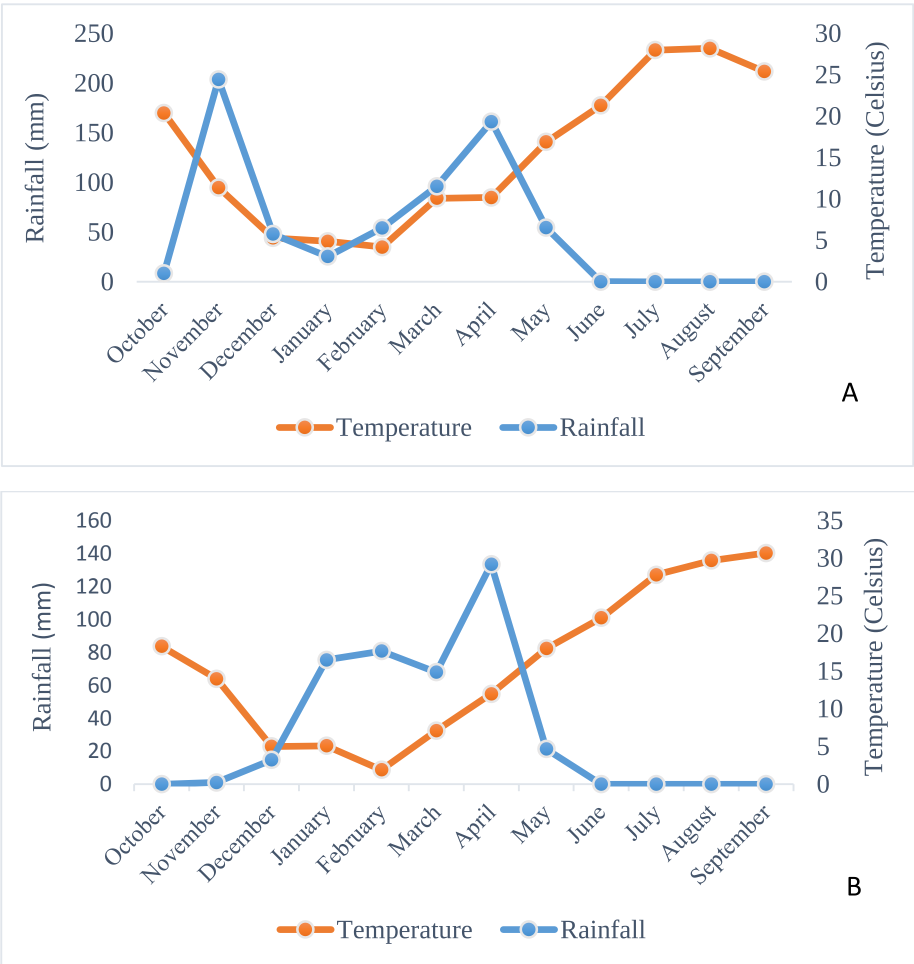

Figure 1. Ambrothermic graphs of the experimental site during 2015-2016 (A) and 2016-2017 (B).

stepwise regression method considering logical relationships between the traits. Pass analysis and calculation of the correlation coefficients were done by SPSS software version 16. The RILs were ranked according to the Arunachalam and Bandyopadhyay (1994) method for the traits affecting the grain yield. Due to the use of separate statistical design and also the difference in the number of RILs examined in two years, it was not possible to perform combined analysis of variance.

Results

Analysis of variance

In the first year (2014-2015), the block effect was significant for the grain yield, days to heading, days to maturity, excised leaf water retention, cell membrane stability, relative leaf water content, and number of tillers per plant. The values of these traits were corrected by the adjustment factor. Also, there was significant difference among the check varieties in terms of the number of spikes per plant, grain filling period, grain filling rate, and number of grains per spike (Table 2).

The results of the analysis of variance in the second year (2015-2016) are shown in Table 2. The lattice design was not more efficient than the randomized complete block design for the relative leaf water content, excised leaf water retention, flag leaf length, plant height, number of spikes per plant, grain length, days to maturity, grain filling period, and flag leaf area. Therefore, analysis of variance was done based on the randomized complete block design for these traits (Table 3). The results showed that there was not significant difference among RILs for any of the traits, except for the grain yield in 2016. Minimum, maximum, mean, and LSD values for the measured traits in two years are shown in Table 4.

Correlation of the grain yield with other traits

Phenotypic correlation coefficients of the grain yield with other measured traits in two years are shown in Table 5. The results showed that in both years, the grain yield had significant positive correlation with harvest index, biomass, number of spikes per plant, number of tillers per plant, straw yield, spike weight, spike density, and grain weight per spike.

Path analysis

The direct and indirect effects of the studied traits in first year are presented in Table 6. When the grain yield was considered as a dependent variable, the number of spikes per plant and the awn length were entered into the model, which together explained 35.1% of the changes in the grain yield. In the study of the relationship between awn length as a dependent variable with other traits, spike length was included in the model, which explained 9% of the changes in awn length. The number of spikes per plant was affected by number of tillers per plant. For the second year, the relationship of the grain yield with number of tillers per plant, grain filling rate, and plant height is shown in Table 7. The results showed that these traits accounted for 27% of the changes in the grain yield. The highest direct effect belonged to the number of tillers per plant and the highest indirect effect was related to the plant height through the grain filling rate. The direct effect of grain filling rate and plant height on the grain yield was also positive and significant. In the study of the relationship of the grain filling rate and plant height with other traits using stepwise regression, peduncle length and flag leaf area entered the model, respectively.

Identifying the best RILs through the Arunachalam and Bandyopadhyay method

The results obtained from the Arunachalam and Bandyopadhyay (1984) method showed that the RILs No. 2, 16, 29, 43, 66, 80, 100, and 118 had the highest ranks in both years and also were superior to their parents (i.e. Zardak and Iran_249) (Table 8). RILs No. 29, 66 and 100 were the best RILs based on the LSD test in both years.

Discussion

The two sites used for the field experiments were characterized by different climatic conditions in spite of the similarities in the location of experiments and soil fertility. The weather was different during two years. In the first year (2015), there was sufficient rainfall with proper distribution, while in 2016 it was marked by water shortage, especially in autumn and April. This may be the reason for some differences between the results of two years. However, due to the use of different experimental designs, it was not possible to combine the two experiments.

Table 2. Analysis of variance of the measured traits in the recombinant inbred lines of durum wheat during 2015-2016.

Year	SOV	df	GY	Bio	SY	HI	NSPP	WGPS	TGW	SW	SpD
2015	Block	4	71.2*	157.4	40.9	81.0	23. 8	0.349	19.7	0.084	114.7
	Check	5	15.0	50.7	36.8	114.8	55.1*	0.109	38.6	0.005	45.4
	RIL	124	35.6*	194.4**	120.2**	112.5	24.9**	0.29	13.4	177.0**	188.5**
	Error	20	16.2	64.2	45.7	80.1	9.7	0.22	21.5	0.006	58.3
	CV (%)		19.2	18.7	30.9	18.1	22.7	30.2	10.6	5.8	29.3
2016	Replication	1	15.5	446.4	295.7	108.3	320.7	3.09	24.9	141.1	719
	Adjusted treatment	120	16.8*	170.9	117.8	161.2	12.8	0.21	24.1	40.3	31.8
	Adjusted block	20	50.8	556.6	309.3	147.5	48.8	0.45	27.6	128.0	88.8
	Error within the block	100	10.6	135.0	94.0	97.1	13.6	0.16	19.1	30.9	31.3
	CV (%)		39.4	43.3	52.0	30.8	44.0	39.0	12.6	38.2	44.1

CV: Coefficient of variation; GY: Grain yield, Bio: Biomass, SY: Straw yield, HI: Harvest index, NSPP: Number of spikes per plant, WGPS: Weight of grains per spike, TGW: Thousand grain weight, SW: Spike weight, SpD: Spike density; *, **: $p \leq 0.05$, and $p \leq 0.01$ respectively.

Table 2 continued

			Mean squares									
Year	SOV	df	NTPP	PL	AL	PL/ Phe	GW	Phe	SL	GL	NGPS
2015	Block	4	17.8*	6.2	9.8	0.82	0.04	315.9	1.28	0.32	23. 8
	Check	5	3.0	9.0	3.2	0.54	0.30	496.4	0.53	0.33	55.1*
	RIL	124	19.8**	14.2	4.5	0.003	0.16	307.0	1.78	0.53**	25.0
	Error	20	6.3	13.8	4.6	0.65	0.23	340.6	1.38	0.20	20.2
	CV (%)		17.2	13.9	21.0	6.31	15.75	20. 9	21.5	6.3	16.8
2016	Replication	1	495	312.5	1.5	0.038	0.20				
	Adjusted treatment	120	15.6	95.1	5.5	0.006	0.12				
	Adjusted block	20	58.6	118.8	8.4	0.010	0.13				
	Error within the block	100	13.3	106.9	5.8	0.006	0.09				
	CV (%)		40.8	19.4	23.1	9. 6	12.0				

CV: Coefficient of variation, NTPP: Number of tillers per plant, PL: Peduncle length, AL: Awn length, PL/Phe: Peduncle length/ Plant height, GW: Grain width, Phe: Plant height, SL: Spike length, GL: Grain length, NGPS: Number of grains per spike; *, **: *: $p \leq 0.05$, and $p \leq 0.01$ respectively.

Table 2 continued

			Mean squares										
Year	SOV	df	DH	GFR	FLW	RWL	CMS	FLL	FLA	DM	KFP	RWC	ELWR
2015	Block	4	5.70*	0.07	.37	141.4	534*	15.05	2.04	15.83*	0.88	389.3**	9.24*
	Check	5	2.16	0.22*	2.95	187.7	162	12.93	2.90	6.00	8.67**	135.7	1.39
	RIL	124	2.24	0.21**	3.28	168.1	132. 98	6.72	1.51	6.54	2.91	63.7	8.12 **
	Error	20	1.56	0.07	2.95	121.8	151	8.75	1.72	4.33	1.82	65.4	2.77
	CV (%)		0.8	0.6	22.9	25.0	16.6	12.7	12.9	0.62	6.3	10.6	1.3
2016	Replication	1	12.50	0.05	0.20	1834	366						
	Adjusted treatment	120	6.49	0.04	0.18*	42.63	340						
	Adjusted block	20	5.45	0.05	0.27	68.99	282						
	Error within the block	100	100.0	0.03	0.12	37.97	255						
	CV (%)		1.3	12.8	43.0	26.0	25.1						

CV: Coefficient of variation; DH: Days to heading, GFR: Grain filling rate, FLW: Flag leaf width, RWL: Relative water loss, CMS: Cell membrane stability, FLL: Flag leaf length, FLA: Flag leaf area, DM: Days to maturity, GFP: grain filling period, RWC: Relative water content, ELWR: Excised leaf water retention; *, **: $p \leq 0.05$, and $p \leq 0.01$ respectively.

Table 3. Analysis of variance of the measured traits for durum wheat recombinant inbred lines during 2016-2017 based on the randomized complete block design.

SOV	df	Mean squares								
		RWC	ELWR	FLL	Phe	NGPS	GL	DM	GFP	FLA
Block	1	18.02*	43.39**	73.86*	27.11	12.04	0.43	1.65	49.09**	10.05*
RIL	120	119.0	5.06	14.06	115.7	17.14	0.37	7.91	0.95	1.86
Error	120	110.3	5.04	13.42	128.15	18.27	0..36	7.90	0.81	1.77
CV (%)		14.3	2.4	17.6	17.4	15.0	9.0	1.3	3.8	17.6

CV: Coefficient of variation; RWC: Relative water content, ELWR: Excised leaf water retention, FLL: Flag leaf length, Phe: Plant height, NGPS: Number of grains per spike, GL: Grain length, DM: Days to maturity, GFP: Grain filling period, FLA: Flag leaf area. *, **: $p \leq 0.05$ and $p \leq 0.01$, respectively.

Table 4. Some statistics for measured traits in the recombinant inbred lines of durum wheat during 2015-2016.

Year	Statistics	GY (g)	Bio (g)	SY (g)	HI (%)	NGPP	WGPS (g)	TGW (g)	SW (g)	NTPP	SpD (%)	NSPP
2015	Max	38.08	118.00	86.00	65.21	30.60	3.80	52.12	54.03	29.00	83.00	44.00
	Min	6.28	13.00	6.72	15.30	5.10	0.67	32.06	9.90	7.00	10.20	12.00
	Mean	20.22	46.80	26.57	27.48	13.39	1.63	42.54	23.53	14.56	27.30	27.15
	LSD (0.05)	12.35	24.60	20.76	15.35	9.54	1.47	14.23	0.54	7.73	23.45	13.79
2016	Max	16.73	54.55	45.24	63.27	15.39	1.99	42.93	26.69	17.62	26.04	36.50
	Min	2.11	3.13	1.15	13.26	2.12	0.29	21.89	4.83	1.01	4.33	20.50
	Mean	8.80	28.49	19.68	32.93	8.87	1.09	35.48	15.45	9.49	13.40	28.42
	LSD (0.05)	6.88	24.46	20.32	20.10	7.74	0.84	8.88	11.70	7.67	11.68	8.60

GY: Grain yield, Bio: Biomass, SY: Straw yield, HI: Harvest index, NGPS: Number of grains per spike, WKPS: Weight of grains per spike, TGW: Thousand grain weight, SW: Spike weight, NTPP: Number of tillers per plant, SpD: Spike density, NSPP: Number of spikes per plant.

Table 4 Continued

Year	Statistics	DH (day)	GFR (day)	FLW (cm)	RWL (%)	CMS (%)	FLL (cm)	FLA (cm)	DM (day)	GFP (day)	RWC (%)	ELWR (%)
2015	Max	154.6	3.49	8.00	68.63	95.51	30.00	13.30	202.0	25.00	98.25	100.00
	Min	151.0	1.63	1.00	11.43	50.52	17.00	6.65	194.6	20.00	54.53	82.14
	Mean	153.9	1.93	5.25	33.02	76.02	22.69	7.89	198.8	20.98	77.97	96.98
	LSD (0.05)	3.84	.85	31.67	3.89	37.77	9.08	4.03	6.39	4.15	24.84	5.11
2016	Max	177.1	1.18	2.16	36.28	94.07	27.50	9.94	231.5	25.50	96.17	99.25
	Min	171.9	0.93	0.28	16.95	24.41	13.00	4.87	219.0	21.00	58.10	91.78
	Mean	173.9	1.48	0.85	24.59	66.82	20.77	7.57	220.8	23.87	73.41	96.04
	LSD (0.05)	4.52	0.37	0.72	12.67	23.29	7.42	2.69	5.56	1.78	21.03	4.60

DH: Days to heading, GFR: Grain filling rate, FLW: Flag leaf width, RWL: Relative water loss, CMS: Cell membrane stability, FLL: Flag leaf length, FLA: Flag leaf area, DM: Days to maturity, GFP: Grain filling period, RWC: Relative water content, ELWR: Excised leaf water retention.

Table 4. Continued

Year	Statistics	PL (cm)	AL (cm)	PL/ Phe (cm)	GW (mm)	Phe (cm)	SL (cm)	GL (mm)
2015	Max	36.00	18.00	0.55	3.59	139.00	9.00	10.05
	Min	17.00	5.00	0.17	2.15	50.00	2.00	5.05
	Mean	26.00	10.10	0.30	3.11	90.00	5.34	7.18
	LSD (0.05)	48.31	6.59	2.48	1.48	56.67	3.61	1.40
2016	Max	77.79	15.30	0.97	3.33	89.00	8.90	7.80
	Min	36.39	6.88	0.62	1.98	48.00	4.46	5.27
	Mean	53.61	10.66	0.82	2.67	64.98	6.75	6.78
	LSD (0.05)	20.67	4.88	0.15	0.63	23.12	2.45	1.22

PL: Peduncle length, AL: Awn length, PL/Phe: Peduncle length/ Plant height, GW: Grain width, Phe: Plant height, SL: Spike length, GL: Grain length.

The purpose of phenotyping is to support the process of selecting superior genotypes by specific traits (Passioura 2012). Identifying the morphological and agronomic traits of durum wheat related to the grain yield is useful in breeding programs. Optimal selection under rainfed conditions will ultimately lead to the improved commercial varieties.

The positive and significant correlation observed between harvest index and grain yield in this study have also been reported in other studies (Bogale and Tesfaye 2016). Due to the relationships between these two traits, it could be used as a criterion for screening high yielding lines in durum wheat. Several authors have suggested that selection of genotypes in the rainfed conditions may be improved by selection of traits related to the grain yield (González-Ribot *et al*. 2017). In the rainfed Mediterranean farming systems, harvest index has been identified as an important determinant of grain yield across cultivars of

Table 5. Correlation coefficients of the measured traits with grain yield in recombinant inbred lines of durum wheat during two years.

Year	RWC	RWL	ELWR	CMS	FLL	FLW	Phe	PL	AL	SL
2015	-0.01	-0.05	-0.15	0.09	-0.08	-0.05	0.12	-0.11	0.12	0.01
2016	0.02	0.05	-0.06	0.06	0.11	0.20**	0.28**	0.28**	0.07	0.28**
Year	TGW	GL	GW	DH	DM	HI	SpD	PL/Phe	SY	WGPS
2015	-0.05	0.12	0.06	0.20*	0.02	0.37**	0.39**	-0.14	0.27**	0.24**
2016	0.45**	0.20**	0.28**	-0.10	-0.01	0.25**	0.33**	0.04	0.49**	0.43**
Year	NTPP	Bio	SW	NSPP	NGPS	FLA	GFR	GFP		
2015	0.42**	0.63**	0.88**	0.57**	0.002	-0.08	-0.04	-0.02		
2016	0.37**	0.71**	0.84**	0.46**	0.02	0.13*	0.34**	0.12		

RWC: Relative water content, RWL: Rate of water loss, ELWR: Excised leaf water retention, CMS: Cell membrane stability, FLL: Flag leaf length , FLW: Flag leaf width, Phe: Plant height, PL: Peduncle length, AL: Awn length, SL: Spike length, NTPP: Number of tillers per plant, Bio: Biomass, SW: Spike weight, NSPP: Number of spikes per plant, NGPS: Number of grains per spike, TGW: Thousand grain weight, GL: Grain length, DH: Days to heading, DM: Days to maturity, SpD: Spike density, PL/Phe: Peduncle length/ Plant height,SY: Straw yield, WKPS: Weight of grains per spike, FLA: Flag leaf area, GFR: Grain filling rate, GFP: Grain filling period; *, **: $p \leq 0.05$, and $p \leq 0.01$, respectively.

Table 6. Direct and indirect effects of traits on the grain yield for 125 recombinant inbred lines of durum wheat and their parents during 2015.

Dependent variable		Indirect effect		Direct effect	Correlation	R^2
		NSPP	AL			
GY	NSPP	-	-0.009	0.582**	0.573**	0.351
	AL	-0.035	-	0.151*	0.116^{ns}	
		SL				
AL		-		.312**	0.312**	0.09
		NTPP				
NSPP		-		0.805**	0.805**	0.647

NSPP: Number of spikes per plant. GY: Grain yield. AL: Awn length. SL: Spike length; *, **: $p \leq 0.05$, and $p \leq 0.01$, respectively.

Table 7. Direct and indirect effects of the traits in the path analysis for 119 recombinant inbred lines of durum wheat and their parents during 2016.

Dependent variable		Indirect effect			Direct effect	Correlation	R^2
		NTPP	GFR	Phe			
GY	NTPP	-	0.017	-0.001	0.356**	0.373**	0.270
	GFR	0.023	-	0.048	0.267**	0.339**	
	Phe	-0.002	0.069		0.184*	0.253*	
			PL				
GFR			-		0.306**	0.306**	0.094
			FLA				
Phe			-		0.197*	0.197*	0.039

PL: Peduncle length. GY: Grain yield. GFR: Grain filling rate. NTPP: Number of tillers per plant. Phe: Plant height. FLA: Flag leaf area.; *, **: $p \leq 0.05$, and $p \leq 0.01$, respectively.

Table 8. Ranking of recombinant inbred lines (RILs) based on the effective traits on grain yield (Arunachalam and Bandyopadhyay 1984) during 2015-2016.

RIL	2015	2016	RIL	2015	2016	RIL	2015	2016
1	7.36	9.17	48	8.43	12.50	95	9.29	9.25
2	4.79	6.67	49	6.64	10.92	96	9.36	6.92
3	7.36	9.33	50	9.50	7.67	97	3.50	8.83
4	7.00	10.08	51	10.86	9.33	98	8.43	9.50
5	10.50	8.58	52	8.64	7.17	99	7.88	8.08
6	9.07	6.67	53	11.29	9.00	100	5.93	4.50
7	9.84	6.83	54	11.93	9.42	101	10.10	8.25
8	7.07	9.08	55	8.43	9.42	102	9.43	4.17
9	8.36	8.97	56	8.68	11.67	103	8.93	7.58
10	9.07	11.38	57	4.50	9.42	104	9.17	7.08
11	9.00	6.92	58	7.07	9.92	105	8.14	7.92
12	11.14	8.25	59	10.53	8.13	106	11.14	7.00
13	10.36	8.42	60	6.93	10.17	107	9.07	11.33
14	9.52	9.50	61	7.80	8.17	108	9.17	7.17
15	11.25	8.92	62	8.50	8.13	109	8.93	9.33
16	5.17	5.83	63	4.14	7.50	110	8.14	3.83
17	7.64	9.42	64	7.00	10.08	111	7.21	8.17
18	6.71	14.33	65	6.45	8.92	112	7.18	7.50
19	9.00	10.50	66	3.86	6.92	113	6.02	8.92
20	9.64	8.92	67	7.79	5.58	114	4.50	7.33
21	9.09	9.83	68	7.79	9.25	115	7.52	6.92
22	9.86	7.33	69	12.50	9.25	116	10.07	7.92
23	8.79	7.75	70	9.14	8.58	117	9.14	5.67
24	7.93	10.58	71	7.50	8.92	118	5.79	6.08
25	10.86	9.58	72	5.50	11.33	119	11.52	9.42
26	9.79	11.08	73	8.43	8.58	**249[P]**	9.29	6.75
27	9.36	7.17	74	7.29	10.50	**Zardak[P]**	7.43	5.75
28	4.36	8.67	75	9.79	4.83	122	9.07	
29	3.45	6.92	76	10.14	10.67	123	8.21	
30	9.63	6.67	77	8.97	7.25	124	11.57	
31	7.36	8.33	78	10.50	9.08	125	8.04	
32	4.57	8.08	79	7.64	7.17	126 [C]	12.07	
33	8.71	6.55	80	6.86	7.33	127 [C]	8.43	
34	5.64	8.25	81	10.02	10.25	128 [C]	4.50	
35	7.68	8.08	82	9.57	9.50	129 [C]	9.71	
36	9.81	9.25	83	11.43	7.75	130 [C]	7.57	
37	7.17	8.25	84	5.57	10.83	131 [C]	10.27	
38	7.86	7.42	85	6.50	8.67			
39	11.07	9.22	86	8.50	9.08			
40	6.79	10.83	87	7.93	7.42			
41	9.17	10.58	88	8.71	9.00			
42	8.86	9.58	89	5.50	9.75			
43	6.64	7.00	90	7.50	8.50			
44	8.60	7.00	91	8.16	7.92			
45	9.86	11.47	92	7.07	9.83			
46	10.36	9.50	93	6.50	9.17			
47	4.81	9.50	94	8.68	9.08			

wheat under high temperature and terminal water-deficit stress conditions (Kobata *et al*. 2018). Selecting for plant height and harvest index could improve both water use efficiency and grain yield under stress-prone environments (Belagrouz *et al*. 2018). The significant correlation between grain yield and biomass in this study showed that for high grain yield, plants with good vegetable growth and proper vegetative power are needed. Farmers prefer cultivars with higher biomass because of their high yield compared to the cultivars with lower biomass (Talebifar *et al*. 2015).

The number of spikes per plant is one of the important components of grain yield and any factor that increases the number of fertile spike per unit area, will increase the grain yield, as shown in the current study. The main reason for the higher grain yield in higher plant densities is the higher number of spikes in these conditions. Yang *et al.* (2019) stated that an increase in the plant density significantly increased the number of tillers and number of spikes per m^2, resulting in a higher grain yield. Zhou *et al.* (2014) showed that the grain yield in wheat had a positive correlation with grain number per square meter and aboveground biomass. Guendouz and Maamari (2012) reported a lack of the correlation between grain yield and 1000 grain weight in durum wheat, which is consistent with the results of this research. In the first and second years of the experiment, a positive and significant correlation between 1000 grain weight and grain filling rate can indicate the importance of earliness under rainfed conditions. One of main objectives of breeding programs in arid and semi-arid regions is the selection of early cultivars tolerant to environmental stresses, so the grain filling rate is considered as an advantage. Drought stress during the grain filling period slows down the seed-filling rate and reduces the filling duration to limit the grain size (Sehgal *et al*. 2018). Thus increasing the grain filling rate can compensate for the reduction in grain weight in the stressful conditions. The lack of correlation between grain yield and grain filling period and days to flowering in both years indicates that late maturity cannot necessarily result in higher yields. Genetic control of the grain yield is indirectly influenced by the traits that are correlated with it (Wu *et al*. 2012). Therefore, selection the yield-related traits with less complex inheritance than the grain yield, can increase the efficiency of selection for the grain yield.

Although correlation coefficient among traits is used in breeding programs, but this statistic by itself does not elucidate causal relationships, nor does it show the relative importance of direct and indirect effects of the traits (Diniz and De Oliveira 2019). Path analysis determines that the correlation of the traits with the grain yield is due to their direct effects on the yield or the result of the indirect effect through other traits. If the correlation of a trait with yield is due to the direct effect of that trait, there is a direct relationship between them, but if indirect effects are involved, selection should be made indirectly via intermediate traits (Saba *et al*. 2018).

In all stepwise regressions models, the remaining variables in the model had significant effect (direct effect) on the grain yield. In the first year, grain yield was increased with increasing the awn length and number of spikes per plant. Awn length is one of the plant organs that is directly related to the spike and seed, and due to the short distance between this organ and the seed, it can play a significant role in re-transferring assimilates and filling the grain; therefore, with increasing this trait, grain yield increased (Navid *et al*. 2022). Long awns are considered to be the important components of the high-yielding wheat ideotype, particularly for the wheat grown under rainfed conditions (Rebetzke *et al*. 2016). Nourmohammadi *et al* (2007) stated that in cereals, the primary components determining grain yield were the number of spikes per unit area, number of grains per spike and 1000 grain weight and the role of spikes per unit area was higher than the other components. The indirect effect of the number of spikes per plant through the awn length was negative but negligible. The awn length was affected by the spike length.

In the second year, according to the results of the path analysis, the higher grain yield was associated with more tillers, higher height, and faster grain filling rate. RILs with more tillers per plant also produces higher yields due to more spikes. Co-occurrence of the grain filling stage with heat can accelerate the aging, cause the weight loss of the grain, and shorten the grain filling period. In these conditions, the higher grain yield can be achieved by higher grain filling rate. Genotypes with higher grain filling rate can produce higher grain yield in areas with short growth period (Gebeyhou *et al*. 1982). It seems that more tillers and higher plant height can reduce the evaporation of moisture from the soil surface and transpiration from the leaves located in the lower part of the canopy. Reducing evapotranspiration can preserve more moisture stored in the soil and increase the grain yield under rainfed conditions (Ghorbani and Harutyunyan 2012). The grain filling rate was affected by peduncle length. The role of peduncle in heat and drought resistance has already been proven due to its role in photosynthesis and stem reserve remobilization (Modarresi *et al*. 2010). When plant height was considered as a dependent variable, the flag leaf area remained in the model. Raising the flag leaf area can lead to an increase in the production capacity of plant photosynthetic materials and increase the plant height. We can imagine that the major differences in the effect of these traits were related to rainfall and temperature values. This has already been reported in studies on the performance of durum wheat genotypes in different environments (Desiderio *et al*. 2019).

The Arunachalam and Bandyopadhyay's (1984) method identified the RILs No. 29 and 66 in the first year and the RIL No. 100 in the second year as the superior lines. These superior RILs can be included in varietal registration trials for the development of high-yielding cultivars suitable for rainfed conditions.

Conclusion

Overall, according to the results obtained in the two years, higher spike weight, weight of grains per spike, number of tillers per plant, number of spikes per plant, biomass, grain filling rate, plant height, peduncle length, and spikes and awn length were correlated with the grain yield in durum wheat. Some of these traits (i.e. number of tillers per plant, number of spikes per plant, awn length, grain filling rate, plant height) had significant direct effect on the grain yield over the two years. All indirect effects of these traits via others were small and negligible. Therefore, to achieve higher yielding genotypes, selection for these traits will be useful in the plant breeding programs under rainfed conditions. Among the evaluated RILs, lines No. 2, 16, 29, 43, 66, 80, 100, and 118 were promising and can be evaluated for traits such as resistance to pests and diseases and some of them could be tested in varietal registration trials.

Author contributions

Negar Aghaei performed the experiments and analyzed the data. Leila Zarei and Kianoosh Cheghamirza conceived and designed the experiments, analyzed the data, authored or reviewed drafts of the paper, and approved the final draft.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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صفات آگرو-مورفولوژیکی و فیزیولوژیکی مؤثر بر عملکرد دانه نسل‌های پیشرفته گندم دوروم در شرایط دیم

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چکیده

تولید گندم دوروم در آب و هوای مدیترانه‌ای در مواجهه با کمبود آب در طول گرده افشانی، محدود می‌شود. برنامه های اصلاحی سعی در افزایش عملکرد دانه تحت شرایط آب و هوایی چالش برانگیز مانند کمبود آب دارند. بهبود ارزیابی فنوتیپی با هدف انتخاب صفات کلیدی گیاه برای تسریع به نژادی امر مهمی است. در این مطالعه، ۱۲۵ و ۱۱۹ لاین اینبرد نوترکیب از نسل‌های F7 و F8 به‌دست‌آمده از تلاقی توده بومی گندم دوروم Iran_249 و واریته زردک در دو سال متوالی (۱۳۹۴ و ۱۳۹۵) در مزرعه در شرایط آب و هوای مدیترانه‌ای معتدل دیم مقایسه شدند. نتایج نشان داد که عملکرد لاین‌ها تحت تأثیر سال قرار داشت. شاخص برداشت، بیوماس، تعداد سنبله در بوته، تعداد پنجه در بوته، عملکرد کاه، وزن سنبله، تراکم سنبله و وزن دانه در سنبله با عملکرد دانه در هر دو سال همبستگی مثبت داشتند. بر اساس تجزیه علیت در سال اول، تعداد سنبله در بوته و طول ریشک اثر مستقیم مثبت و معنی‌دار بر عملکرد دانه داشتند. در حالی که در آزمایش سال دوم تعداد پنجه در بوته، سرعت پر شدن دانه و ارتفاع بوته از اثر مستقیم مثبت و معنی‌دار بر عملکرد دانه برخوردار بودند. به طور کلی، بر اساس تجزیه و تحلیل صفات در دو سال، لاین‌های دارای وزن سنبله، وزن دانه در سنبله، تعداد پنجه در بوته، بیوماس، سرعت پر شدن دانه و ارتفاع بوته بالاتر و نیز دارای سنبله‌های بلندتر با طول ریشک بلندتر در شرایط دیم، عملکرد بالاتری داشتند. این صفات امیدوارکننده‌ترین صفات برای انتخاب غیرمستقیم عملکرد دانه هستند. لاین‌های شماره ۲، ۱۶، ۲۹، ۴۳، ۶۶، ۸۰، ۱۰۰ و ۱۱۸ بهترین رتبه‌ها را در هر دو سال داشتند و نسبت به والدین خود برتر بودند.

واژه‌های کلیدی: تنش خشکی؛ صفات آگرو-مورفولوژیکی؛ گندم دوروم؛ لاین‌های اینبرد نوترکیب