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ORIGINAL PAPER

The effects of drought after anthesis on the grain quality of bread wheat depend on drought severity and drought resistance of the variety

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Abstract

The quality responses of two resistant (Müfitbey, Gün 91), two moderately resistant (Sönmez 2001, Gerek 79), two moderately sensitive (Çetinel 2000, Bereket), and two sensitive (Kırik, Bezostaja 1) bread wheat varieties to drought after anthesis were investigated in field experiments conducted in irrigated and drought conditions during the 2011–2012 and 2012–2013 seasons in Erzurum, Turkey. In drought conditions, for the 2011–2012 and 2012–2013 seasons, the highest grain yield was obtained from the Müfitbey variety, the highest protein content from Kırik and Müfitbey, the highest wet gluten content from Kırik and Gün 91, and the highest sedimentation volume from Müfitbey and Bereket, respectively. Drought stress decreased the grain yield, 1000-kernel weight, test weight, and kernel hardness but increased grain ash content in both years, compared with irrigated conditions. Protein content, wet gluten content, and sedimentation volume were increased by drought stress in 2011–2012, but decreased in 2012–2013. The environmental factors had a greater effect on the variations of quality traits than genetic factors. The influence of drought after anthesis on quality traits was primarily dependent on stress severity. The results suggest that moderate drought stress enhances the grain quality traits of wheat, but severe drought stress reduces its quality. The quality response of a wheat variety to drought stress is related to its drought resistance, and drought-resistant varieties can maintain quality characteristics under moderate stress conditions.

Keywords Protein · Wet gluten · Sedimentation · Hardness · Ash · Variety × environment interaction

Introduction

Wheat is a strategic crop that provides 19.0% of the daily calorie needs and 20.8% of the protein daily needs of the world population (Shiferaw et al. 2013). Drought can occur in different development periods of wheat in dry farming areas, and this is accepted as the most essential factor that limits crop quantity and quality. In Turkey, a significant portion of rainfall occurs during the period from November to April, and drought generally starts close to the heading stage of the wheat, increasing its effect in the grain filling period. The effect of drought on yield and grain quality closely depends on the plant development period in which stress occurs, and is related to the severity and duration of stress and genotype (Gupta et al. 2001; Ozturk and Aydin 2004). The grain quality of wheat is important in terms of nutritional value and economics, and this varies according to genotype, environmental factors, and genotype × environment interaction (Zhao et al. 2009; Li et al. 2013; Begcy and Walia 2015). Drought after anthesis affects the duration and rate of grain filling and changes the size and composition of grain (Dupont and Altenbach 2003). Drought accelerates leaf senescence and reduces the area and period of photosynthesis, often limiting the amount of assimilate, which results in lower grain yields and higher grain protein content (Ozturk and Aydin 2004; Balla et al. 2011). Drought also changes the carbohydrate and nitrogen assimilation rates, which gives rise to significant changes in chemical composition (Panozzo and Eagles 2000), protein composition, and starch granule size (Balla et al. 2011). Zhao et al. (2009) reported that mild water stress during the grain filling period

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positively affected bread quality by increasing the protein, gluten, gliadin, globulin, phosphorus and zinc content in grain. In contrast, other researchers stated that severe drought in the first 14 days of grain development reduced sedimentation volume (Gooding et al. 2003). Moreover, it has been reported that severe drought decreases the protein ratio, gluten rate, and sedimentation volume (Guler 2001), hectoliter weight, sedimentation volume, and gluten rate (Tsenov et al. 2015). Drought stress that occurs on the second to fourth days after anthesis negatively affects grain weight by both delaying endosperm cell division and quality and decreasing the protein content of gliadin, gluten, and avenin (Begcy and Walia 2015). It has been emphasized that the macro-polymers of gluten, which are the most important determinant of bread quality, are more sensitive to environmental conditions and growing techniques than the protein content (Spiertz et al. 2006). Although drought after anthesis increases the rate of grain protein, it may reduce the synthesis of high molecular weight protein subunits and the ratio of glutenin macromolecules (Jiang et al. 2009). The effect of drought on the distribution rate of *A*, *B* and *C* type starch granules and protein composition may differ according to the variety (Singh et al. 2008). While drought improves quality characteristics in some varieties, it decreases the protein ratio, gluten rate, and sedimentation volume in varieties in which the photosynthesis rate is reduced due to stress (Ali et al. 2011). Li et al. (2013) determined that drought increased sedimentation volume, alveograph tenacity, and glutenin index, and decreased alveograph extensibility and water retention capacity. The effect of environment on wheat quality may be higher than that of genetic factors (Panozzo and Eagles 2000), and varieties may respond differently to drought stress in terms of protein composition (Saint Pierre et al. 2008a; Ali et al. 2011).

There is quite limited information concerning the quality response to drought after anthesis in bread wheat varieties with different drought sensitivity. This study aimed to examine the quality responses of bread wheat varieties classified as resistant, moderately resistant, moderately sensitive and sensitive to drought after anthesis. A better insight into the similarities and differences in the quality responses of genotypes can help the identification and development of varieties that can maintain grain quality under stress conditions, as well as assisting in the choice of genotypes suitable for certain environments and explaining the relationship between drought resistance and grain quality.

Materials and methods

Field experiments and plant materials

Two field experiments were conducted under irrigated and drought conditions at Ataturk University Plant Production Application and Research Centre in Erzurum, Turkey during the years of 2011–2012 and 2012–2013 using 64 bread wheat varieties. From the beginning of stem elongation to maturity, the volumetric soil water content was determined by a soil moisture meter. The irrigated plots were watered three times to maintain the average water content in the top 60 cm soil profile as not being less than 50% of the field capacity. To avoid the effect of rain, from the booting stage to maturity in the drought treatment, the plots were covered with polyethylene. From September 1 to August 31, the total rainfall was 250.5 mm for 2011–2012 and 311.1 mm for in 2012–2013, which was lower than the long-term average (398.8 mm). In 2012–2013, temperatures were higher than in 2011–2012, but soil moisture content was lower due to the limited quantity of water stored in the soil at sowing time. Soil water content in the top 60 cm was 47.2 and 45.4% at field capacity and 19.2 and 18.0% at a permanent wilting point in 2011–2012 and 2012–2013, respectively. At the physiological maturity stage, as drought stress increased, the water content gradually decreased to 18.9% in 2011–2012 and to 14.1% in 2012–2013. Therefore, the second year of the research was characterized by severe drought stress after anthesis. The plants were harvested at maturity and grain yield (GY) was weighed. Based on the 25 physiological traits measured, the varieties were evaluated for resistance to drought stress after anthesis using a ranking method. The varieties were classified as resistant, moderately resistant, moderately sensitive, and sensitive. The growing conditions and agronomic details of the field experiments were presented in a previous paper (Öztürk and Aydin 2017). Two varieties were selected from each of the four groups and used in the laboratory experiments for quality analysis (Table 1).

Analytical methods

The grain samples were cleaned and stored in glass jars until being used for the physicochemical tests. The quality analysis of the grain samples was conducted at the Cereal Quality Laboratory of Ataturk University, Faculty of Agriculture, Department of Food Engineering during January-June 2014. The laboratory experiments were organized in a completely randomized factorial design with four replications, using the eight bread wheat varieties and two water regimes (WR) [irrigated (IR) and drought after anthesis (DAA)]. Thousand-kernel weight (TKW) was determined by weighing four sets of 100 kernel samples. Test weight (TW) was estimated on a ¼ liter grain test weight scale and values were reported on a 14% moisture basis. Grain ash content (GAC) was determined according to the official standard method (AACC 2000). A 10 g subsample of grain was oven-dried at 80 °C for 48 h and ground for ash analysis. Approximately 1.5 g of dry mass was incinerated at 575 °C for 16 h (until light gray ash was obtained), and the ash content was

Table 1 Drought resistance groups and some traits of the bread wheat varieties used in the study

Groups	Varieties	Originator and year of registration	Some traits
Resistant	Müfitbey	Anatolia Agricultural Research Institute, Eskişehir—2006	Winter, white spike, awny, white-hard grain
	Gün 91	Central Research Institute of Field Crops, Ankara—1991	Winter, white spike, awny, red-hard grain
Moderately resistant	Sönmez 2001	Anatolia Agricultural Research Institute, Eskişehir—2001	Winter, white spike, awnless, red-hard grain
	Gerek 79	Anatolia Agricultural Research Institute, Eskişehir—1979	Winter, brown spike, awny, white-medium hard grain
Moderately sensitive	Çetinel 2000	Anatolia Agricultural Research Institute, Eskişehir—2000	Winter, white spike, awny, white-soft grain
	Bereket	Trakya Agricultural Research Institute, Edirne—2010	Winter, red spike, awnless, red-medium hard grain
Sensitive	Kırik	Eastern Anatolia Agricultural Research Institute, Erzurum—2010	Facultative, colored spike, awnless, white-hard grain
	Bezostaja 1	Anatolia Agricultural Research Institute, Eskişehir — 1968 (Introduction, Russia)	Winter, white spike, awnless, red-hard grain

expressed on a dry mass basis. The grain samples were ground, and their N percentages were measured using the micro Kjeldahl procedure (AACC 2000). Grain protein content (GPC) was calculated as 5.7 × percent N in dry matter. The wet gluten contents (WGC) of the flour samples were determined according to the standard method 137-1 (ICC 2000) using a Glutomatic 2200 system and expressed on a 14% moisture basis. The Zeleny sedimentation volumes (ZSV) of the flour samples were measured according to the standard method 56-60.01 (AACC 2000) and reported on 14% moisture basis. Grain hardness (GH) was recorded in a TA-XT-plus texture analyzer (Stable Micro Systems, Godalming, UK) using a 10-mm aluminum cylinder probe with 30 kg load cell, 0.5 mm/s test speed, and 5.0 g trigger force. The hardness value was reported as the mean of 15 measurements and defined as the maximum force needed to compress the disk to 40% of its height. The falling number (FN) was determined on a 6.76 g sample of wheat flour using the AACC method 56-81B (AACC 2000), and the results were reported on a 14.0% moisture basis. The color L value (CL) of kernel was determined by a Minolta colorimeter CR200 (Minolta Camera Co., Osaka, Japan), with the L value (0 = black, 100 = white) referring to the lightness of kernel from dark to light.

Statistical analysis

Data obtained from the 2 × 8 × 2 factorial arrangement in a randomized complete design were analyzed using the PROC GLM procedure in SAS (v 9.3, SAS Institute, Inc., Cary, NC). The influences and sum square percentage of year (Y), variety (V), water regime (WR), and their interactions were determined for all the traits investigated (Table 2). Since the main effect of year and their interactions were significant for most of the quality traits, the data were analyzed separately for each year. The least significant difference (LSD) test was applied at significance level to determine the level of significant differences in $V \times$ WR interactions values.

Results

The results of the analysis of variance showed that most of the traits (except GH) were significantly influenced by year (Table 2). The lower soil moisture contents during the growth cycle in 2012–2013 decreased GY, TKW, TW, GPC, WGC, ZSV, and FN, but increased GAC and CL. The differences between the varieties were significant for all the traits (except GPC in 2012–2013). There was a marked effect of WR on the studied traits (except CL in 2011–2012). The $V \times$ WR interactions were significant for the investigated characteristics (except TKW in 2011–2012 and 2012–2013, WGC and GH in 2011–2012) (Tables 3, 4, 5). WR was the main factor controlling GY and GH, accounting for 74.69% and 41.99% of the total variance, respectively. Variety was the main factor for CL and FN, accounting for 75.00% and 45.46% of the total variance, respectively, while year was main factor for WGC, GPC, ZSV, and GAC accounting for 44.99%, 41.51%, 41.20%, and 39.79%, respectively. It was also determined that variety and WR were the main factors equally controlling TKW and TW (Table 2).

In the average of years, the highest GY was obtained from Gün 91 in IR, whereas the lowest GY was determined in Kırik in DAA (Table 3). GY, which was 6416 kg ha^{-1} in IR conditions, decreased by 33.9% due to the negative impact of DAA on yield components. The decrease in GY in DAA was lowest in Müfitbey (19.5%) and highest in Kırik (47.9%). The GAC of the varieties ranged from 1.490% to

Table 2 Analysis of variance and sum square percent of year (*Y*), variety (*V*), water regime (WR) and their interactions of grain yield and 9 quality traits for the wheat varieties across crop seasons 2011–2012 and 2012–2013

Traits[c]	*F* values[a]							
	Model	Y	V	WR	$Y\times V$	$Y\times$WR	$V\times$WR	$Y\times V\times$WR
GY		31.97**	5.60**	308.63**	2.28	1.53	1.48	0.8
GAC		155.63**	10.54**	97.37**	6.60**	0.07	1.36	1.21
TKW		126.59**	18.79**	121.32**	2.80*	8.53**	1.21	0.97
TW		58.83**	88.09**	573.62**	4.47**	81.81**	5.94**	5.75**
GPC		439.73**	9.55**	129.64**	2.39*	320.11**	11.54**	0.78
WGC		1245.51**	41.36**	387.00**	5.25**	736.56**	8.30**	2.21
ZSV		2248.08**	37.49**	1168.41**	10.25**	1395.19**	33.35**	10.97**
GH		1.19	9.83**	96.20**	4.36**	4.19*	2.47*	1.58
FN		852.81**	191.81**	135.89**	21.56**	344.57**	6.95**	11.15**
CL		69.81**	162.28**	53.87**	13.66**	65.36**	6.29**	7.15**
% of model SS[b]								
		Y	V	WR	$Y\times V$	$Y\times$WR	$V\times$WR	$Y\times$V$\times$WR
GY		7.74	9.48	74.69	3.87	0.37	2.51	1.35
GAC		39.79	18.87	24.9	11.82	0.02	2.43	2.17
TKW		29.94	31.11	28.69	4.63	2.02	2	1.6
TW		4.07	42.7	39.72	2.17	5.67	2.88	2.79
GPC		41,51	12,24	12,24	1.58	30.22	7.63	0.52
WGC		44.99	10.44	13.98	1.33	26.6	2.1	0.56
ZSV		41.2	4.81	21.41	1.31	25.57	4.28	1.41
GH		0.52	30.2	41.99	13.3	1.83	7.54	4.8
FN		28.87	45.46	4.6	5.11	11.67	1.65	2.64
CL		4.61	75	3.56	6.31	4.32	2.9	3.3

[a] *F* values marked with * and ** are significant at 0.05 and 0.01 probability levels, respectively

[b] *SS* sum square; % of model SS = SS of Y (or V, or WR, or $Y\times V$, or $Y\times$WR, or $V\times$WR, or $Y\times V\times$WR)/SS of model

[c] *GY* grain yield, *GAC* grain ash content, *TKW* thousand kernel weight, *TW* test weight, *GPC* grain protein content, *WGC* wet gluten content, *ZSV* Zeleny sedimentation volume, *GH* grain hardness, *FN* falling number, *CL kernel* color *L* value

1.784%. The lowest and highest GAC values were determined in Müfitbey and Kırik, respectively. In IR and DAA, the GAC values were 1.495% and 1.687%, respectively. DAA increased GAC by 12.8% (Table 3).

Müfitbey had the highest TKW in IR for both years, while Sönmez 2001 and Müfitbey had the highest TKW in the DAA condition in the first and second years, respectively. DAA reduced TKW in all the varieties, with the least decrease being observed in Gerek 79. In 2011–2012 and 2012–2013, for the IR condition, the highest TW was obtained from Bezostaja 1 and Sönmez 2001, respectively, whereas for the DAA condition, it was obtained from Sönmez 2001 and Gün 91, respectively. The lowest reduction in TKW due to DAA was determined in Gerek 79 and Gün 91 varieties in 2011–2012 and 2012–2013, respectively (Table 4, Fig. 1).

The highest GPC was obtained from Kırik under both WR in 2011–2012. In 2012–2013, the highest GPC was determined in Kırik under IR and in Müfitbey under DAA. DAA significantly increased GPC in 2011–2012 but significantly decreased it in 2012–2013, compared to IR. DAA increased GPC in all the varieties except for the drought-sensitive Bezostaja 1 in 2011–2012, while it caused a decrease in all the varieties in the second year. In 2012–2013, the reduction in GPC was 12.7% in Müfitbey, 33.6% in Bezostaja 1, and 26.4% in Kırik, (Table 4, Fig. 2). The highest WGC was obtained from Kırik in 2011–2012 and from Bezostaja 1 and Gün 91 in 2012–2013 in IR and DAA conditions, respectively. DAA significantly increased WGC in the first year and significantly reduced it in the second year. In 2012–2013, DAA reduced WGC by 32.2% and 33.4% in the drought-resistant Müfitbey and Gün 91 varieties, respectively. This decrease was determined as 45.2% in Bezostaja 1, which is a drought-sensitive variety (Table 4, Fig. 3).

The highest ZSV was obtained from Kırik in the IR condition. For DAA, the highest ZSV obtained from Müfitbey and Bereket in 2011–2012 and 2012–2013, respectively. DAA reduced ZSV in the Bereket, Kırik and Bezostaja-1 cultivars while increasing it in the remaining varieties in 2011–2012. Severe drought stress in 2012–2013 reduced

Table 3 Experimental data for grain yield and grain ash content under irrigated (IR) and drought after anthesis (DAA) in 2011–2012 and 2012–2013 crop seasons

Water regime (WR)	Grain yield (kg ha^{-1})				Grain ash content (%)			
	2011–2012		2012–2013		2011–2012		2012–2013	
	IR	DAA	IR	DAA	IR	DAA	IR	DAA
Variety (*V*)								
Müfitbey	6800	5400	6534	4810	1.228	1.453	1.604	1.675
Gün 91	6976	4843	6715	4675	1.329	1.564	1.609	1.878
Sönmez 2001	6814	4400	5463	4059	1.203	1.38	1.657	1.804
Gerek 79	7157	4598	5605	4256	1.552	1.595	1.49	1.637
Çetinel 2000	6667	4443	6260	4243	1.359	1.585	1.677	1.872
Bereket	6905	4500	5987	4050	1.284	1.646	1.567	1.809
Kırik	6315	3257	5755	3135	1.621	1.859	1.756	1.901
Bezostaja 1	7100	4689	5600	2530	1.396	1.467	1.593	1.871
Mean	6842	4516	5990	3970	1.371	1.568	1.619	1.806
F value								
V	1.56		17.31**		10.45**		5.67**	
WR	104.12**		441.4**		42.23**		58.75**	
V×WR	0.52		4.61**		1.4		1.1	
CV (%)	11.35		5.46		5.67		4.14	
LSD for *V*×WR	–		957		–		–	

F values marked with ** are significant at 0.01 probability level

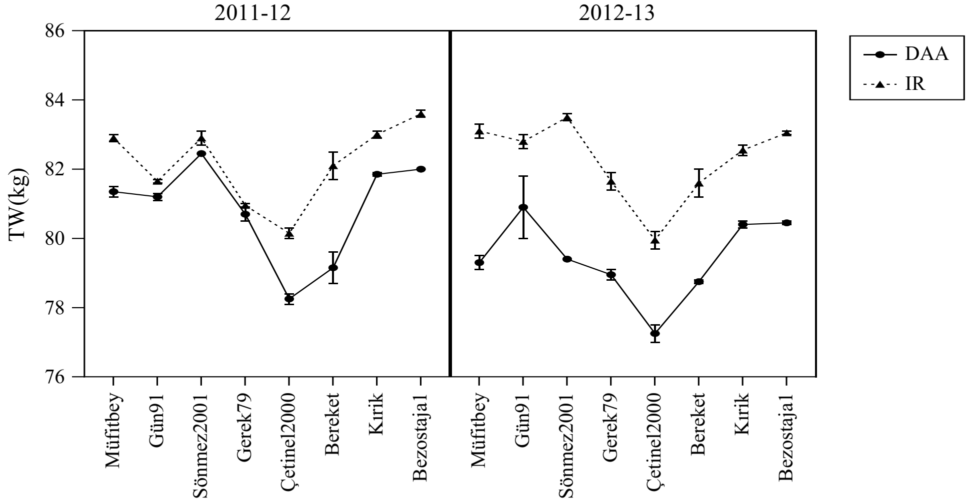


Fig. 1 Changes in test weight (TW) of the wheat varieties in response to irrigated (IR) and drought after anthesis (DAA) treatments in 2011–2012 and 2012–2013

ZSV in all the varieties. The reduction rate was 41.3% in the drought-resistant Müfitbey, while it was 60.4% and 67.0 in the drought-sensitive Bezostaja 1 and Kırik, respectively (Table 5, Fig. 4). For the IR condition, the highest GH was measured in Müfitbey in both years. In the DAA condition, it was determined in Müfitbey in 2011–2012 and Gün 91 in 2012–2013. DAA significantly reduced GH in both years. In 2012–2013, the decreases in the GH value due to DAA were 34.5% and 2.8% in the Müfitbey and Kırik varieties, respectively (Table 5, Fig. 5).

The lowest FN was determined in Sönmez 2001. Considering the average of varieties, DAA increased FN in the first year but decreased it in the second year, compared with IR. In 2011–2012, DAA increased FN by 4.6% in Kırik and by 107.6% in Çetinel 2000. In 2012–2013, DAA increased FN in Sönmez 2001 but decreased it in the remaining varieties (Table 5, Fig. 6). In DAA, the highest CL value (bright) was measured in Çetinel 2000 in 2011–2012 and in Kırik in 2012–2013. The effect of DAA on the CL value was only significant in 2012–2013 (Table 5, Fig. 7).

Table 4 Experimental data for 1000-kernel weight, test weight, grain protein content and wet gluten content under irrigated (IR) and drought after anthesis (DAA) in 2011–2012 and 2012–2013 crop seasons

Water regime (WR)	1000-kernel weight (g)		Test weight (kg)		Grain protein content (%)		Wet gluten content (%)	
	2011–2012							
	IR	DAA	IR	DAA	IR	DAA	IR	DAA
Variety (*V*)								
Müfitbey	48.1	40.7	82.9	81.4	12.7	13.7	32.8	36.7
Gün 91	40.5	39.8	81.7	81.2	12.8	14.1	36.5	38.6
Sönmez 2001	47.6	44.9	82.9	82.5	13	13.6	33.5	35.4
Gerek 79	38.3	37.7	81	80.7	13.5	14.5	34.5	36.8
Çetinel 2000	42.1	34.5	80.2	78.3	13.7	14.8	31.9	33.7
Bereket	43.4	37.9	82.1	79.2	12.8	13.7	28.1	32.5
Kırik	43.5	37.5	83	81.9	14.8	15	39.3	40.6
Bezostaja 1	46.1	44	83.6	82	14.6	13.2	36.6	35.2
Mean	43.7	39.6	82.2	80.9	13.5	14.1	34.1	36.2
F value								
V	5.69**		88.43**		10.34**		23.36**	
WR	19.03**		189.45**		22.19**		23.04**	
V×WR	1.2		11.84**		5.67**		2.14	
CV (%)	6.32		0.33		2.7		3.42	
LSD for *V*×WR	–		0.77		1.09		–	
2012–2013								
Müfitbey	46.4	38.2	83.1	79.3	12.6	11	32.3	21.9
Gün 91	40.4	33.2	82.8	80.9	12.9	10.7	34.1	22.7
Sönmez 2001	40.8	33.5	83.5	79.4	12.6	10.4	32.7	14.5
Gerek 79	34	28	81.7	79	13	10.2	30.8	20.2
Çetinel 2000	35.1	28.9	80	77.3	13.2	10.6	28.3	16.7
Bereket	39.2	32.3	81.6	78.8	12.9	10.4	27.4	17.7
Kırik	39.6	32.6	82.6	80.4	14.3	10.5	34.4	19.7
Bezostaja 1	40.6	33.4	83.1	80.5	14	9.3	35.4	19.4
Mean	39.5	32.5	82.3	79.4	13.2	10.4	31.9	19.1
F value								
V	42.35**		28.80**		1.99		23.15**	
WR	348.50**		385.07**		409.59**		1386.96**	
V×WR	0.4		3.36**		6.61**		10.03**	
CV (%)	2.94		0.5		3.27		3.81	
LSD for *V*×WR	–		4.99		1.12		2.84	

F values marked with ** are significant at 0.01 probability level

Discussion

The GY and GAC values of the wheat varieties have been previously discussed by Öztürk and Aydin (2017) in terms of drought resistance. In terms of the average of crop seasons, the DAA treatment decreased spike number per m^2 by 12.2%, grain number per spike by 21.6%, and TKW by 14.4%, compared with the irrigated treatment. DAA caused significant reductions in yield components and grain yield, with similar results being reported by Ozturk and Aydin (2004) and Monneveux et al. (2005). GAC is an indication of the extent to which flour separates from the bran, and to obtain white flour, it is desirable to have a low ash content (Yang et al. 2018). Drought after anthesis increases GAC more in drought-sensitive wheat genotypes (Merah et al. 2001; Tsialtas et al. 2005). In this study, DAA increased GAC in all the cultivars, but the rate of increase was not related to drought resistance.

TKW is an indicator of flour yield and determined mainly by post-anthesis development processes and environmental conditions. Undersized and wrinkled grains are undesirable due to their low flour yield and losses during cleaning operations. DAA reduces grain weight by increasing leaf senescence rate and shortening grain filling period (Balla et al. 2011). TW is related to the shape, size and density of grain, and varieties with higher TW have higher flour yields

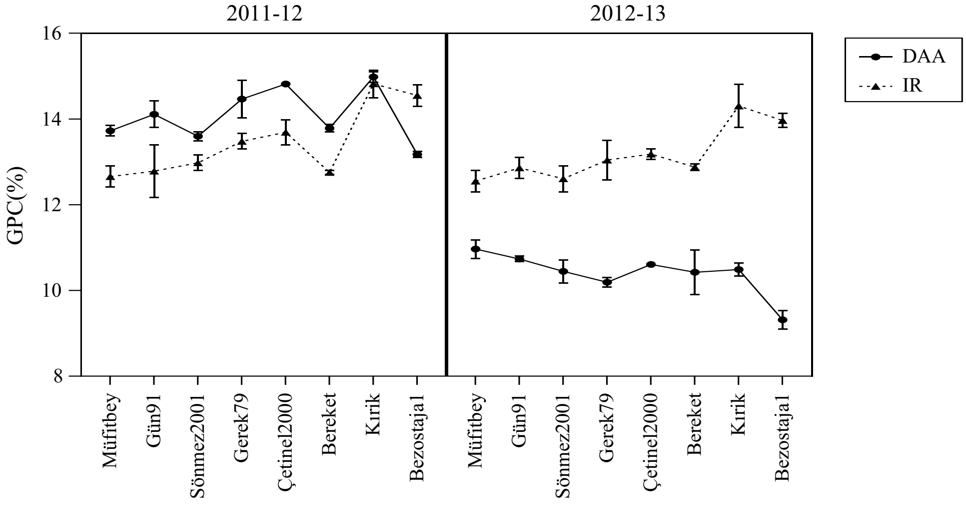


Fig. 2 Changes in grain protein content (GPC) of the wheat varieties in response to irrigated (IR) and drought after anthesis (DAA) treatments in 2011–2012 and 2012–2013

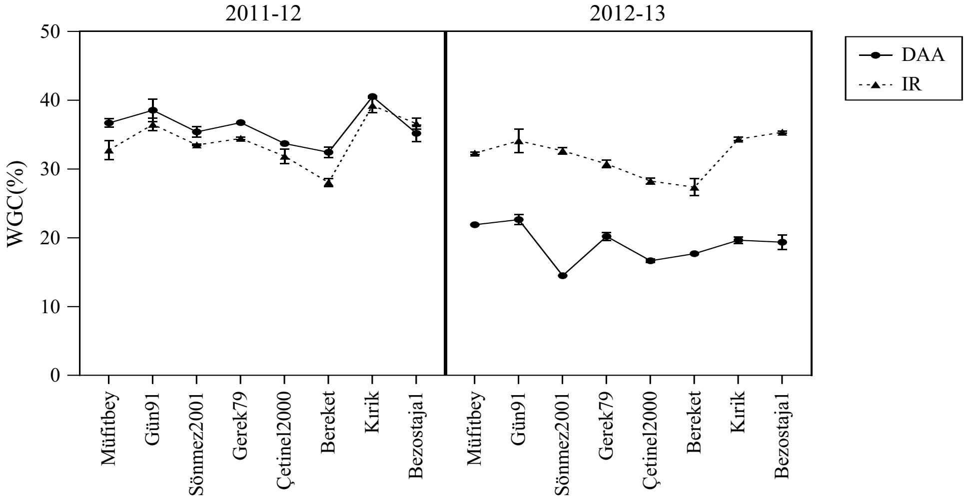


Fig. 3 Changes in wet gluten content (WGC) of the wheat varieties in response to irrigated (IR) and drought after anthesis (DAA) treatments in 2011–2012 and 2012–2013

(Ivanova et al. 2013). It was found in previous studies that DAA decreased TW (Gooding et al. 2003; Saint Pierre et al. 2008a; Ivanova et al. 2013), and this is in accordance with our findings. Mohan and Gupta (2015) reported that high hectoliter weights are associated with a longer grain filling period; on the other hand, Mirzaei et al. (2011) reported that the decrease in hectoliters weight due to drought stress was owing to the increase in weak and broken grain rate and the decrease in grain weight. Decreases in TW due to drought stress may vary according to genotypes (Saint Pierre et al. 2008a).

The GPC of wheat is the most important criterion that determines the product price and bread quality of flour, and it differs according to varieties due to the differences in the genetic structure and nitrogen use efficiency (Guarda et al. 2004). Shortening the grain filling period of moisture deficiency reduces the synthesis and storage of carbohydrates in the grain, allowing the opportunity to accumulate more protein per unit of starch (Panozzo and Eagles 2000; Ozturk and Aydin 2004). Our findings for 2011–2012 were that DAA increased GPC, which is consistent with the results of most previous research (Gooding et al. 2003; Saint Pierre et al. 2008a; Jiang et al. 2009; Flagella et al. 2010; Balla et al. 2011; Reena et al. 2015). The effect of drought after anthesis on GPC may vary depending on the time, severity and duration of stress (Ashraf 2014). Zhao et al. (2009) and Kong et al. (2013) suggested that moderate moisture stress should be present in the soil during grain filling for an increase in protein content. Since severe drought may reduce nitrogen uptake by restricting the nitrogen mineralization rate (Kharel et al. 2011), root development, and ion movement in soil (Fahad et al. 2017), it can result in lower GPC (Ercoli et al. 2008), which is confirmed by (El-Kareem and El-Saidy 2011) observing that drought stress reduced GPC. Similar to our findings, Singh et al. (2008) and Noorka et al. (2009) reported that the response of wheat varieties to drought stress differed in terms of GPC. These results show that the effect of DAA on GPC is related to both the severity

Table 5 Experimental data for Zeleny sedimentation volume, grain hardness, falling number and grain color (L) value under irrigated (IR) and drought after anthesis (DAA) in 2011–2012 and 2012–2013 crop seasons

2011–2012	Zeleny sedimentation volume (ml)		Grain hardness (*N*)		Falling number (*s*)		Grain color (*L*) value	
Water regime (WR)	IR	DAA	IR	DAA	IR	DAA	IR	DAA
Variety (*V*)								
Müfitbey	37.6	44.2	179.2	141.3	975.5	1525	51.4	53.5
Gün 91	41.7	43	151.6	112.7	816.5	1214.5	49.2	48.7
Sönmez 2001	36.3	41.1	167.2	131.2	307.5	515.5	48.7	48.4
Gerek 79	35.9	36.6	122.8	87.1	390.5	703.5	56.5	58
Çetinel 2000	39.9	42.6	128.3	107.9	500	1038	57.5	58.8
Bereket	37.6	36.1	139.4	122.7	607	1113	55.3	49.7
Kırik	46.1	43.1	154	111.9	591.5	619	57.1	56.5
Bezostaja 1	42.6	37.8	160	119.2	1039	1411.5	49.2	50
Mean	39.7	40.5	150.3	116.7	653.4	1017.5	53.1	52.9
F value								
V	30.03**		9.43**		93.34**		81.95**	
WR	5.75*		72.30**		255.71**		0.3	
V×WR	14.49**		0.74		7.79**		7.72**	
CV (%)	2.53		8.36		7.7		1.63	
LSD for *V*×WR	2.97		32.61		188.08		2.53	
2012–2013								
Müfitbey	32.9	19.3	168.3	110.3	741.5	557.5	53.9	59
Gün 91	39.6	20.7	162	143.1	624.5	513.5	50.3	49
Sönmez 2001	33.6	17.6	148.5	100.5	184	307.5	51.5	55.9
Gerek 79	31.2	14.8	117	113	373.5	180	57.2	59.5
Çetinel 2000	37.6	13.8	137.4	122.9	487	429	57.9	62.1
Bereket	35.4	22.8	116.8	111.8	587	536.5	48.1	52.5
Kırik	44.9	14.8	136.4	132.6	461.5	368.5	57.7	63.7
Bezostaja 1	40.7	16.1	145	121.5	743	644	48.9	51.6
Mean	36.9	17.5	141.4	119.4	525.3	442.1	53.2	56.6
F value								
V	19.09**		4.87**		217.82**		93.02**	
WR	2272.02**		29.30**		111.24**		109.53**	
V×WR	28.11**		3.23*		19.48**		5.86**	
CV (%)	4.24		8.8		4.61		1.71	
LSD for *V*×WR	3.37		33.54		65.16		2.76	

F values marked with * and **are significant at 0.05 and 0.01 levels, respectively

of drought and the resistance of cultivars to drought. The changes in GPC under drought conditions may be related to varietal differences in terms of root development, nitrogen use efficiency, and dry matter remobilization efficiency.

Approximately 80% of the total proteins in wheat grain are composed of gluten proteins, and the gluten rate has a determining role in the physical and chemical properties of grain (Begcy and Walia 2015). Gluten, an elastic protein, is an important criterion for bread quality, and flour with high WGC is considered good for dough properties and bread quality. WGC, which is generally positively associated with GPC (Ozturk and Aydin 2004; Flagella et al. 2010), provides an insight into the protein content and nutritional value of grain, as well as the gluten content and protein quality in flour (Ivanova et al. 2013). Significant differences between bread wheat varieties in terms of WGC have been identified in previous studies; this value was reported as 34.7–37.1% in the USA (Saint Pierre et al. 2008b), 18.1–25.0% in Bulgaria (Ivanova et al. 2013), and 33.5–44.1% in Sudan (Mutwali et al. 2016). WGC is more sensitive to changes in environmental conditions and cultural applications than GPC (Spiertz et al. 2006). DAA affects the rate of protein components (Balla et al. 2011), and the effect of drought on grain protein composition varies according to the severity and time of stress (Flagella et al. 2010; Begcy and Walia 2015). Zhao et al. (2009) and Reena et al. (2015) found that

Fig. 4 Changes in Zeleny sedimentation volume (ZSV) of the wheat varieties in response to irrigated (IR) and drought after anthesis (DAA) treatments in 2011–2012 and 2012–2013

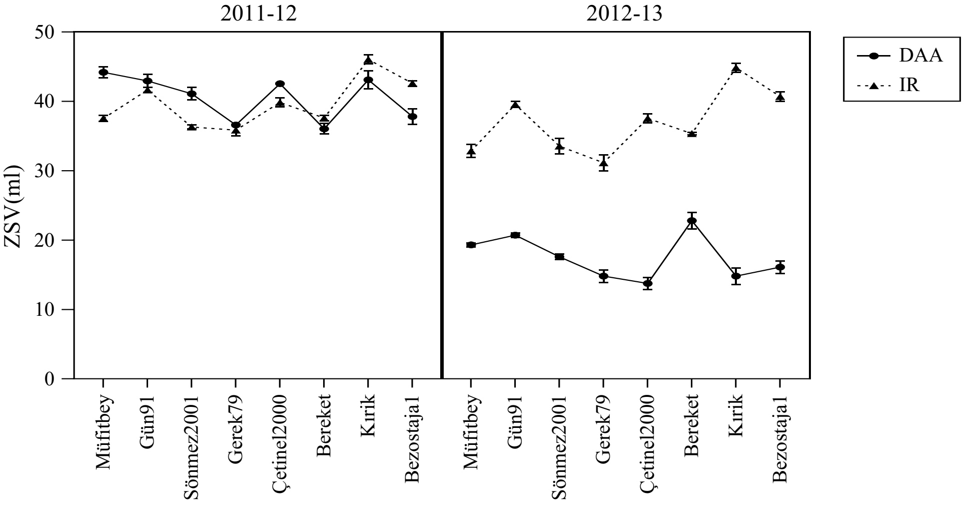


Fig. 5 Changes in grain hardness (GH) of the wheat varieties in response to irrigated (IR) and drought after anthesis (DAA) treatments in 2011–2012 and 2012–2013

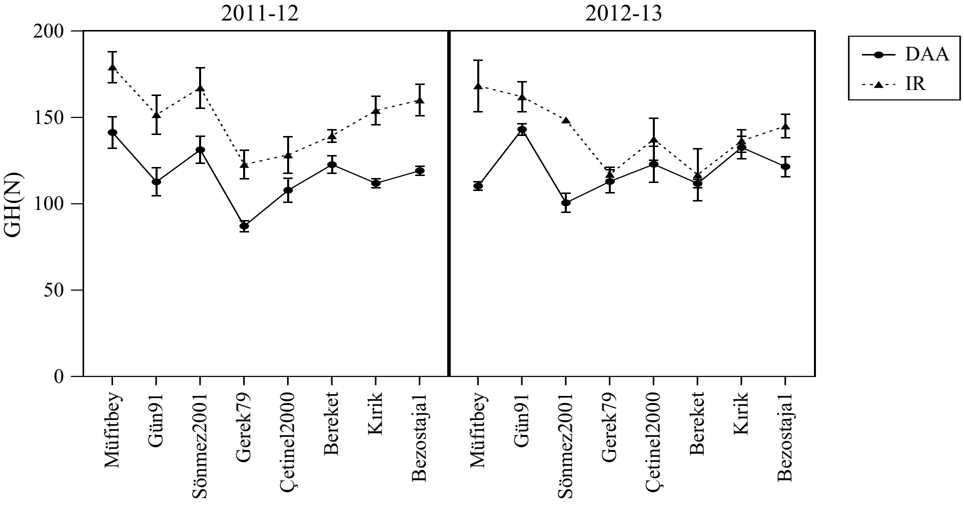
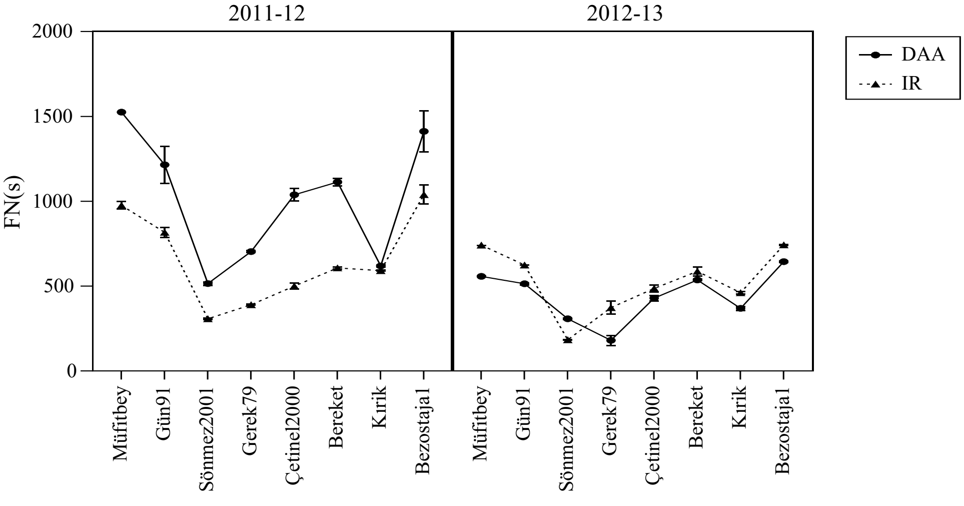


Fig. 6 Changes in falling number (FN) of the wheat varieties in response to irrigated (IR) and drought after anthesis (DAA) treatments in 2011–2012 and 2012–2013



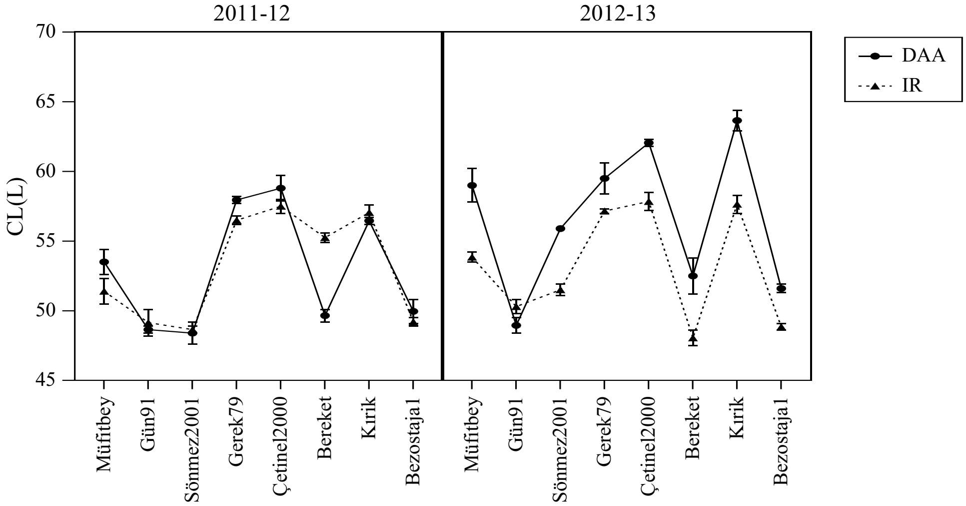


Fig. 7 Changes in kernel color L value (CL) of the wheat varieties in response to irrigated (IR) and drought after anthesis (DAA) treatments in 2011–2012 and 2012–2013

post-anthesis moisture stress increased WGC compared to irrigated conditions, which is in accordance with our first-year results. In contrast, in parallel to our second-year results, Jiang et al. (2009), Balla et al. (2011) and Begcy and Walia (2015) emphasized that DAA reduced WGC and grain quality. These results have strengthened the thesis of Flagella et al. (2010) that the effect of DAA on WGC and grain protein composition depends on the severity and time of stress. Singh et al. (2008) determined that the effect of DAA on the assimilation of gluten proteins varied according to the variety.

The ZSV trait is a criterion for grinding and bread-making processes (Mutwali et al. 2016) and positively related to GPC (Noorka et al. 2009; Li et al. 2013). It is accepted as an indirect indicator of gluten amount (Noorka et al. 2009; Houshmand et al. 2014) and flour quality (Ivanova et al. 2013). In the literature, the ZSV of the wheat varieties was determined between 26–43 ml under USA (Saint Pierre et al. 2008b) and 21.7–31.1 ml under Sudan conditions (Mutwali et al. 2016). Li et al. (2013) commented that the variation in sedimentation volume was primarily determined by the genotype. In line with our 2011–2012 results, Ercoli et al. (2008), Saint Pierre et al. (2008b), Flagella et al. (2010), Li et al. (2013) and Reena et al. (2015) also found that post-anthesis moisture deficiency increased ZSV. Gooding et al. (2003) noted that drought on the 1st–14th and 15th–28th days after anthesis decreased ZSV despite the increase in GPC. Guler (2001) and Balla et al. (2011) reported that drought in the grain filling period decreased sedimentation volume, which is in accordance with our second-year findings. Saint Pierre et al. (2008b) and Houshmand et al. (2014) stated that the effect of drought after anthesis on ZSV varied according to genotypes. The results showed that ZSV was more susceptible to DAA than GPC and WGC, and the effect of DAA on ZSV depended on the severity of drought stress and the resistance of the variety to drought.

The endosperm structure is considered in the classification of wheat as it affects grinding quality, energy consumption, particle size, flour yield, and bread quality. Wheat is classified as soft, medium soft, medium-hard, hard and extra hard according to GH (Pasha et al. 2010). GH is generally positively associated with protein ratio and controlled by major genetic factors. It depends on the assimilation of friabilin protein in grain, and genotypes with lower friabilin have harder grain while those with higher friabilin have softer grain (Szabó et al. 2016). Significant differences between wheat varieties in terms of GH have been identified in previous research (Saint Pierre et al. 2008a; Li et al. 2013). Pasha et al. (2010) stated that assimilation of friabilin, which determines GH, was independent of environmental conditions during the plant development period. Li et al. (2013) determined that moisture deficiency did not significantly change GH. Saint Pierre et al. (2008a) and Reena et al. (2015) reported that drought increased GH and the grain protein ratio compared with irrigated conditions. (Saint Pierre et al. 2008a) and Yang et al. (2018) noted that genotypes had higher GH at higher nitrogen doses, and Sedaghat et al. (2017) reported that every factor that increased or decreased GPC had the same effect on GH. Besides the protein content, GH can also vary according to grain moisture content, grain size, grain pentosan, and fat content. Unlike the findings in the literature, in the current study, there was a significant reduction in GH under the DAA condition, which may be related to the effects of severity stress or other grain characters. In this study, the GH responses of the varieties to the treatments were not related to their drought resistance or grain texture characters.

FN provides an indication in term of the enzymatic status of wheat grain, the degree of germination in the spike before harvest, and bread volume, and its normal value is between 200 and 250 s (Elgün et al. 1999). If FN is higher than 300 s, α-amylase activity and bread volume are lower, and the crust will be dry; an FN value less than 150 s indicates that the amylase activity will be high, the grain will be germinated, and the crust will be sticky (Elgün et al. 1999; Mutwali et al. 2016). Auld and Paulsen (2003) reported that drought stress did not significantly change FN. In accordance with our first-year findings, Gooding et al. (2003) and Torrion and Stougaard (2017) found that DAA increased FN. Guler (2001), on the other hand, determined that drought stress significantly reduced FN compared with irrigated conditions, which is similar to our second-year findings. These results show that the effect of drought on FN may vary depending on the time and severity of drought stress, and varietal responses. Torrion and Stougaard (2017) have determined that the effect of drought on FN varies based on varieties.

CL is controlled by environmental conditions, grain characters and genetic structure, and it affects the color and market value of the product (Ram et al. 2002; Horváth and Véha 2015). Significant differences between cultivars in terms of CL have also been identified in previous research. It was measured between 36.7 and 49.1 by Peterson et al. (2001) and 57.9 and 73.6 by Ram et al. (2002). Peterson et al. (2001) showed that the environmental factors and the cultivation techniques affected CL, and the white-grain varieties that could maintain their color under changing environmental conditions were defined as genetically superior. Since CL is negatively related to protein content, GH, and grain size (Horváth and Véha 2015), drought stress, which harms these characters, may have led to an increase in CL. Konopka et al. (2007) determined that the effect of drought on the CL value varied according to wheat varieties, with drought stress increasing CL in drought-sensitive varieties.

Conclusion

The $V \times$ WR interaction was significant for most of the quality characteristics, and the quality responses of the wheat varieties to DAA were mainly associated with their GPC responses. Considering the changes in the CPC, ZSV and WGC, it appears that in DAA conditions, grain quality is related to drought-resistance, and resistant wheat varieties can better maintain their quality in stress conditions. It was determined that environmental factors had a higher effect than genotype characteristics on the variation in quality traits (except FN and CL). It is concluded that the effects of DAA on quality traits mainly depend on the severity of drought and secondarily on the drought resistance of the variety. Moderate stress generally improves grain quality characteristics but severe drought stress negatively affects quality parameters.

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Compliance with ethical standards

Conflict of interest The authors declare to have no conflict of interest.

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