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Influence of Anthesis Irrigation on Yield, Functional Quality and Antioxidant Properties of Durum Wheat

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ABSTRACT

Soil moisture has become increasingly crucial for sustaining winter crop yield potential under induced water scarcity resulted climate change. Durum wheat has strategic importance in Mediterranean agriculture, serving as both a staple food crop and a key economic commodity. This study aimed to evaluate the effects of supplemental irrigation in anthesis on yield performance, grain quality, technological traits, and health-related characteristics of durum wheat. A field experiment was conducted under irrigated and rainfed conditions with different growth habit durum wheat varieties during two growing seasons (2019/2020 and 2020/2021). Yield and its components, rheological and technological parameters, grain quality traits, total phenolic content, and antioxidant activity were assessed. Supplemental irrigation significantly enhanced grain yield, particularly under dry seasonal conditions, but slightly reduced technological quality, rheological properties, and antioxidant capacity. In contrast, rainfed conditions ensured the expression of desirable grain quality traits relevant to health, nutrition, and pasta end-use quality. Significant correlations were observed, with grain yield negatively associated with protein content (r = –0.41**) and antioxidant activity (r = –0.49***), while protein content exhibited strong positive correlations with gluten index (r = 0.34**), fiber content (r = 0.70**), and antioxidant activity (r = 0.30*). These findings highlight the trade-off between yield and quality under contrasting water regimes. Overall, the results demonstrate that durum wheat exhibits high production potential in Mediterranean environments, with rainfed conditions enhancing quality attributes, thereby providing valuable insights for future breeding and agronomic strategies aimed at balancing yield stability with nutritional and technological quality.

1. INTRODUCTION

Durum wheat [*Triticum turgidum* L. ssp. *durum* (Desf.)] is the 10th most important commonly cultivated cereal and represents 5% of total wheat production worldwide. It represents essential ingredients for human health and nourishment because of its universal use of pasta, semolina, bulgur, couscous and wheat-based products in daily consumption (Laus et al. 2012). Durum wheat is a traditional crop consumed and included in most dishes in the Mediterranean region, where 60% of the world's durum wheat is produced. The climate is ideal for producing high yields of high-quality durum wheat (Abad et al. 2004). The production of pasta requires grain with a high protein content and gluten strength, as well as a high yellow pigment content (mostly resulting from lutein), which gives pasta its characteristic yellow color. Only a few regions in the world are capable of producing durum that meets high standards for end-use quality (Beres et al. 2020). In the context of climate change, wheat production and productivity are being adversely affected by water scarcity and drought, particularly during spring months in recent years. Projections for Mediterranean climate regions indicate a sustained decline in spring precipitation under high-emission scenarios, accompanied by an even more pronounced drying trend during the summer months (EURO-CORDEX, SSP5-8.5). These projections contrast with the conditions observed during the 1971-2000 period (EEA, 2024). Alterations in spring precipitation patterns particularly changes in their temporal distribution result in water scarcity for wheat at a time when crop water demand begins to increase markedly during the generative growth stages. This situation causes yield reductions, even when the winter budget is sufficient to sustain healthy plant growth (Al-Ghzawi et al. 2018; Zeng et al. 2023; Monteleone et al., 2023). Water scarcity during grain filling causes adverse physiological responses of wheat; early senescence, reducing photosynthesis, shortened grain filling stages, reduced grain set and assimilate translocation so supplemental irrigation (SI) may be required in generative growth stages (Demirel et al. 2023). The changes in climate conditions in Mediterranean regions also cause significant quality losses in addition to yield reductions. This situation occurs especially in grain development stages. Grain development is crucial for durum wheat quality involves transport and mobilization of macromolecules in biochemical processes. For this reason, proteins, carbohydrates, starch, nutrients and secondary metabolite components accumulate in seeds affected by adverse climate conditions and in particular, drought stress leads to damages to membrane, chlorophyll and photosynthesis metabolism (De Santis et al. 2021).

Durum wheat has been shown to exhibit greater adaptability to water-related stress than other crops (Grosse-Heilmann et al. 2024). In general, durum wheat is better adapted to high temperatures and semi-arid climates than bread wheat, which is important for this crop. This tolerance to higher temperatures appears to be connected to greater resilience in photosynthesis (Dias et al. 2011). Overall, observations on climate related stress conditions in the Aegean part of Türkiye caused to wonder about the yield and quality performance of durum wheat in the region (Aydın). In general terms, the study aims to evaluate the performance of durum wheat production in the region, rather than bread wheat production, in light of climatic changes. This study aims to examine i) changes in yield characteristics, ii) responses in detailed technological and nutritional quality characteristics with SI in post-anthesis stages, iii) biochemical changes in rainfed vs irrigated conditions and iv) examine the production potential in terms of yield and quality in the region.

2. MATERIALS AND METHODS

Plant material and experimental conditions

The experiment was conducted in Aydın province of Türkiye (37°45′22′′N 27°45′36′′E) during 2019/2020 and 2020/2021 wheat growing seasons. The material set consists of totally 6 durum wheat [*Triticum turgidum* L. ssp. *durum* (Desf.)] varieties (C-1252, Kiziltan, Mirzabey, Eminbey, Imren and Poyraz) obtained from Aegean Agricultural Research Institute, İzmir, Türkiye and Field Crops Central Research Institute, Ankara, Türkiye. The varieties were selected for the purpose of observing the yield and quality response of winter and facultative growth habit properties to rainfed and irrigated conditions in Mediterranean hot climate conditions (Csa-Hot summer Mediterranean climate: Köppen-Geiger climate subtype classification) (Table 1).

Table 1. Botanical and growth habit description of varieties

Variety	Growth habit	Spike type	Institute/company
C-1252	Facultative	Brown, awned	Field Crops Central Agricultural Research Institute
Kiziltan 91	Winter	Brown, awned	Field Crops Central Agricultural Research Institute
Mirzabey	Facultative	Red, white awned	Field Crops Central Agricultural Research Institute
Eminbey	Winter	White, awned	Field Crops Central Agricultural Research Institute
Imren	Facultative	Brown, awned	Field Crops Central Agricultural Research Institute
Poyraz	Facultative	White, awned	Aegean Agricultural Research Institute

The experiment was laid out in randomized split-split block design with three replications and irrigated and rainfed applications were applied as the main plot effect. For the purposes of this study, supplemented irrigation (SI) was administered during the anthesis (BBCH 61-65) period (Meier, 1997). This was achieved by performing flood irrigation and measuring and correcting the soil moisture level to 100% WHC (water holding capacity) after irrigation. The field soil WHC was measured at 24.6% (gravimetric method). To maintain properly irrigated vs. rainfed conditions, the distance between main plots was set to 8 m in the experimental design. Plots requiring supplementary irrigation were formerly prepared by constructing embankments along their edges (40 cm in height) and flood irrigation was subsequently implemented. In order to achieve this objective, in anthesis stage of the plants (completed 50% for all varieties) in the 2019/2020 season, 48 mm of water was applied on May 16, 2020, and in the 2020/2021 season, a total of 59.4 mm of water was applied on May 8, 2021 using irrigation pipes and water meters, calculated to achieve 100% of soil WHC. Plot size and sowing distance between rows were 1,2 x 6 m and 20 cm (500 seeds m^{-2}), respectively. During the growing season nitrogen fertilizer was applied as; 150 kg N ha^{-1} (divided into three doses-before sowing (30 kg N ha^{-1}; 20.20.20, at the tillering period (Urea)-BBCH 21, and at the stage of stem elongation (Urea)-BBCH 31).

Table 2. Monthly and long-term (1927-2024) weather conditions during the experimental period

	Monthly Mean Temperature ⁰C			**Monthly Sum Precipitation (mm)**		
	2019/2020	**2020/2021**	**Long Term**	**2019/2020**	**2020/2021**	**Long Term**
November	15.3	12.6	7.3	50.1	1.5	31.6
December	9.5	11.1	2.6	118.3	110.5	44.3
January	6.6	9.5	0.3	66.0	119.9	40.0
February	9.4	10.2	1.8	82.6	38.2	34.9
March	11.9	10.1	5.8	67.4	66.9	39.6
April	15.6	15.7	11.3	43.8	13.4	41.7
May	21.5	22.4	16.1	40.3	3.3	52.0
June	24.6	25.2	20.0	8.7	1.9	36.9

Long Term: 1927-2024 period, Turkish State Meteorological Service, Kocarli Climate Station (Id: 18427)

Precipitation patterns exhibited marked variations during the spring season in both growing seasons. It is evident that the rainfall levels observed in April and May of the 2020/2021 season were considerably lower than those recorded in the initial year of the study and the long-term average precipitation levels resulting in an especially arid spring season of this year. In the first year, April and May rainfall were 4.7% higher and 22.5% lower than the long-term average, respectively, while in the second year, these figures dropped to 67.8% and 93.6% below the long-term average. A comparison of temperature values from both seasons reveals that they are generally similar. However, when compared to the long-term average, higher temperatures were recorded in both years, resulting in a warmer climate overall during the two seasons (Table 2).

In harvesting season, the plant height (PH, cm) was measured from soil surface to the top of spikelet of the 10 randomly selected plant in each plot. The plants were harvested by removing border lines in each plot in both harvesting times (7th of June 2020 and 1st of June 2021) and the remaining area was harvested to calculate the yield and its components. The harvested seeds were then threshed, cleaned and stored at 4°C until chemical analysis.

Physical and chemical grain quality analysis

All samples were milled to whole meal flour using a laboratory mill (UDY Corporation, USA) for the determination of chemical and biochemical properties of durum wheat samples. Grain vitreousness ratio was determined using the Grobacker wheat shears tool (Bastak Instruments, Türkiye) by counting the vitreous ratio five times in 100 grains, expressed as % according to Bipea Ref. method 204-1104. Near-Infrared Reflected Spectroscopy (NIRS, Bruker MPA) method (Oliveira & Franca 2011) was used to determine grain ash, fiber, lipid and starch ratio (expressed in dry matter, % dm). The protein ratio of flour samples was determined by Dumas Nitrogen Analyzer (Velp Scientifica, Italy) according to the AOAC 997.09 method.

Grain color and rheological analysis

Grain color analyses (L*, a*, b*) were measured by ColorFlex EZ Spectrophotometer (HunterLab, Reston, VA, USA). The wet gluten and gluten index were determined using the Bastak® 6000 (ICC Standard No. 137/1) and Bastak® Index 2002 (ICC Standard No. 155) devices with whole-grain flour.

Health-promoting biochemical analysis and extraction

Whole wheat flour was used to determine total phenolic content and antioxidant activity analysis. For the extraction, a methanol solution (HCl/methanol/water; 1:80:10) was prepared, and then the samples were shaken in a Gerhardt Thermoshake for 1 h. under nitrogen gas, then centrifuged at 5000 rpm for 20 min. In a Hettich centrifuge (Ragaee et al., 2006; Ma et al., 2014). The Folin-Ciocalteu method was used by using gallic acid as a standard to determine the total phenolic content of whole durum wheat flour, as described by Kaluza et al. (1980) and Ragaee et al. (2006). The DPPH (2,2-diphenyl-1-picrylhydrazyl) free radical method was used to determine the total antioxidant activity (%) of whole durum wheat flour samples according to the method proposed by Brand-Williams et al. (1995). After the chemical extractions the absorbance levels of 725 and 517 nm (wavelength) in Thermo Scientific spectrophotometer used for total phenolic content and antioxidant activity, respectively.

Statistical analysis

Data of the obtained results were evaluated in variance for each parameter by using ANOVA test and LSD test techniques of IBM SPSS V20 statistical analysis software. In addition, the correlogram was performed in R studio using the "metan" package to reveal relationships between the evaluated parameters (Olivoto and Lúcio, 2020).

3. RESULTS AND DISCUSSION

ANOVA results of evaluated parameters

The present study was conducted to examine the effects of spring rainfall and SI on the anthesis period of durum wheat plants. Results of statistical analysis for the effects of experimental factors [Year (Y), I (Irrigation), and Genotype (G)] on yield and detailed nutritional, functional quality parameters and antioxidant properties of durum wheat with significance levels were given in Table 3 and Table 4. As indicated by the results of the analysis of variance (ANOVA), the climatic variations observed during the growing seasons also exerted an influence on the outcomes. Considering that the changes in the precipitation pattern observed in both seasons had a significant effect on the parameters studied, it was concluded that the year factor was statistically significant at the 1% level for many parameters. Wheat is commonly grown in rainfed conditions in the Mediterranean areas and so yield and quality properties are frequently affected by post-anthesis drought (Ilker et al. 2011). In the study both years and irrigation treatments caused significant changes in evaluated parameters. Similarly, irrigation treatment (rainfed vs SI) was found to be statistically significant ($p \leq 0.01$) effects on yield and quality traits (except for grain vitreousness, grain ash, lipid ratio, brightness L* and total phenolic content).

Table 3. The mean of squares and significance levels found as a result of ANOVA analysis for yield, yield parameters and some evaluated grain quality parameters for 2019/2020 and 2020/2021 periods

Source	dF	PH	EY	GN	GY	TGW	GVIT	PRO	ASH	LIP
Rep. (R)	2	8.39	0.04	0.03	10051	1.58	440.2	0.96	0.00	0.01
Year (Y)	1	320.4**	2.56**	61.0**	838041**	0.62	4170.8**	25.6	7.67**	13.8
R*Y	2	2.86	0.08	0.60	33594	2.31	144.7	3.16	0.01	0.03
Irri. (I)	1	438.5**	1.24**	686.3**	1512793**	933.8**	46.7	61.8**	0.01	0.21
Y*I	1	9.31	4.50**	72.6**	1183411**	6.66	2005.5**	86.7**	0.06**	0.09
R*I(Y)	4	4.35	0.03	5.97	7724	31.5*	488.0	0.48	0.00	0.00
Geno(G)	5	205.8**	1.02**	33.4**	231910**	38.7**	1294.8**	12.7**	0.19**	0.24*
Y*G	5	87.4**	0.28**	106.4**	89283**	4.38	368.8	9.67**	0.07**	0.18*
I*G	5	113.6**	0.37**	46.8**	101121**	161.5**	574.7*	11.6**	0.03**	0.21*
Y*I*G	5	101.9**	0.63**	104.9**	272784**	21.6	381.5	7.00**	0.11**	0.20*
Error	40	5.33	0.03	2.96	9772	10.6	216.4	1.17	0.00	0.07
CV (%)		2.34	9.34	4.98	9.29	7.13	18.3	6.36	8.74	15.3

PH: Plant height (cm), EY: Ear yield (g), GN: Number of grains per ear, GY: Grain yield (kg ha^{-1}), TGW: Thousand grain weight (g), GVIT: Grain vitreousness (%), PRO: Grain protein ratio (% dm), ASH: Grain ash ratio (% dm), LIP: Grain lipid ratio (% dm), *: $p \leq 0.05$, **: $p \leq 0.01$ significance level.

The genetic effect (G) was statistically significant ($p \leq 0.01$) for the parameters examined and was effective (greater impact) across all parameters. It is important to mention that grain lipid ratio, grain brightness color (L*) and total phenolic content changed statistically significantly only in genotype effect except year and irrigation factors. Kernel quality traits are often quantitative and are therefore controlled by multiple genes/QTL. These traits have a strong influence on the quality of the product of commercial wheat varieties and determine the types of products that can be produced. However, high heritability for grain color, gluten strength, yield and milling potential was observed in durum wheat that this approach has great potential to identify high quality performing genotypes breeding (Sissons et al. 2020; Marcotuli et al. 2022). Simultaneously, the additive effects of the genes responsible for yellowness will result in the generation of enhanced plants through multiple breeding cycles (Colasuonno et al. 2019). In general, these traits showed and resulted dominant genetic control and limited environmental sensitivity, indicating high breeding performance. Durum wheat varieties cultivated in different growing seasons exhibited significant variations depending on irrigation practices. The significant differences ($p \leq 0.01$) were observed in interaction (Y*I*G) of combined factors for many evaluated parameters while no significant differences were observed in thousand-grain weight, grain vitreousness and grain yellowness (b*) parameters (Table 3 and Table 4).

Table 4. The mean of squares and significance levels found as a result of ANOVA analysis for functional quality, total phenol content and antioxidant activity parameters for 2019/2020 and 2020/2021 periods

Source	dF	FBR	STR	L*	a*	b*	GLU	GLUIN	PHE	AAC
Rep. (R)	2	0.01	1.30	5.00	0.52	0.50	25.6	17.6	9149.0	89.9
Year (Y)	1	1.35	890.2**	55.6	0.10	0.80	21.4	49.7*	970.2	520.2**
R*Y	2	0.24	0.19	8.01**	0.03	2.72	1.99	0.28	627.0	200.8**
Irri (I)	1	17.7**	58.5**	2.22	7.43**	42.1**	327.5**	115.6**	312.0	1551.4**
Y*I	1	13.6**	316.3**	2.54*	11.6**	22.9**	234.5**	51.4*	14435.8**	558.0**
R*I(Y)	4	0.05	0.96	0.65	0.47	0.54	23.1**	5.98	1382.3	25.3
Geno(G)	5	2.33**	47.7**	9.20**	3.34**	8.95**	312.6**	324.2**	14953.7**	92.2**
Y*G	5	1.11**	23.5**	5.35**	0.93**	6.94**	114.3**	29.6*	3845.0	113.4**
I*G	5	0.53**	96.9**	4.58**	0.56**	1.11	37.8**	159.4**	17540.1**	183.9**
Y*I*G	5	1.38**	18.3**	3.57**	0.39*	0.79	87.1**	74.6**	10732.2**	101.0**
Error	40	0.11	0.78	0.56	0.14	0.84	5.18	11.4	1950.4	11.8
CV (%)		7.83	1.37	1.33	4.61	4.40	7.25	3.92	7.60	9.00

FIBER: Grain fiber ratio (% dm), STR: Grain starch ratio (% dm), L*: Brightness color, a*: redness color, b*: yellowness color, GLU: Gluten content (%), GLUIN: Gluten strength (%), PHE: Total phenolic content (µg/100 g GAE equivalent), AAC: Total antioxidant activity (% DPPH radical scavenging)

The results of yield and yield formation

It has been determined that year, irrigation type, and variety are important factors affecting yield formation in durum wheat plants, and it has been revealed that yield is a complex trait influenced by polygenic genetic trait and shaped by many abiotic and biotic drivers (Curtis and Halford, 2014). Plant height, ear yield, and number of grains per ear reached higher values in the first year of the experiment, while grain yield was higher in the second year. This situation can be attributed to the lower spring rainfall in the second year and the fact that contribution of SI during the anthesis period reached significantly higher values compared to first year. During the drier season (2020/2021), an increase in soil moisture levels by SI has been observed, resulting in a more significant increase in yield compared to the mid-season (2019/2020). The positive effect of SI during the anthesis period was observed in all yield and yield components examined. C-1252 and Kiziltan varieties demonstrated the highest values in terms of plant height, while the Eminbey, Imren, and Poyraz varieties achieved higher values in terms of ear yield and number of grains per ear, reaching and resulting with the highest values in grain yield during 2019/2020 and 2020/2021 seasons (Figure 1.).

An examination of the factorial interaction demonstrated that the Poyraz variety exhibited the highest value (2.94 g) in terms of ear yield in the first year under supplementary irrigation. Conversely, the minimum ear yield was documented for the Mirzabey variety (1.15 g) in the second year under rainfed conditions. With regard to ear yield, Eminbey (2.81 g), Imren (2.55 g), and Poyraz (2.39 g) varieties achieved higher values, especially in the first year under rainfed conditions, while in the second year, ear yield values were quite low under rainfed conditions (Table 5). This decline can be attributed to the decrease in soil moisture levels during the generative period, which was caused by lower spring rainfall (-67.8 and -93.6%, April and May, respectively).

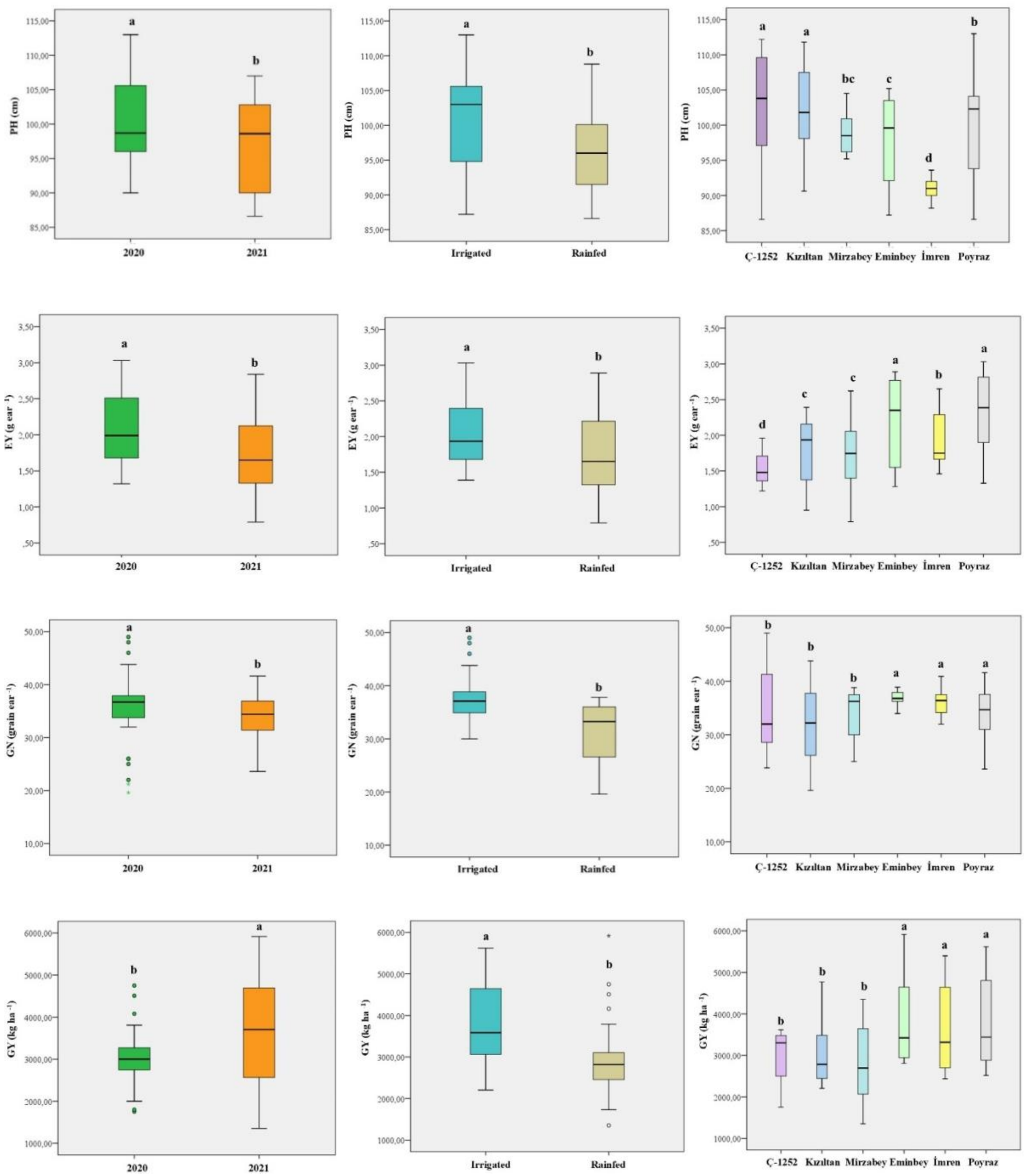

Figure 1. Boxplots of yield (GY) and yield parameters (PH, EY, GN) with standard deviations of durum wheat varieties grown under irrigated and rainfed conditions during the period 2019/2020 and 2020/2021 (For abbreviations see Table 3 and Table 4).

With regard to the grain number per ear, the C-1252 variety demonstrated the highest result, achieving a value of 47.6 g in the first year with SI. Conversely, the lowest value was once again observed in the first year in the rainfed condition with the Kiziltan variety, attaining a value of 20.9 g. A considerable increase in the number of grains per ear was observed in both seasons where SI was applied. The anthesis stage of durum wheat is highly sensitive to water stress, controlling fertility/sterility of generative organs and final grain set. SI boosts yield and yield-related parameters like grain number (up to ≈40.8) especially in arid and semi-arid zones areas (Bouazzama et al. 2024; Al-Ghzawi et al. 2018; Fellah et al. 2018).

Table 5. Mean values of evaluated yield (GY) and yield parameters (PH, EY, GN) of durum wheat varieties grown under irrigated and rainfed conditions, 2019/2020 and 2020/2021 (For abbreviations see Table 3 and Table 4).

		2020		2021			2020		2021	
		Irrigated	Rainfed	Irrigated	Rainfed		Irrigated	Rainfed	Irrigated	Rainfed
PH (cm)	C-1252	111.2 a	105.6 cd	103.2 cde	89.5 hi	EY (g)	1.89 fg	1.43 jkl	1.50 ijk	1.29 kl
	Kiziltan	110.0 ab	97.4 fg	104.6 cd	96.8 g		2.15 ef	2.15 ef	1.82 gh	0.96 lm
	Mirzabey	98.3 fg	95.8 g	103.3 cde	97.8 fg		1.47 ijk	1.91 fg	2.31 de	1.15 m
	Eminbey	104.0 cde	96.2 g	88.1 i	102.5 de		1.74 ghi	2.81 ab	2.69 abc	1.41 jkl
	Imren	91.5 hi	91.8 hi	89.2 hi	91.8 h		1.63 g-j	2.55 bcd	1.87 fg	1.63 g-j
	Poyraz	106.5 bc	100.9 ef	103.4 cde	88.2 hi		2.94 a	2.39 cde	2.37 de	1.53 h-k
LSD Y:, 1.71; LSD I: 1.36; LSD G: 1.90; LSD Y*I*G: 3.72						LSD Y:, 0.29; LSD I: 0.12; LSD G: 0.14; LSD Y*I*G: 0.30				

		2020		2021			2020		2021	
		Irrigated	Rainfed	Irrigated	Rainfed		Irrigated	Rainfed	Irrigated	Rainfed
GN (grain ear^{-1})	C-1252	47.6 a	34.2 e-h	31.0 i	25.0 j	GY (kg ha^{-1})	3473 de	1851 i	3506 de	3134 ef
	Kiziltan	43.3 b	20.9 k	32.0 ghi	31.6 hi		2541 gh	2805 fgh	4424 b	2540 gh
	Mirzabey	37.4 cd	25.6 j	37.4 cd	35.4 c-f		2532 gh	2885 fgh	4276 bc	1672 i
	Eminbey	36.4 cde	36.3 cde	37.9 c	36.3 cde		2980 e-h	2921 fgh	4663 b	4622 b
	Imren	38.3 c	34.8 d-g	37.6 cd	33.2 f-i		3814 cd	3005 efg	5300 a	2461 h
	Poyraz	34.3 e-h	36.4 cde	38.2 c	27.7 j		3100 ef	4338 bc	5230 a	2605 fgh
LSD Y:, 0.78; LSD I: 1.59; LSD G: 1.42; LSD Y*I*G: 2.90						LSD Y:, 587; LSD I: 181; LSD G: 257; LSD Y*I*G: 535				

In terms of grain yield, the highest values were achieved in the second year, when there was a drier spring and irrigation was used to support the Imren (5300 kg ha^{-1}) and Poyraz (5230 kg ha^{-1}) varieties. The lowest yield values were achieved in both seasons for the Mirzabey (1672 kg ha^{-1}) and C-1252 (1851 kg ha^{-1}) varieties under rainfed conditions. Additionally, when considering both seasons, the remaining varieties also achieved high values in the second year with additional irrigation. The additional irrigation carried out during the period of reduced spring rainfall had a significant impact on yield. The effect of SI on grain yield in a dry season context was examined, with results indicating a significant increase in grains per ear. This finding aligns with the ~18% gains previously reported under SI in wheat. In contrast, the impact of SI during the wet season was found to be less effective (Table 5). This outcome is consistent with the well-documented sensitivity of floret survival and grain set in durum wheat to water statues around anthesis (Al-Ghzawi et al. 2018; Vahamidis et al. 2019).

The results of physical, chemical and grain color quality traits

In recent years, irregularities in spring rainfall have had a detrimental effect on both yield and quality characteristics of durum wheat. Changes (temperature and rainfall) occurring during the grain formation stage have been shown to result in either improvements or adverse effects on quality. It has been reported that climatic conditions during grain filling can influence the relationships among quality traits.

For instance, soil moisture stress has been shown to increase protein/vitreousness, while concurrently reducing TGW. This suggests that quality can be affected in beneficial or adverse directions, depending on the extent of the stress (Rharrabti et al. 2003). In the context of the ecological conditions exhibited by the region of Aydın, TGW values of the durum wheat varieties exhibited significant variation, ranging from 35.0 to 50.8 grams, under conditions of rainfed and SI (Table 6). Drought and heat stress in generative growth periods of durum wheat are the main stress factors affecting end-use quality and yield. As demonstrated by Moayedi et al. (2021), the presence of sufficient soil moisture and moderate temperate during the process of grain filling has been shown to have a beneficial effect on both test weight (TW) and thousand kernel weight (TKW). This is due to the fact that such conditions support photosynthesis and starch accumulation over a more extended period. As Jabbour et al. (2023) demonstrated, terminal drought, a prevalent stressor in durum, exerts a substantial impact on grain filling, thereby affecting TKW through genetic regulation. In the rainfed condition, lower values were obtained regarding grain weight. It was determined through comprehensive analysis that the Poyraz and Eminbey varieties, which demonstrated the highest grain yield, also exhibited the greatest grain weight among the diverse range of durum wheat varieties examined (Figure 2).

Grain vitreousness is a significant factor in determining the quality of durum wheat, which in turn ensures a higher yield of semolina, enhanced color (glassy appearance) and texture, superior cooking quality, and higher milling properties (Dowell, 2000; Vatter et al. 2022). High vitreousness is correlated with the protein content, hardness, milling and baking properties (improved loaf volume) (Fu et al. 2017; Cha et al. 2025). Grain vitreousness attained notably elevated values in the 2nd year, reaching these levels during the dry generative season. Furthermore, genetic factor came to the forefront (not significant in rainfed vs irrigated) and Poyraz has the highest value characterized by facultative and white, awned spike type (Figure 2).

The quality of durum wheat is influenced by several stakeholders, including seed companies, grain dealers, farmers, the milling and pasta industries, and consumers. This complicates the provision of a single, exhaustive definition. The quality of the end-use product is impacted by consumer expectations and the inherent characteristics of the grain. These characteristics are primarily determined by genotype, though they are also influenced by environmental conditions, nutrient status and crop management (Troccoli et al., 2000). Protein content is a key factor, with levels above 13% improving pasta quality and tolerance to overcooking (Saini et al., 2022).

In particular, technological and nutritional properties have undergone significant changes in terms of protein, lipid, fiber, and starch, depending on the interaction (Y*I*G) (Table 3 and Table 4). It has been concluded that environmental factors have a significant impact on quality characteristics, in addition to genetic characteristics. Grain protein content values were found to be elevated in nearly high for all varieties (with the exception of C-1252) under conditions of rainfed condition, particularly in the 2nd year when spring rainfall levels were minimal. The highest protein content value (22.7%) was obtained in the Mirzabey variety under rainfed conditions during the 2020/2021 season (Table 6).

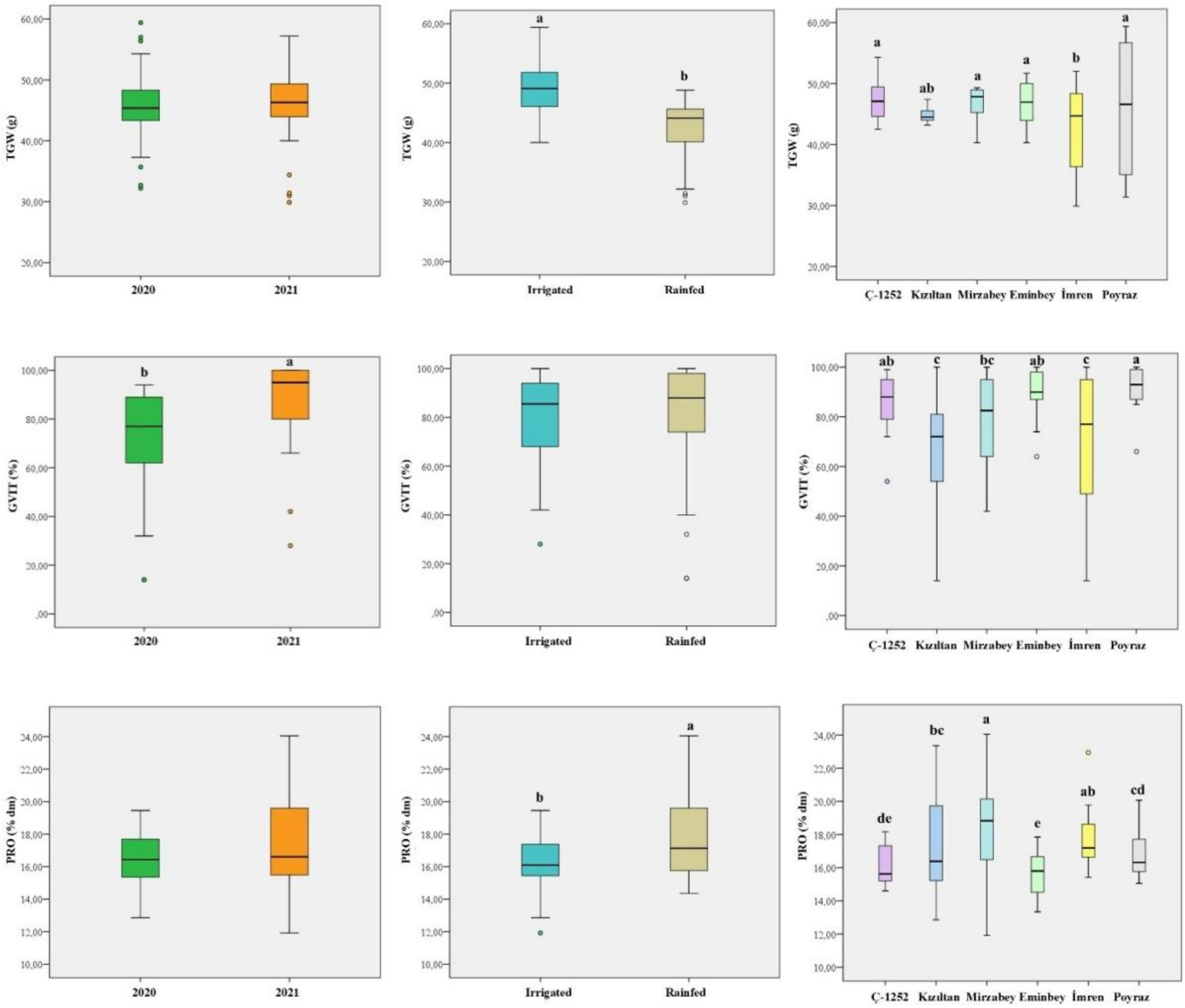

Figure 2. Boxplots of thousand grain weight (TGW), grain vitreousness (GVIT) and grain protein ratio (PRO) traits with standard deviations of durum wheat varieties grown under irrigated and rainfed conditions during the period 2019/2020 and 2020/2021 (For abbreviations see Table 3 and Table 4).

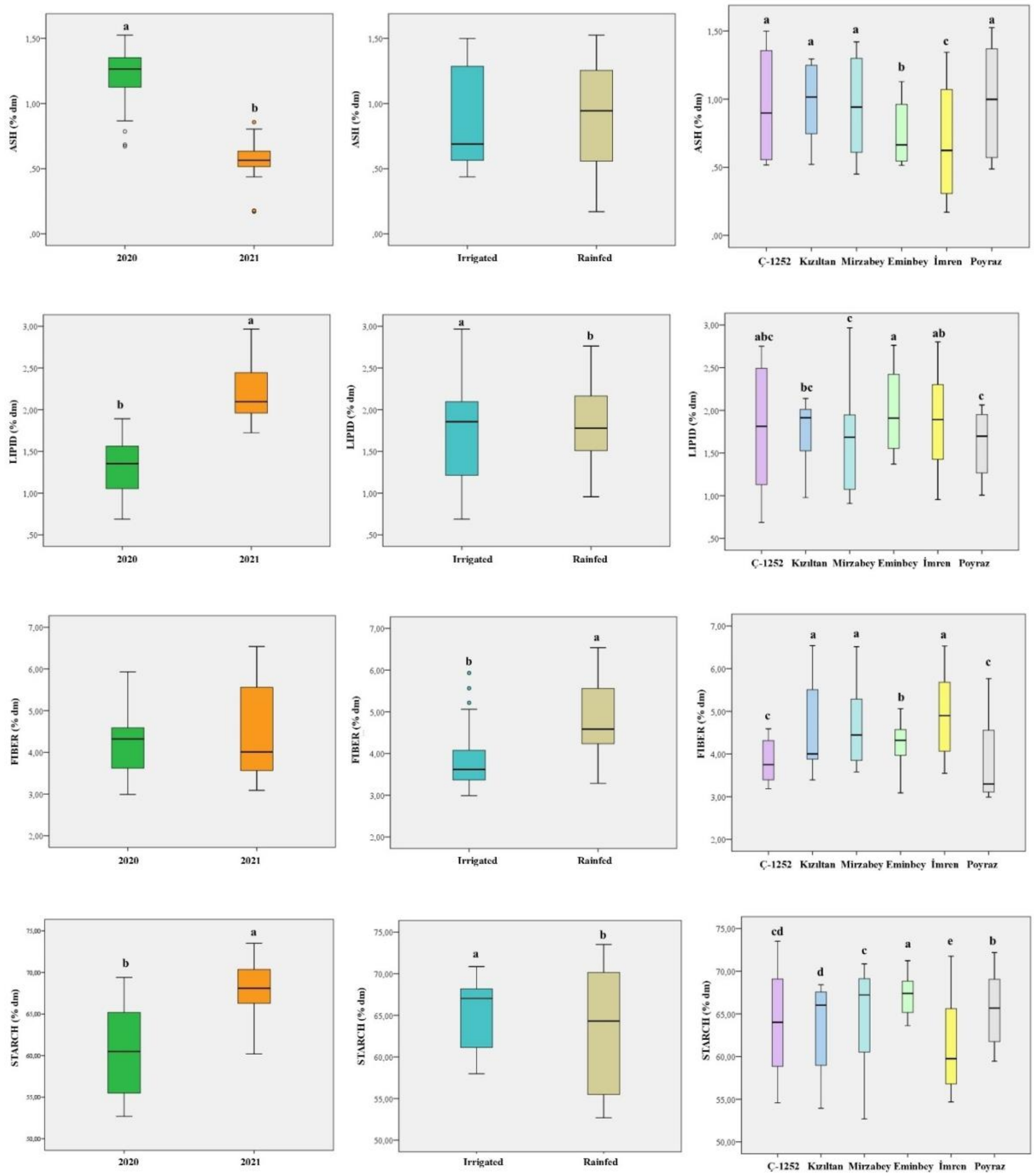

Figure 3. Boxplots of nutritional quality (grain ash, lipid, fiber and starch ratio) with standard deviations of durum wheat varieties grown under irrigated and rainfed conditions during the period 2019/2020 and 2020/2021 (For abbreviations see Table 3 and Table 4).

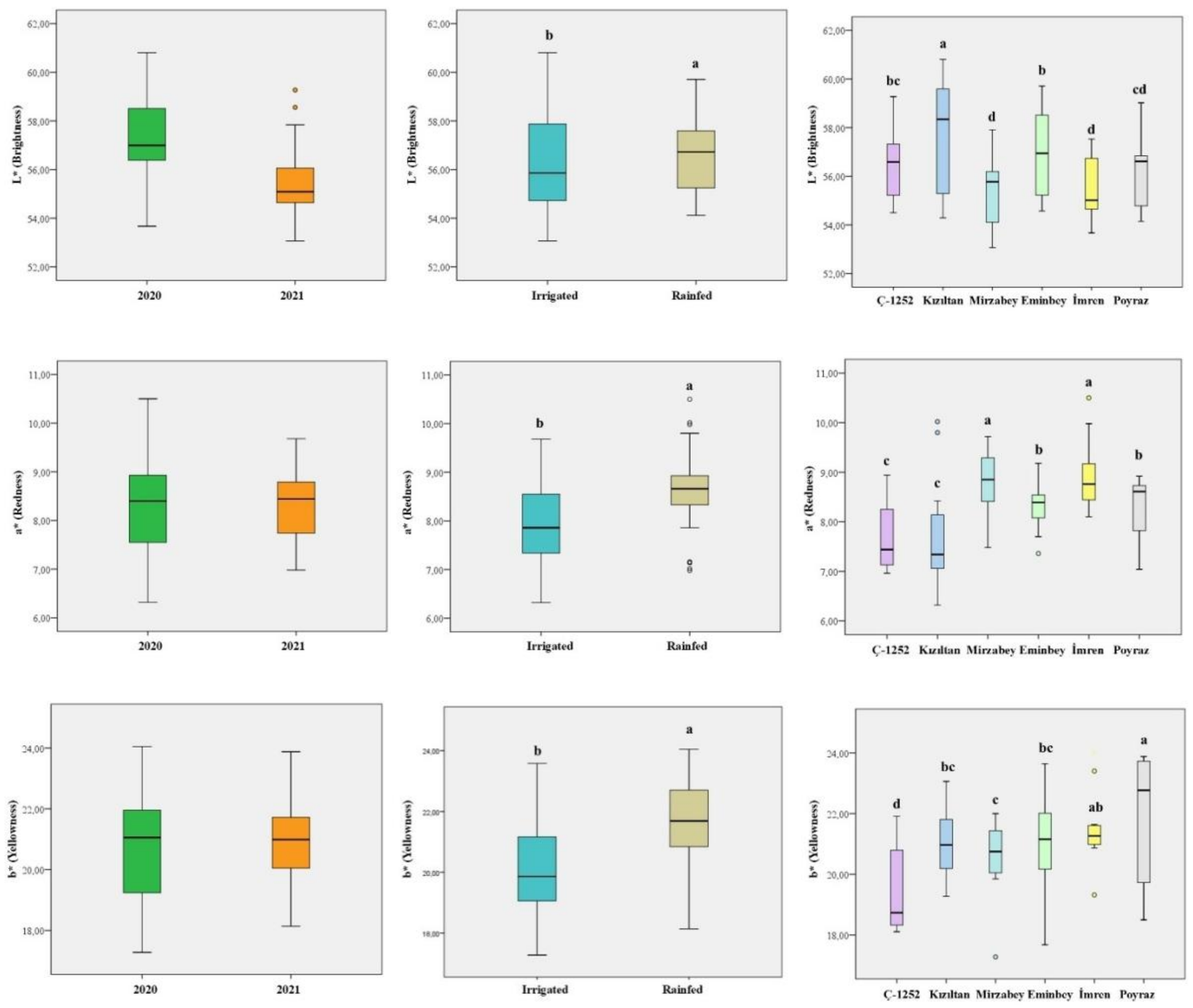

Figure 4. Boxplots of grain color quality traits with standard deviations of durum wheat varieties grown under irrigated and rainfed conditions during the period 2019/2020 and 2020/2021 (For abbreviations see Table 3 and Table 4).

In general, the Mirzabey reached a high protein content values in both seasons, but a significant decrease (lowest 13.8%) also observed in the dry spring season with SI. The previous studies indicate that drought and water scarcity tend to increase grain protein concentration, although the effects on specific protein fractions vary depending on the timing and intensity of the stress experienced during grain development stages (De Santis et al. 2021; Groose-Heilmann et al. 2024).

Durum wheat grain quality and its composition is intricately linked to technological properties of it. In addition to protein content the evaluated varieties have a good quality potential to production high quality durum products. Total ash content is regarded as one of the main durum wheat quality characteristics that has an influence on pasta color and dough kneading (Feillet et al. 2000; Cabas-Lühmann et al. 2021). The presence of a high ash content can be associated with a loss of color in semolina, which may be attributable to elevated extraction rates. The total ash level is preferred to have premium grade semolina lower than 0.9% otherwise the obtained pasta tends to have a brown color (El-Khayat et al. 2006). The total ash content attained notably elevated levels during the first year of the study. In the second year, ash content values were found to be below 0.9% (Figure 3). The highest ash content was found in the C-1252 variety under irrigated conditions in the first year (1.47%), while the lowest value (0.17%) was found in the Imren variety under rainfed conditions in the 2020/2021 season (Table 6). The implementation of SI in anthesis does not exert an influence on the ash content. In durum wheat grain, germ is the richest part of lipid content followed by aleurone layer and bran fractions. Wheat germ contains several health and functional properties considered as unsaturated fatty acids, dietary fibers, vitamin E and B, minerals and flavonoids (Perri et al. 2022). In whole meal durum pasta has higher germ oil that can enhance nutritional and health value but during milling processes it is removed to produce durum wheat products because of increases risk shorter shelf life due to oxidation (Marzocchi et al. 2022). According to the total lipid content results, the values obtained demonstrated a substantial increase, notwithstanding the decline in ash content values during the 2nd year. This positive change in quality is of particular importance in years with low rainfall in the spring and when obtained with additional irrigation (Figure 3). Furthermore, an increase in lipid content values was observed in response to irrigation during the anthesis, contingent on the prevailing rainfed conditions. The total lipid content values ranged from 0.77 to 2.72 (% dm) with the Eminbey variety exhibiting the highest value in the second year under rainfed conditions. In terms of total fiber content, it was found that values increased significantly (values in 4.16–6.32 % dm) in rainfed production in the second year of the experiment (Table 6). Additionally, it was found that providing additional irrigation during this dry season resulted in a significant decrease in fiber values (values in 3.22–3.69 % dm). This situation can be explained in particular by the effect of drought on grain; drought and heat stress are related to redesigning the seed volume, weight and its composition in post-anthesis stages. Although increasing drought severity causes decreases in grain weight and volume, it also causes increases in properties such as dietary fiber content (Rakszegi et al. 2019).

Table 6. Mean values of evaluated physical, chemical and grain color quality traits of durum wheat varieties grown under irrigated and rainfed conditions, 2019/2020 and 2020/2021 (For abbreviations see Table 3 and Table 4).

		2020		2021			2020		2021	
		Irrigated	Rainfed	Irrigated	Rainfed		Irrigated	Rainfed	Irrigated	Rainfed
TGW (g)	C-1252	50.2	43.7	49.0	46.7	GVIT (%)	86.6	73.3	93.6	88.6
	Kiziltan	44.2	44.3	45.6	44.8		72.0	41.3	58.0	93.3
	Mirzabey	47.8	44.0	48.9	46.4		60.0	82.6	70.6	99.3
	Eminbey	49.0	44.8	50.8	42.3		90.6	79.3	91.3	95.3
	Imren	44.4	41.8	48.4	35.5		63.3	40.6	88.6	86.0
	Poyraz	57.6	35.0	55.1	35.2		88.3	90.0	86.6	99.3
LSD I: 3.67; LSD G: 2.69						LSD Y: 12.2; LSD G: 12.1				

		2020		2021			2020		2021	
		Irrigated	Rainfed	Irrigated	Rainfed		Irrigated	Rainfed	Irrigated	Rainfed
PRO (% dm)	C-1252	18.0 de	15.7 g-k	15.3 h-l	15.6 g-l	ASH (% dm)	1.47 a	1.19 de	0.58 gh	0.56 gh
	Kiziltan	14.7 jkl	16.4 e-i	15.9 f-k	22.4 ab		1.26 cd	1.22 d	0.64 g	0.78 f
	Mirzabey	18.9 cd	18.0 de	13.8 l	22.7 a		1.31 bcd	1.27 cd	0.59 gh	0.58 gh
	Eminbey	14.4 kl	14.6 jkl	16.2 f-j	17.3 d-g		0.81 f	1.08 e	0.53 gh	0.58 gh
	Imren	17.5def	16.8 e-h	16.1 f-k	20.7 bc		0.77 f	1.30 bcd	0.48 h	0.17 i
	Poyraz	16.0 f-k	15.9 f-k	16.1 f-k	19.0 cd		1.36 abc	1.42 ab	0.59 gh	0.54 gh
LSD I: 0.45; LSD G: 0.89; LSD Y*I*G: 1.80						LSD Y: 0.11, LSD G: 0.06; LSD Y*I*G: 0.12				

		2020		2021			2020		2021	
		Irrigated	Rainfed	Irrigated	Rainfed		Irrigated	Rainfed	Irrigated	Rainfed
LIPID (% dm)	C-1252	0.77j	1.49 gh	2.28 bcd	2.55 ab	FIBER (% dm)	3.38 gh	4.45 cd	3.42 fgh	4.16 cde
	Kiziltan	1.49 gh	1.39 ghi	2.08 cde	1.97 def		3.96 def	4.45 cd	3.69 efg	6.32 a
	Mirzabey	0.99 ij	1.26 hi	2.45 abc	1.76 efg		4.60 c	4.29 cd	3.60 fg	6.03 ab
	Eminbey	1.56 fgh	1.58 fgh	2.08 cde	2.72 a		4.27 cd	4.48 cd	3.67 efg	4.50 cd
	Imren	1.36 ghi	1.44 gh	2.26 bcd	2.33 a-d		5.57 b	4.46 cd	3.64 efg	5.84 ab
	Poyraz	1.23 hi	1.31 hi	1.95 def	1.97 def		3.03 h	3.42 fgh	3.22 gh	5.56 b
LSD Y:, 0.17; LSD G: 0.22; LSD Y*I*G: 0.42						LSD I: 0.14; LSD G: 0.28; LSD Y*I*G: 0.55				

		2020		2021			2020		2021	
		Irrigated	Rainfed	Irrigated	Rainfed		Irrigated	Rainfed	Irrigated	Rainfed
STARCH (% dm)	C-1252	61.2 h	55.5 k	67.1 ef	72.2 a	L* (Brightness)	56.1 d-j	57.2 cd	55.2 g-k	57.3 cd
	Kiziltan	67.7 de	54.3 k	67.7 de	64.3 g		60.0 a	58.9 ab	57.1 cde	54.8 jkl
	Mirzabey	68.8 cd	54.3 k	69.7 bc	65.9 f		56.7 d-g	55.2 g-k	53.5 l	56.4 d-i
	Eminbey	67.0 ef	63.8 g	67.6 de	70.2 bc		58.5 bc	58.4 bc	55.1 h-k	55.6 e-k
	Imren	58.4 j	55.2 k	60.6 hi	70.7 b		54.5 kl	56.9 c-f	54.9 i-l	55.6 f-k
	Poyraz	59.7 ij	63.9 g	67.3 e	71.1 ab		57.5 bcd	56.7 d-h	54.7jkl	55.3g-k
LSD Y: 0.44; LSD I: 0.64; LSD G: 0.72; LSD Y*I*G: 1.44						LSD G: 0.61; LSD Y*I*G: 1.55				

		2020		2021			2020		2021	
		Irrigated	Rainfed	Irrigated	Rainfed		Irrigated	Rainfed	Irrigated	Rainfed
a* (Redness)	C-1252	7.25 ef	8.74 bcd	7.58 e	7.08 ef	b* (Yellowness)	18.4	21.8	19.1	18.3
	Kiziltan	6.72 f	9.41 ab	7.51 e	7.34 ef		19.5	22.2	20.8	21.4
	Mirzabey	8.33 d	9.10 bc	9.42 ab	8.54 cd		19.6	21.1	20.8	20.6
	Eminbey	7.64 e	8.68 cd	8.43 cd	8.55 cd		19.4	22.3	20.4	21.8
	Imren	8.40 d	9.84 a	8.60 cd	8.84 bcd		21.1	22.9	20.7	21.1
	Poyraz	7.32 ef	8.58 cd	8.49 cd	8.70 cd		18.7	22.3	22.9	23.8
LSD I: 0.45; Lsd G: 0.31; Lsd Y*I*G: 0.67						LSD I: 0.48, ; Lsd G: 0.76				

Wheat bran is clearly the highest in dietary fiber and health-promoting components compared to other parts of grain. Dietary fiber includes more health benefit components compared to fiber-free products. However, it causes modifying the pasta structure and has adverse contribution to pasta quality. Fiber components cause starch leaching and can increase sample adhesiveness results with cooking loss (Bianchi et al. 2022). From this perspective, lower fiber content achieved through additional irrigation and during the dry season has had a more significant impact on cooking quality.

In contrast to the predictions made on the basis of the total starch content, the values were found to be elevated in the second year of the study, during which period the rainfall was lower. However, the average starch content increased significantly in 2020/2021 period (Figure 3). The most significant contribution to this situation was the substantial increase in starch content observed with additional irrigation compared to rainfall-based application in the first year. With a starch content of 67.1%, the Eminbey variety achieved the highest value among the varieties. According to the interaction (Y*I*G) results, the highest value was obtained in the 2020/2021 season by the C-1252 variety with a value of 72.2%. The lowest values were observed in the 2019/2020 season under rainfed conditions, with the C-1252, Kiziltan, and Mirzabey varieties having values of 55.5%, 54.3%, and 54.3%, respectively (Table 6). The starch values obtained in this study were largely consistent with those obtained by Demirel et al. (2023) (55.7-70.1%). Total starch content is a key determinant of both yield and quality of durum wheat. It consists of 65-75 % of the grain dry weight and up to 80 % of the endosperm dry weight and accumulates mostly in grain filling phases. Drought in these crucial periods shortens the duration of these periods resulting with reducing total starch accumulation in grains (Lu et al. 2019). And on the other hand, high temperature conditions reduce the activity of enzymes responsible for starch synthesis in grain filling period (Moayedi et al. 2021).

In addition to quality traits evaluated above, grain/flour color (L*, a*, b*) is the most desirable durum wheat quality trait for use in pasta, semolina, and spaghetti production. The color of semolina and pasta is subject to variation due to the presence of different pigments. The yellow (amber-yellow) pigments (yellowness; b*) are preferable, with brown/grey hues being indicative of low-quality products. The carotenoid is responsible for the yellow pigmentation, and it is instrumental in ensuring the quality attributes of the pasta and semolina that are intended for consumption (Ficco et al. 2014; Saini et al., 2022). The concentration of these yellow pigments is generally located in the outer than inner layers of the grain. During milling processes endosperm is coarsely ground into semolina and results in reductions of these pigments (Cabas-Lühmann et al. 2021).

A comprehensive investigation into these key characteristics revealed that irrigation treatments and varieties exhibited significant impacts, while the year factor was found to be statistically not significant. The genetic factor was found to be effective on the L* brightness parameter, while irrigation applications were found to be non-significant. The effect of interaction was found to be statistically significant on L* and a* characteristics except for b* (Table 4). During the anthesis, significant decreases in all color parameters were observed, particularly in response to supplemental irrigation in this period.

It was evident that elevated values were achieved for all color characteristics during the anthesis with SI was administered. With regard to the variety of the samples, Kiziltan exhibited the highest average L* value, Mirzabey and Imren demonstrated the highest a* value, and Poyraz showed the highest b* value (Figure 4). The L* value ranged between 53.5% and 60.0%, with the highest value being achieved in the first year under SI conditions in the Kiziltan variety, and the lowest value being achieved in the second year under SI conditions in the Mirzabey variety. Kiziltan variety, which exhibited the highest L* value, demonstrated the lowest (6.72%) a* value in SI conditions during 2019/2020 period, while the highest value was attained in the first year in rainfed conditions by the Imren variety (9.84%) (Table 6). The b* value, a key color parameter in terms of quality and health, has been observed to reach its maximum value in the Poyraz variety. This variety is notably found to exhibit superior performance in numerous yield and quality parameters in the study.

The results rheological properties (gluten content and gluten strength)

Gluten value and its quality (strength, extensibility) is just as crucial as pigment and nutritional quality in determining end-use quality. In durum wheat quality, gluten index has potential to predict processing quality (especially in pasta firmness) than protein content alone. High values of gluten index in semolina yields pasta with better firmness, less stickiness and low cooking losses (Wang et al. 2022). Gluten strength is defined as the ability of solids to resist mechanical stress during processing. It has been demonstrated that gluten strength allows proteins to form a regular and continuous network, which in turn promotes good cooking quality (Cecchini et al. 2021).

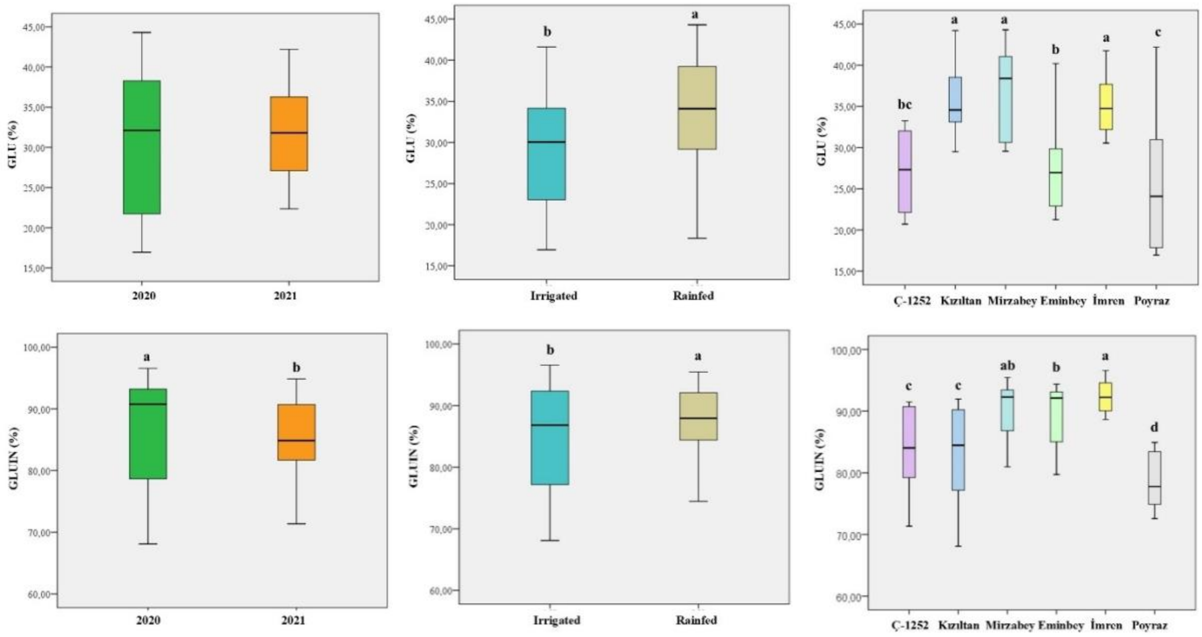

Figure 5. Boxplots of wet gluten content (GLU) and gluten index (GLUIN) traits with standard deviations of durum wheat varieties grown under irrigated and rainfed conditions during the period 2019/2020 and 2020/2021 (For abbreviations see Table 3 and Table 4).

With regard to both characteristics, the study identified values that were classified as weak (low-high gluten content) and high quality (medium-high gluten index) in terms of gluten content (17.1-42.5%) and index (74.1-95.3%) (Table 7). Both rheological characteristics were affected by SI in anthesis with adverse results (Figure 5). Wet gluten content sharply decreased by SI in grain filling period in Aydın province (Erekul et al. 2012). In the study, higher amount of gluten and gluten strength values were obtained in rainfed conditions supported by gluten index was slightly higher in drylands compared to irrigated conditions (Ames et al. 2003). This situation was also explained and synthesized by Si et al. (2023) as explaining excessive precipitation/irrigation reduces protein and gluten; increasing irrigation exerts a dilution effect so wet gluten declines from anthesis to grain filling period. Gluten index resulted with significant improvement in the lately occurred drought conditions.

It is notable for its elevated gluten content and strength; Imren variety came to the forefront with the highest value being recorded in both these parameters. A similar situation has been observed in the Mirzabey variety, which exhibits slightly lower gluten index values than Imren. In contrast to this situation, the Kiziltan variety had high gluten values but low gluten index values in terms of gluten strength. The highest gluten values were obtained in the first year with Kiziltan (41.1%) and Mirzabey varieties under rainfed conditions, while the highest gluten index value (95.3%) was obtained with SI conditions and Imren variety (Table 7).

Table 7. Mean values of wet gluten content (GLU) and gluten index (GLUIN) traits of durum wheat varieties grown under irrigated and rainfed conditions, 2019/2020 and 2020/2021 (For abbreviations see Table 3 and Table 4).

		2020		2021			2020		2021	
		Irrigated	Rainfed	Irrigated	Rainfed		Irrigated	Rainfed	Irrigated	Rainfed
GLU (%)	C-1252	21.3 i	32.1 def	30.5 fg	24.9 hi	GLUIN (%)	90.9 a-d	79.1 h-k	78.3 ijk	86.5 def
	Kiziltan	33.6 c-f	41.1 a	31.9 ef	36.0 b-e		74.1 k	90.8 a-d	79.4 g-k	87.4 c-f
	Mirzabey	35.4 b-e	42.5 a	39.4 ab	30.3 fg		91.6 a-d	93.7 ab	82.3 f-i	92.5 abc
	Eminbey	21.6 i	35.4 b-e	27.5 gh	26.3 gh		92.6 abc	86.9 def	92.9 ab	83.7 fgh
	Imren	32.1 def	36.3 bcd	35.5 b-e	36.7 bc		95.3 a	93.8 ab	90.6 a-d	89.5 b-e
	Poyraz	17.1 j	20.9 ij	24.5 hi	39.0 ab		74.5 k	79.8 g-j	75.3 jk	84.7 efg
LSD I: 3.14; LSD G: 1.87; LSD Y*I*G: 4.22						LSD Y:, 0.54; LSD I: 1.60; LSD G: 2.79; LSD Y*I*G: 5.32				

The results of health-promoted biochemical traits of durum wheat

Pasta has also potential to contribute health benefits with regard to phytochemicals such as phenolic compounds, vitamins, and minerals originating from the raw material used in its preparation. In addition to these compounds, yellow pigments (carotenoids) provide protection from chronic diseases which have provitamin A activity and all of them show antioxidant capacity which reduces risk of degenerative diseases (Ficco et al., 2014;

Zingale et al. 2023). The total phenolic content exhibited a significant difference with the genotype, with the highest values recorded in the Poyraz variety and the lowest in Kiziltan (Figure 4). Conversely, antioxidant activity exhibited a response to both year and irrigation factors. Higher antioxidant activity was observed in the first year of the experiment, while SI resulted in a reduction of mean values. Among the genotypes, Eminbey demonstrated the highest antioxidant activity, whereas Imren and Poyraz exhibited the lowest values (Figure 6).

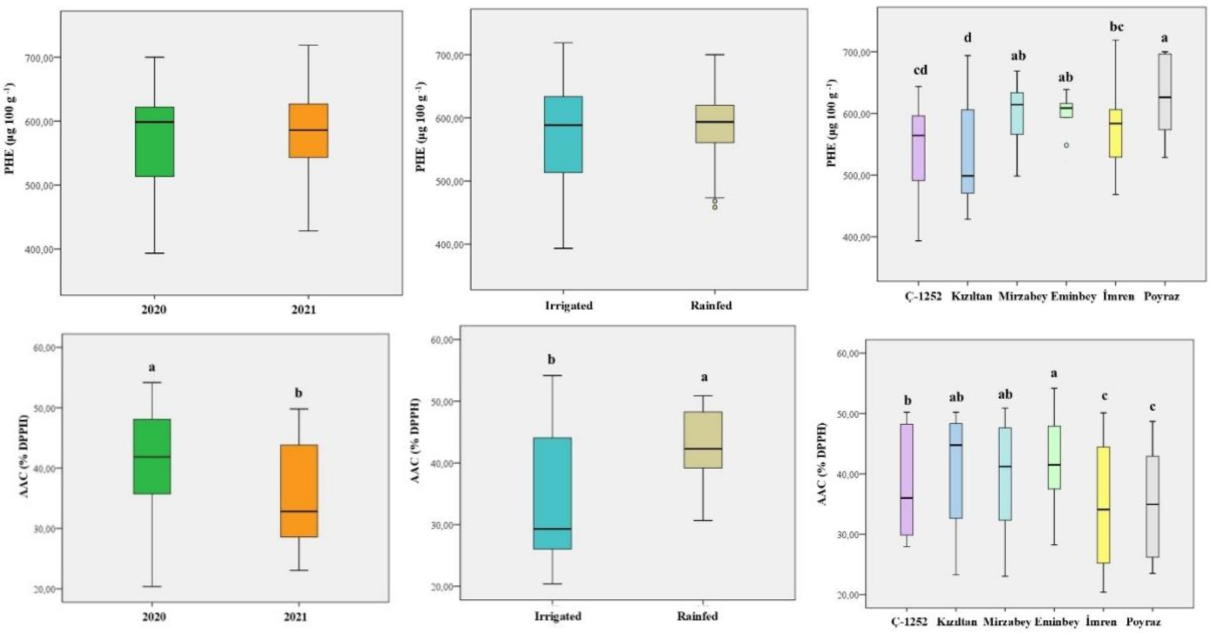

Figure 6. Boxplots of total phenolic content (PHE) and total antioxidant activity (AAC) traits with standard deviations of durum wheat varieties grown under irrigated and rainfed conditions during the period 2019/2020 and 2020/2021 (For abbreviations see Table 3 and Table 4).

In both growing seasons, the total phenolic content of durum wheat varieties under different irrigation practices ranged from 458.5 to 692.1 µg GAE 100 g^{-1}, which was slightly lower than in previous studies (Fu et al. 2017; de Camargo et al. 2021; Garcia-Oliveira et al. 2023). The Poyraz variety was distinguished by its remarkable achievement in attaining the maximum total phenolic content in the 2^{nd} year under SI conditions. However, in terms of total antioxidant activity, both years demonstrated relatively low values (26.2% and 27.3%) under SI conditions (Table 8). With regard to antioxidant activity, the C-1252 and Kiziltan varieties exhibited the highest levels of antioxidant properties under SI conditions during the initial year. De Santis et al. (2021) also reported increased biochemical properties of durum wheat grain, including total antioxidant capacity (TAC) and levels of free phenolic acids, which were most influenced by year/environment, with the highest values recorded in the driest environments or crop seasons. These conditions correspond to those with lower rainfall and higher temperatures during grain filling. The antioxidant activity values obtained in this study were largely slightly higher to those reported in previous study (Mareček et al. 2014).

Table 8. Mean values of total phenolic content (PHE) and total antioxidant activity (AAC) traits of durum wheat varieties grown under irrigated and rainfed conditions, 2019/2020 and 2020/2021 (For abbreviations see Table 3 and Table 4).

		2020		2021			2020		2021	
		Irrigated	Rainfed	Irrigated	Rainfed		Irrigated	Rainfed	Irrigated	Rainfed
PHE (µg 100 g^{-1})	C-1252	458.5 g	621.9 abc	540.7 def	562.0 cde	AAC (% DPPH)	49.1 a	37.1 cd	28.6 ef	38.3 cd
	Kiziltan	613.5 bc	483.6 fg	568.3 cde	475.0 fg		48.6 a	41.9 abc	25.6 ef	44.0 abc
	Mirzabey	595.7 b-e	620.7 bc	530.9 ef	653.4 ab		40.2 bc	47.3 ab	28.5 ef	40.9 bc
	Eminbey	593.5 b-e	600.2 b-e	590.1 b-e	609.0 bcd		47.4 ab	43.9 abc	31.0 de	44.3 abc
	Imren	487.4 fg	590.2 b-e	655.7 ab	571.7 cde		22.4 f	43.5 abc	27.3 ef	46.1 ab
	Poyraz	615.3 bc	642.3 ab	692.1 a	561.9 cde		26.2 ef	42.5 abc	27.3 ef	43.7 abc
LSD G: 36.4; LSD Y*I*G: 70.5						LSD I: 3.29; LSD G: 2.83; LSD Y*I*G: 7.57				

Correlation results of evaluated parameters

A comprehensive correlation analysis of the examined traits was performed to understand the relationships among monitored components presented in Figure 7. Plant height demonstrated no significant correlation with grain yield; however, it exhibited a positive correlation with single ear yield (r = 0.35**) and number of grains per ear (r = 0.25*) related to yield components (Figure 7).

The most significant relationship with grain yield was the negative correlation observed with grain protein content (r = –0.41**) and total antioxidant activity (r = –0.49***). Limited water availability and its unfavorable distribution in the soil can lead to high variability in yield and quality. In addition to this, it is well known that negative relationship between yield and protein has been accepted for a long time (Erekul et al. 2012). Despite the evidence presented in previous studies demonstrating significant variations in the relationship between antioxidant activity and grain yield, it has been observed that higher levels of anti-radical activity are associated with a reduction in yield potential (Ben Mariem et al. 2020; Yigit et al. 2024). This outcome underscores the trade-off between yield and quality, as the enhancement of grain yield was associated with a decline in protein concentration, a fundamental technological quality trait of durum wheat, and antioxidant activity, a parameter of health contribution significance.

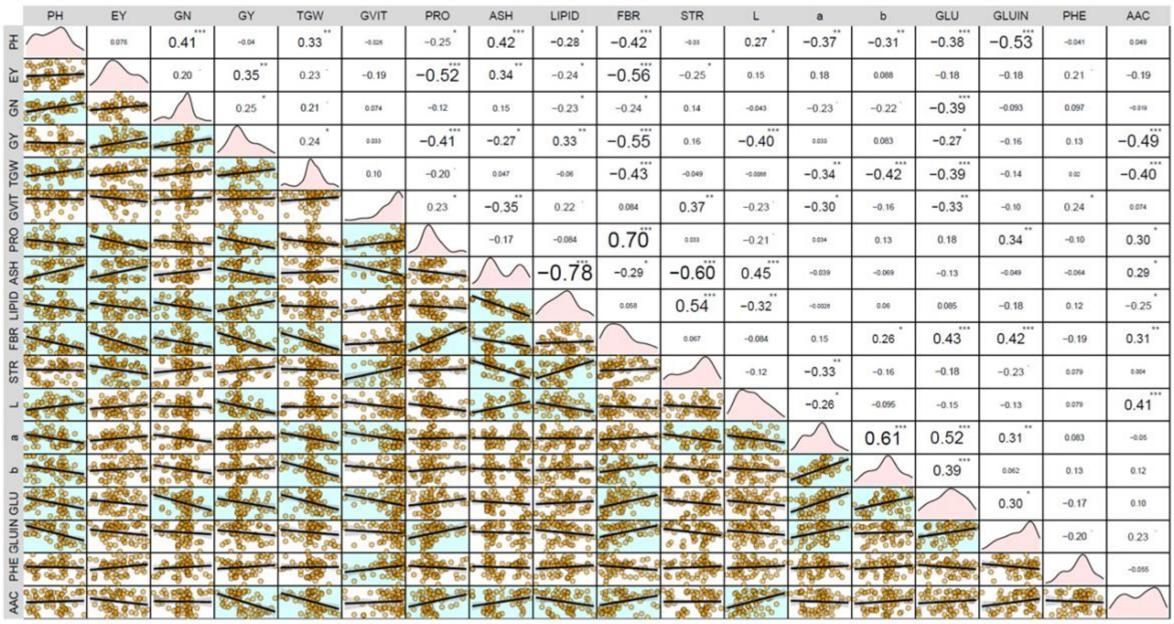

Figure 7. Correlation matrix showing relationships between yield, quality, color and antioxidant properties of durum wheat varieties grown under irrigated and rainfed conditions during the period 2019/2020 and 2020/2021. (PH: Plant height (cm), EY: Ear yield (g), GN: Number of grains per ear, GY: Grain yield (kg ha^{-1}), TGW: Thousand grain weight (g), GVIT: Grain vitreousness (%), PRO: Grain protein ratio (% dm), ASH: Grain ash ratio (% dm), LIP: Grain lipid ratio (% dm), FBR: Grain fiber ratio (% dm), STR: Grain starch ratio (% dm), L*: Brightness color, a*: redness color, b*: yellowness color, GLU: Gluten content (%), GLUIN: Gluten strength (%), PHE: Total phenolic content (µg/100 g GAE equivalent), AAC: Total antioxidant activity (% DPPH radical scavenging))

Grain protein content demonstrated the strongest positive association with fiber content (r = 0.70**), while also exhibiting a significant positive correlation with the gluten index (r = 0.34**). This suggests that protein accumulation contributes to both nutritional value and gluten strength. Furthermore, an association between protein content and total antioxidant activity was observed, underscoring its dual role in enhancing technological and nutritional quality.

The correlation between ash content and lipid content (r = –0.78***), fiber content (r = –0.29*) and starch content (r = –0.60***) was found to be negative, indicating a dilution effect of nutrient accumulation on other compositional traits. From a nutritional perspective, a noteworthy positive relationship was detected between fiber content and total antioxidant activity (r = 0.31**), suggesting that fiber-rich genotypes may provide enhanced health-related benefits (Figure 5). This situation was supported by Esposito et al. (2005), who explained that antioxidant activity was higher in the internal bran fractions, and all bran fractions had marked antioxidant activity.

In consideration of the parameters associated with grain color, the b* parameter (yellowness), a critical determinant of semolina and pasta quality, exhibited a negative correlation with thousand-kernel weight (r = –0.42**). This finding suggests that increasing grain weight is associated with reduced yellowness. A robust positive correlation was identified between gluten content and gluten index (r = 0.30*), suggesting that elevated gluten levels are associated with enhanced gluten strength and solubility (Figure 7). These characteristics are considered crucial for optimal processing quality in durum wheat.

4. CONCLUSION

The present study demonstrated that changes in precipitation patterns (decline spring rainfall), intensified by climate change, critically affect bread wheat production in the Aegean region. For this reason, searching for stability of wheat production in the face of climate change with more tolerance to adverse environmental conditions of durum wheat was evaluated in a detailed screening of yield and quality traits.

The implementation of supplemental irrigation during the anthesis stage resulted in a notable enhancement in grain yield and its components, particularly observed in the high-performing Poyraz variety. However, this practice was found to be associated with a decline in specific technological quality traits and antioxidant capacity. Conversely, rainfed conditions were found to have a favorable impact on the biochemical properties of the grain, especially antioxidant and protein-related parameters.

The findings of this study underscore the trade-offs between yield and grain quality under varying water regimes, thereby emphasizing the necessity of identifying yield–antioxidant and protein–antioxidant relationships, which have limited previous studies. Consequently, the strategy of supplemental irrigation during anthesis is a viable option for ensuring high yields of pasta-quality durum wheat in the region. However, it is essential to carefully consider its impact on the nutritional and technological quality of wheat.

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