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Evaluation of Flour Quality Attributes and Bran Functional Properties in Wheat Varieties: Effects of Genotype, Growing Conditions, and Year

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Abstract

In the study, the effects of genotype (G), growing conditions (C), and year (Y) on the polyphenol and total dietary fiber (TDF) content of wheat bran, as well as on the bread-making quality of flours obtained from the corresponding wheat samples, were investigated. For this purpose, eight bread wheat brans obtained from different red and white wheat genotypes were characterized for their total polyphenol content, ABTS and DPPH free radical based scavenging activity and TDF content for two succeeding harvesting years. The grain and flours of the same varieties were also characterized for their physical, chemical and rheological properties. The study assessed the relative contributions of G, C, Y, and the interactions (G×C and G×Y) to the properties of wheat bran and flour, along with the correlations among these properties. Results indicated that the irrigated and rainfed conditions significantly influenced protein content (PC) and TDF in wheat bran. While both red and white wheat brans generally exhibited higher PC and TDF content under irrigated conditions, red wheat bran (RWB) was found to have a higher TDF content than white wheat bran (WWB) under the same conditions. Significant differences were also observed in several flour quality parameters under the tested conditions. Overall, this study emphasizes the importance of using diverse genotypes and varying growing conditions in breeding programs aimed at improving the functional and quality properties wheat.

Buğday Çeşitlerinde Unun Kalite Özellikleri ve Kepeğin Fonksiyonel Özelliklerinin Değerlendirilmesi: Genotip, Yetiştirme Koşulları ve Yıl Etkileri

Özet

Çalışmada, genotip (G), yetiştirme koşulları (C) ve yılın (Y), buğday kepeklerinin polifenol ve toplam diyet lifi (TDF) içeriği ile aynı buğday örneklerine ait unların ekmek yapım kalitesi üzerindeki etkileri araştırılmıştır. Bu amaçla, farklı kırmızı ve beyaz buğday genotiplerinden elde edilen sekiz ekmeklik buğday kepeği, iki ardışık hasat yılı için toplam polifenol içeriği, ABTS ve DPPH serbest radikal süpürme aktivitesi ile TDF içeriği bakımından karakterize edilmiştir. Aynı çeşitlerin tane ve unları da fiziksel, kimyasal ve reolojik özellikleri açısından incelenmiştir. Bu çalışma, G, C, Y ve etkileşimlerinin (G×C ve G×Y) buğday kepeği ve unu özelliklerine göreceli katkıları ile bu özellikler arasındaki korelasyonları da değerlendirilmiştir. Sonuçlar, sulu ve kuru koşulların, buğday kepeğinde protein içeriği (PC) ve TDF üzerinde önemli etkilerinin olduğunu göstermiştir. Kırmızı ve beyaz buğday kepeklerinin her ikisinin de sulu koşullar altında genellikle daha yüksek PC ve TDF içeriğine sahip olduğu belirlenirken, kırmızı buğday kepeğinin (RWB) aynı koşullarda, TDF açısından beyaz buğday kepeğinden (WWB) daha yüksek içeriğe sahip olduğu tespit edilmiştir. Test edilen koşullar altında un kalitesi parametrelerinde de önemli farklılıklar gözlenmiştir. Bu çalışmada, buğdayın fonksiyonel ve kalite özelliklerinin iyileştirilmesine yönelik, ıslah programlarında çeşitli genotiplerin ve farklı yetiştirme koşullarının kullanılmasının önemi vurgulanmaktadır.

1. Introduction

Wheat is one of the most widely consumed (Chalamacharla et al., 2018) and nutritionally valuable cereal crops worldwide (Chalamacharla et al., 2018; Manisseri & Gudipati, 2010; Stevenson et al., 2012). The wheat kernel is composed of approximately 80–85% endosperm, 13–17% bran, and 2–3% germ (Boukid et al., 2018; Chalamacharla et al., 2018).

Wheat bran, a by-product of the milling process, is derived from the outer layers of the grain and is utilized in both food and non-food applications (Apprich et al., 2014). It primarily consists of the pericarp, testa, hyaline, and aleurone layers (Stevenson et al., 2012). Wheat bran, is rich in B vitamins, minerals such as iron, manganese, zinc, magnesium and phosphorus (Chalamacharla et al., 2018), dietary fiber, and bioactive compounds (Preuckler et al., 2014).

Growing consumer awareness and demand for healthy and functional foods have sparked using natural resources over time. In particular, the wheat aleurone layer is known to contain high levels of antioxidants, phenolic acids, and lignans, which contribute to the prevention of various chronic diseases and enhance additional values to wheat brans (Chalamacharla et al., 2018). Cultivation conditions, wheat variety and extraction method affect the composition of wheat bran. Besides these factors, the methods used for the separation of bran play a role in determining the content of bran by defining the amount of attached starch to the aleurone layer after the separation (Anson et al., 2012; Chalamacharla et al., 2018).

Among bioactive compounds, phenolic acids represent the most abundant and diverse group in wheat bran, with ferulic acid (FA) being the predominant form (Anson et al., 2012). Antioxidant activity and total phenolics are highly correlated. Phenolic compounds have antioxidant properties and support human health by protecting the body against oxidation (Gutteridge and Halliwell, 1994; Alu'Datt et al., 2012). A diet with high content of natural antioxidants can significantly increase the reactive antioxidant potential of the organism and thus substantially reduce the risk of some illnesses caused by free radicals (Sikora et al., 2008). Cereal brans are also an important source of dietary fiber (Patel, 2015) that mainly consist of b-1,3, b-1,4-glucan, arabinogalactan peptide, fructan, cellulose, arabinoxylans, resistant starch and lignin (Escarnot et al., 2015). According to the Food and Agriculture Organization of the United Nations (FAO) and the World Health Organization (WHO), an adequate daily intake of dietary fiber, at least 25 grams, is essential for maintaining good health (Guiné et al., 2016). Dietary fiber intake has been associated with reduced risks of colon disease (Gill et al., 2021), improved management of irritable bowel syndrome (Fardet et al., 2010; El-Salhy et al., 2017), lower glycemic response, and reduced risk of type II diabetes (De Santis et al., 2018).

Wheat can be cultivated across a broad range of climatic conditions (Zubair et al., 2021) and its quality characteristics are influenced by environmental factors, genotypic variation, and their interactions (Hossain et al., 2013). In Turkey and many parts of the world, wheat is predominantly grown under rainfed conditions, with irrigation used only occasionally. So, the results obtained from existing genotypes cultivated in both irrigated and rainfed conditions by agronomists and wheat breeders are used to determine the specific requirements of genotypes (Farshadfar, 2012; Aktas, 2017). Despite the growing interest in the use of wheat bran, limited research has addressed the influence of irrigated and rainfed conditions on its functional properties. The current screening study addresses this gap by evaluating the effects of these growing conditions on the functional properties of bran, including TDF, PC, and antioxidant activity, from a diverse set of red and white wheat genotypes grown over two subsequent harvesting seasons. The results of this study also elucidate the relative influences of G, Y, and their interactions (G×C and G×Y) to the characteristics of wheat bran and flour, as well as the correlations among these traits.

2. Materials and Methods

This trial included four red-grained (Konya 2002, Ekiz, Taner, Sönmez-2001) and four white-grained (Tosunbey, Şehzade, Müfitbey, Bayraktar-2000) registered commercial bread wheat varieties, cultivated under both rainfed and irrigated conditions at the Bahri Dağdaş International Agricultural Research Institute during the 2018-2019 and 2019-2020 growing periods. Analyses of kernels, refined flours and brans of these varieties were conducted as a part of a project funded by General Directorate of Agricultural Research and Policy (TAGEM), Turkey (Project no: TAGEM/HSGYAD/Ü/20/A3/P1/1765). Reagents used in the study included 2,2′-azino-bis-3-ethylbenzthiazoline-6-sulphonic acid (ABTS), 6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid (Trolox), 2,2-Difenil-1-pikrilhidrazil (DPPH), FA, all obtained from Sigma-Aldrich (St. Louis, MO, USA). Folin-Ciocalteu was purchased from Merck (Darmstadt, Germany). Megazyme Total Dietary Fiber Assay kit, Celite® 545 was obtained from Megazyme (Wicklow, Ireland). All the other chemicals were reagent grade.

2.1 Growing conditions

The 2018–2019 growing season experienced cooler and wetter conditions, with an average temperature of 10.6°C and total precipitation of 380.8 mm (between October-July). In contrast, the 2019–2020 season was warmer, with an average growing season temperature of 11.2°C and total precipitation of 305.8 mm (between October-July). Table 1 presents monthly average temperature and precipitation data of the field. Under rainfed conditions, fertilization rates were 7 kg/da of P_2O_5 and 7.5 kg/da of nitrogen. Under irrigated conditions, fertilization rates were increased to 9 kg/da of P_2O_5 and 12 kg/da of nitrogen, along with the application of totally 180 mm of irrigation water. Wheat grains were sampled on 30 July, 2019 and 27 July, 2020.

Table 1. Monthly precipitation and mean temperature throughout growing seasons

		Month									
Year	**Parameter**	**10**	**11**	**12**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
2018-19	**Precipitation (mm)**	41.6	27.4	63.4	66.6	31.6	20.8	32	10.2	45.6	41.6
	Temperature (ºC)	13.39	7.35	2.96	0.48	4.1	6.35	9.56	17.77	20.94	23.01
2019-20	**Precipitation (mm)**	13	45.8	112.4	36	29	6.4	3.4	23.4	35.8	0.6
	Temperature (ºC)	16.32	7.91	2.87	0.36	4.35	6.47	12.05	16.15	20.25	25.51

2.2 Preparation of brans and color measurement

Brans were obtained by tempering wheat samples for 12 h to 14.5 % moisture content (AACC 26-95) and milling to 82 mesh powder with Brabender Quadrumat Junnior (model 880101, Brabender Ohg Duisburg, Germany) according to the AACC 26-50 method (AACC, 2000). By using the Hunter Lab Color device (MiniScan XE Plus, Model 45/0-L, USA), the color of the brans were determined in terms of L (for lightness), a (for redness), and b (for yellowness) values. All analyses were performed on samples derived from eight bread wheat genotypes, each grown under both rainfed and irrigated conditions, resulting in a total of 16 trial materials for a year.

2.3 Antioxidant activity of brans

To prepare the bran extract used in the analysis, 2 g of bran sample was mixed with 20 mL of 70% ethanol (v/v) and shaken for 15 hours at room temperature using an Orbital Shaker (model OS-20, Germany). The mixture was then filtered through Whatman No. 1 filter paper, following the method described by Abozed et al. (2014).

2.3.1 DPPH˙ scavenging activity

Antioxidant activity using DPPH was carried out according to Brand-Williams et al. (1995) method with slight modifications. 0.4 mL of extracts were mixed with 4 mL of DPPH solution prepared in $6x10^{-5}$ mol L^{-1} methanol. After keeping the mixtures in the dark for 30 minutes at ambient conditions, they were centrifuged at 6000 rpm for 5 minutes. Absorbance measurements of the samples were performed using a spectrophotometer at 515 nm. (Shimadzu, Model UV-1601, Japan)**.** The results were expressed as the IC_{50}, representing the concentration of extracts and standard required to scavenge 50% of DPPH radicals in the reaction mixture, using FA as a standard material (IC_{50} FA: 0.00784 mg/ml). The tests were carried out in duplicate for two replicates.

2.3.2 ABTS$^{\cdot+}$ scavenging activity

The Trolox equivalent antioxidant capacity (TEAC) of bran extracts was measured spectrophotometrically according to the method described by Re et al. (1995). The ABTS radical cation (ABTS$^{\cdot+}$) was generated by preparing 7 mM ABTS solution containing 2.45 mM potassium persulfate and keeping in the dark for 16 hours. The absorbance of the prepared ABTS$^{\cdot+}$ solution was set to 0.700 with ethanol at 734 nm. 25 µL of extracts samples were reacted with 2 mL ABTS radical solution and their absorbances were measured at 734 nm after 10 minute. Trolox equivalence of the samples was computed by using the standard curve prepared with Trolox as a reference standart. The measurements were conducted in duplicate for two replications.

2.4 Total phenolic content of brans

The total phenolic content (TPC) in bran extracts was measured spectrophotometrically (Shimadzu, Model UV-1601, Japan) according to the method of Singleton and Rossi (1965) by using Folin-Ciocalteu as reactive reagent and expressed as gallic acid (GA) equivalents. Each sample was analyzed in duplicate for two replications.

2.5 Total dietary fiber contents of brans

For the determination of the TDF content, bran samples were analyzed according to the product manual of the Megazyme Total Dietary Fiber Assay Kit that based upon the methods AOAC 985.29 (AOAC, 1986) and AACC 32-05.01 (AACC, 2000).

2.6 Protein content of brans

PC of the bran samples was determined using a nitrogen analyzer LECO FP 528 (Leco Inc, St Joseph, MI), following the AOAC Official Method 992.23 (AOAC, 2000).

2.7 Kernel and refined flour analyses

Thousand-kernel weight (TKW) and test weight (TW) of grain samples were measured according to Williams et al. (1988) and AACC International official method 55-10. Zeleny sedimentation (ZS) test, PC and wet gluten (WG) of milled refined flour were determined with ICC-116, AOAC 992.23, and AACC 38-12A methods, respectively. To measure PC and WG, Leco FP 528 analyzer (Leco Inc, St Joseph, MI) and Glutomatic (Bastak, Ankara, Turkey) were used, respectively.

Water absorption capacity (WAC), dough development time (DDT) of the flour samples were determined according to the method AACC 54-21 using Farinograph-AT (model 810151.001, Brabender, Duisburg, Germany). Alveograph characteristics (energy value (W), configuration ratio (P/L), elasticity index (Ie)) of wheat flour were assessed using a Chopin Alveograph (Model Alveo PC, Chopin, France) in accordance with AACC method 54-30A.

Mixograph analysis was performed using a mixograph device (National Mfg.Co. Lincoln. NE, USA) based on AACC 54-40A method (AACC, 2000). Mixograph peak width at the end of analysis (PW), peak area (Tint), and total area of the mixograph curve (TTint) parameters were evaluated at the end of analysis.

Energy (E_{135}), resistance (R_{135}), and extensibility (Ext_{135}) values of dough were detected with an extensograph device (Ekstensograf E, Brabender Germany) at 135 minute according to ICC Standard Method No: 114/1 (ICC, 2008).

2.8 Statistical analysis

The obtained data were evaluated by variance analysis using the JMP11 (2014) statistical program (SAS Institute, ISBN:978-1-62959-560-3), and significant differences ($p< 0.01$) were determined using the Student's t-test.

3 . Results and Discussion

3.1 Genotype effects

The data presented in Table 2 reveal that G significantly affected TPC, PC and TDF levels in WWB. Additionally, significant differences were observed in L and b color parameters ($p < 0.01$). In RWB, G had a notable effect on TPC, TEAC, TDF ($p<0.05$), as well as on the b value ($p < 0.01$). Figures 1a and 1b indicate that WWB exhibited higher PC compared to RWB. The PC values, ranging from 16.07% to 20.34%, align with findings reported by Hossain et al. (2013) and Sharanappa et al. (2016), which underscore the significant role of genetic factors ($p < 0.01$). The influence of G on TPC and TDF was significant for both bran types ($p < 0.05$), with TPC values ranging from 1417 to 1785 mg GA/kg bran dm, as illustrated in Figures 1c and 1d. These data are in line with the observations of Vaher et al. (2010) and López-Perea et al. (2019), who reported that phenolic compounds are predominantly located in the germ and bran layers and are often esterified to arabinoxylan side chains. Genotypic differences have been shown to affect the accumulation of phenolic acids, resulting in compositional variation among cultivars within the same wheat species (López-Perea et al., 2019, Akram et al., 2025). The TDF content also varied significantly across genotypes, with values ranging from 34.08% to 50.98% (Figures 2a and 2b), which is in agreement with previous reports (Curti et al., 2013; Saini et al., 2023). Multisite tests further confirmed the high heritability of arabinoxylan fiber content, as noted by De Santis et al. (2018). In terms of bran color, significant genotypic effects were observed for L and b values in WWB and the b value in RWB. These variations may influence the final product color and are potentially linked to caramelization and Maillard reactions during processing.

Various analytical methods are employed to assess wheat quality. It is important to note that the quality parameters obtained from these analyses reflect the genetic potential of the genotype and serve as reliable predictors of the final product quality. Table 3 summarizes the mean values of quality traits related to kernel, flour, and dough for both red and white wheat varieties, along with LSD and CV% values. Most traits showed significant genotypic differences, except for R_{135} in white wheat flour (WWF) and for PC and WG in red wheat flour (RWF), as noted in Table 4.

Dough rheological properties were evaluated using several instruments, including the Farinograph, Alveograph, Mixograph, and Extensograph. The Farinograph assessed WAC, DDT, and dough stability, all of which are influenced by gluten strength. In this study, WAC values ranged from 51.2% to 65.3%, while DDT values varied from 4.2 to 14.14 minutes. These variations reflect differences in gluten quality and flour strength among genotypes. The Alveograph, which measures the resistance of dough to extension (swelling), was used to evaluate the W value, a key indicator of bread-making quality, along with the Ie value and the P/L ratio. The W value, a critical indicator of bread-making quality, ranged from 97 to 250 × 10^{-4} J. Corresponding Ie and P/L values ranged from 40.5% to 66% and 0.42 to 1.76, respectively, with all parameters showing significant genotypic variation. By using the Extensograph to measure the balance between the viscous and elastic properties of dough, E_{135}, R_{135}, Ext_{135} were determined to be 24–129 cm^2, 82-266 BU, and 164-253 mm, respectively. Higher dough resistance to kneading was also reflected in the mixograph values: PW, Tint, and total TTint ranged from 4.2–12.8%, 81–146 (% tork*min) and 263-390 (% tork*min) respectively. Zečević et al., (2011) also reported that the rheological properties of flour were influenced by cultivars, environment, and years. Additional kernel and flour quality traits, including TKW, TW, PC, ZS, and WG values, were found within the ranges of 33.9-44.16 g, 74.17-79.8 kg/100 lt, 13.0-14.38 %, 26.00-53.75 ml and 25.70-2.68%, respectively. Analysis of Tables 2 and 4 indicates that genotypes with higher PC and ZS values generally also exhibited higher values for PW, Tint, TTint, W, and WAC, traits associated with stronger and higher quality flours.

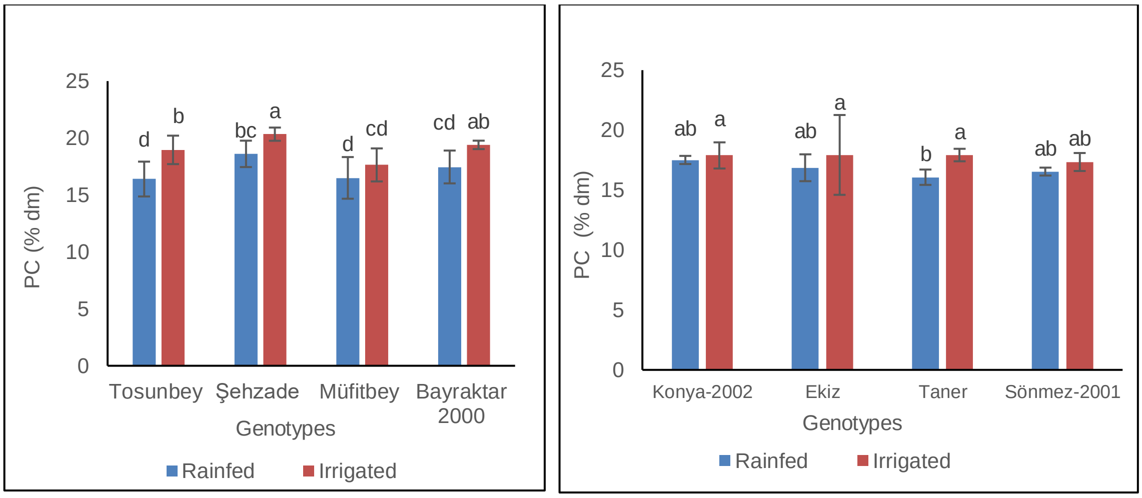
Table 2. Effects of G, C, Y and their interactions (G×C, G×Y) on selected wheat bran properties in eight bread wheat varieties grown under rainfed and irrigated conditions over two succeeding years

	White Wheat Bran				
	G	**C**	**Y**	**GxC**	**GxY**
PC	25.88**	27.23**	9.40**	2.04	9.39*
TPC	257366*	1384	474909**	36347	32101
IC_{50}	0.46	1.66	48.09*	1.49	3.49

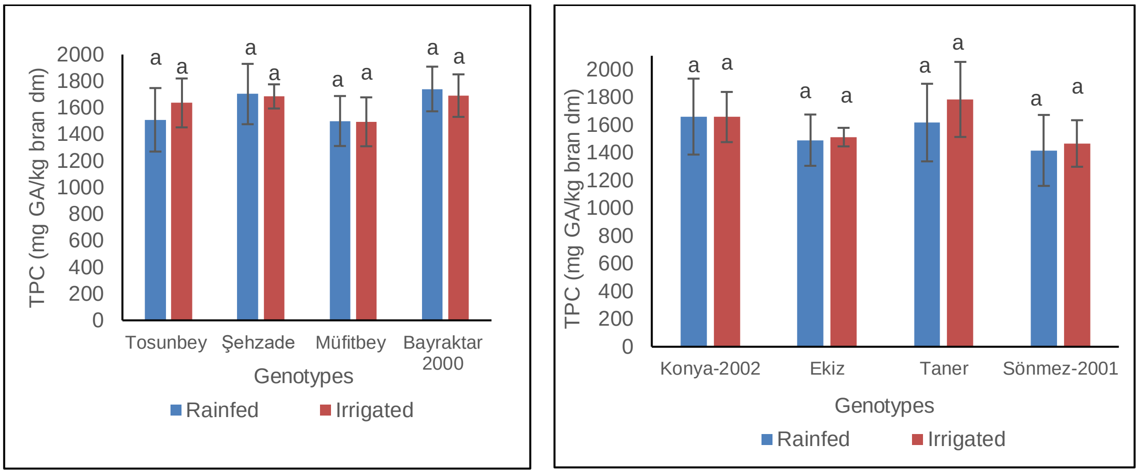
TEAC	19.56	0.14	0.29	10.45	10.32
TDF	323.8*	108.69*	40.46	118.41	32.84
L	744.22**	2.37	6.88*	1.69	11.03*
a	333.47	82.14	43.92	283.64	268.17
b	21.74**	0.62*	7.39	1.17*	17.67**

	Red Wheat Bran				
	G	**C**	**Y**	**GxC**	**GxY**
PC	3.10	8.40**	17.81**	2.29	11.82**
TPC	369498*	27556	545290**	33879	55556
IC_{50}	8.83	5.47	47.29**	1.53	3.1
TEAC	49.01*	0.45	39.5**	34.93*	26.28
TDF	253.78*	469.33**	0.16	75.34	160.15
L	2.71	2.74	0.56	1.51	2.22
a	0.59	0.14	10.01	0.02	0.12**
b	2.91**	0.11	31.76**	0.13	0.05

G: Genotype, C: Condition, Y: Year, GxC: Interaction of genotype and condition, GxY: Interaction of genotype and year, PC: Protein content, TPC: Total phenolic content, IC_{50}: The concentration of bran extracts to quench 50% of DPPH radicals in the reaction mixture, TEAC: Trolox equivalent antioxidant capacity, TDF: Total dietary fiber, L: Lightness, a: Redness, b: Yellowness, CV: Coefficient of variation, LSD: Least significant differences, *: Significance at the level of 0.05, **: Significance at the level of 0.01

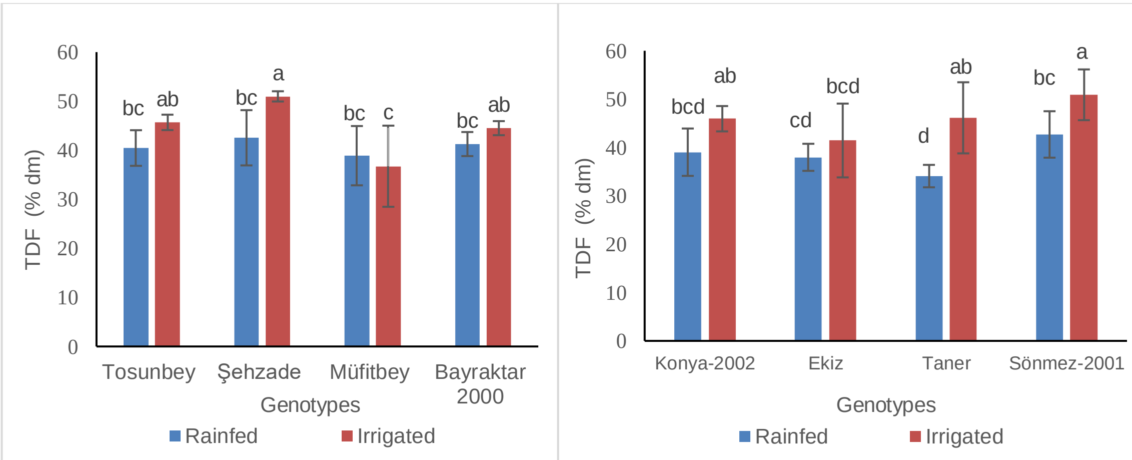


(a) **(b)**



(c) (d)

Figure 1. PC and TPC of white (a, c) and red (b, d) wheat brans grown under rainfed and irrigated conditions for 2 succeeding years.



(a) (b)

Figure 2. TDF content of white (a) and red (b) wheat brans grown under rainfed and irrigated conditions over 2 succeeding years

3.2 Effects of growing condition (C), year (Y), and their interaction with genotype (GxC, GxY)

As presented in Table 2, significant effects of C were observed for PC ($p < 0.01$) and TDF ($p < 0.01$ for RWB, $p < 0.05$ for WWB). These effects are attributable to factors such as nitrogen application rates, total precipitation, and the timing of rainfall, which have been reported to influence the amount of bioactive compounds (De Santis et al., 2021). Massoudifar et al. (2013) reported that nitrogen availability significantly enhances grain yield, protein content, and quality. Tiwari and Cummins (2009) also noted that nitrogen fertilization positively influences β-glucan content in cereals. As shown in Figures 1a and 1b, PC values were consistently higher under irrigation across both wheat types, with WWB maintaining a higher PC than RWB under both conditions. In contrast, no significant effects of C were observed for antioxidant characteristics (Figure 3). TEAC values ranged from 8.11 µmol Trolox/g bran dm to 13.75 µmol Trolox/g bran dm (Figure 3a, Figure 3b), and IC_{50} values varied between 5.50 to 8.00 mg bran dm/ml for the bran (Figure 3c, Figure 3d).

Significant condition effects were also observed in flour-related traits. For WWF, traits such as TW, ZS, Ie, WAC, E_{135}, Ext_{135} were significantly influenced. For RWF, TW, PW, WAC, E_{135}, R_{135} were notably affected (Table 4). In most cases, values under irrigation were higher, except for ZS in WWF and PW in RWF. This suggests that irrigation combined with fertilization improves flour quality, consistent with Massoudifar et al. (2013). The findings of Yang et al. (2023) indicate that supplemental irrigation under a ridge–furrow system improved wheat quality while maintaining high grain yields. The G×C interaction had a smaller effect on flour quality traits compared to the alone effects of G, C, or Y. However, the G×Y interaction had a more substantial impact on WWF traits and less on RWF traits.

The crop year significantly affected PC, TPC, antioxidant capacity, and b color values for RWB ($p < 0.01$). For WWB, significant year-to-year variation was observed in PC, TPC ($p < 0.01$), IC_{50}, and L color values ($p < 0.05$) (Table 2). These differences are attributed to climatic variations between years, particularly the first year, which experienced higher precipitation (380.8 mm) and lower average temperature (10.6°C).

Table 3. Average values of selected quality characteristics of white and red wheat grown under rainfed and irrigated conditions over two succeeding years

	White Wheat Genotype										
	Rainfed				Irrigated						
Quality Parameters	**Tosunbey**	**Şehzade**	**Müfitbey**	**Bayraktar-2000**	**Tosunbey**	**Şehzade**	**Müfitbey**	**Bayraktar-2000**	**Mean value**	**CV (%)**	**LSD**
					Grain Traits						
TKW (g)	33.9	40.6	33.9	37.5	35.1	39.8	35.5	38.2	36.81	2.35	3.00
TW (kg/100 lt)	75.9	78.2	75.8	77	77.3	79.8	76.5	76.7	77.15	1.90	1.16
					Flour Traits						
PC (%)	14.04	13.71	14.38	13.0	14.09	13.84	14.18	13.0	13.78	0.95	3.24
ZS (ml)	48.8	44.5	47.0	29.8	44.5	47.8	40.0	26.0	40.55	5.71	6.53
WG (%)	32.4	31.1	39.0	25.7	33.3	34.0	33.9	27.7	32.13	11.27	16.34
					Dough Traits						
Mixograph Parameters											
PW (%)	9.3	4.2	10.6	9.2	11.8	5.0	12.8	8.0	8.86	4.54	24.00
Tint (%tork*min.)	138	95	146	115	135	94	126	97	118.25	42.71	16.94
TTint (%tork*min.)	343	311	373	276	349	298	338	263	343	60.35	8.87
Alveograph Parameters											
W (10^{-4} J)	228	163	241	97	239	168	233	106	228	60.58	15.43
P/L	0.70	0.79	1.53	0.47	1.11	0.69	1.76	0.42	0.93	0.62	31.30
Ie (%)	60	52	57	56	66	61	56	54	60	6.82	5.54
Farinograph Parameters											
DDT (min.)	14.14	5.23	10.40	6.70	9.13	6.55	5.12	9.21	8.31	7.24	40.91
WAC (%)	59.6	54.8	62.3	51.2	61.5	56.1	64.5	52.4	57.8	3.38	2.75
Extensograph Parameters											
E_{135} (cm^2)	92	79	47	79	129	99	84	106	89.37	42.28	22.16
R_{135} (BU)	220	217	149	247	266	238	205	250	194.25	111.83	23.43
Ext_{135} (mm)	203	183	191	185	227	201	189	195	196.75	32.39	7.72

	Red Wheat Genotype										
	Rainfed				Irrigated						
Quality Parameters	**Konya 2002**	**Ekiz**	**Taner**	**Sönmez 2001**	**Konya 2002**	**Ekiz**	**Taner**	**Sönmez 2001**	**Mean value**	**CV (%)**	**LSD**
					Grain Traits						
TKW(g)	40.33	34.01	39.15	37.35	44.16	34.33	37.30	38.31	38.11	3.31	4.08
TW (kg/100 lt)	77.21	76.46	77.30	74.17	78.21	76.77	78.51	78.76	77.13	1.11	0.67
					Flour Traits						
PC (%)	13.76	13.17	14.01	13.60	13.71	13.74	13.81	13.35	13.64	0.85	2.93
ZS (ml)	53.75	44.00	50.25	44.00	52.25	47.00	49.75	38.25	47.40	5.95	5.89
WG (%)	36.93	36.58	35.65	38.13	41.30	41.85	37.23	42.68	38.79	12.83	15.52
					Dough Traits						

Mixograph Parameters											
PW (%)	9.55	5.13	8.26	5.25	6.49	5.0	7.23	5.37	6.53	2.61	18.72
Tint (%tork*min.	123	88	121	83	121	98	124	81	105	17.83	7.98
TTint (%tork*min.)	370	334	376	361	390	349	371	356	363	38.08	4.91
Alveograph Parameters											
W (10^{-4} J)	201	124	250	117	179	144	225	131	179	65.25	17.87
P/L	1.46	0.78	1.49	0.75	1.62	0.82	0.98	0.80	1.09	0.67	29.07
Ie (%)	45.8	42.2	50.1	45.9	47.3	46.6	58.9	40.5	47.2	16.11	15.70
Farinograph Parameters											
DDT (min.)	4.5	5.0	5.7	4.6	4.2	5.9	7.8	4.2	5.2	2.88	25.95
WAC (%)	63.7	61.5	58.6	61.3	65.3	62.6	62.7	62.8	62.3	2.96	2.24
Extensograph Parameters											
E_{135} (cm^2)	24	29	113	35	48	58	128	39	59	31.78	25.10
R_{135} (BU)	89	94	218	82	117	156	246	96	137	68.51	23.42
Ext $_{135}$ (mm)	167	194	229	242	217	164	237	253	213	68.44	15.09

TKW: Thousand kernel weight, TW: Test weight, PC: Protein content, ZS: Zeleny sedimentation value, WG: Wet gluten, PW: Mixograph peak width at the end of analysis, Tint: Mixograph peak area, TTint: Total area of mixograph curve, W: Alveograph dough energy, P/L: Alveograph tenacity/extensibility (curve configuration) ratio, Ie: Alveograph elasticity index, DDT: Farinograph dough development time, WAC: Farinograph water absorption capacity, E_{135}: Extensograph energy value at 135 min., R_{135}: Extensograph resistance value at 135 min., Ext_{135}: Extensograph extensibility value at 135 min., CV: Coefficient of variation, LSD: Least significant difference.

Under these conditions (2018-2019), the PC, TPC, IC_{50}, and L value of the WWB were higher. Also, for the RWB, higher PC, TPC, TEAC, and IC_{50} values, along with a lower b value, were observed in the first year, which experienced higher rainfall and lower temperatures. However, the TDF content was not significantly influenced by Y factor in either wheat type. Many factors influence changes in the content and composition of bioactive compounds (De Santis et al., 2021). The findings are consistent with those of Heimler et al. (2010), who reported significant differences in TPC, flavonoid content, and antioxidant capacity between two years across soft modern, old wheat, and durum wheat varieties. It has been shown that a low amount of rainfall and high temperatures in the 30 days preceding harvest lead to a reduced amount of flavonoids and decreased antiradical capacity.

The crop year also significantly affected physical and rheological parameters in both WWF and RWF. Notable effects were observed for TKW, TW, PC, WG, PW, Tint, W, and WAC in WWF; and for TKW, TW, PC, WG, PW, Tint, TTint, P/L, DDT, WAC, and R_{135} in RWF (Table 4). Rainfall amount and distribution are important under rainfed field conditions, while irrigation combined with nitrogen fertilization in the study contributed to improvements in physical grain quality and flour performance. Nonetheless, excessive nitrogen under water-limited conditions negatively impacted grain quality, highlighting the importance of balanced nutrient and water management (De Santis et al., 2021). Overall, in this study, G, C, and Y exerted stronger effects on bran characteristics than G×C, G×Y interactions. In the study conducted by Kowalska et al. (2025), it was shown that winter wheat cultivars exhibited significant differences in bioactive compounds depending on the cultivars, farming systems, and years.

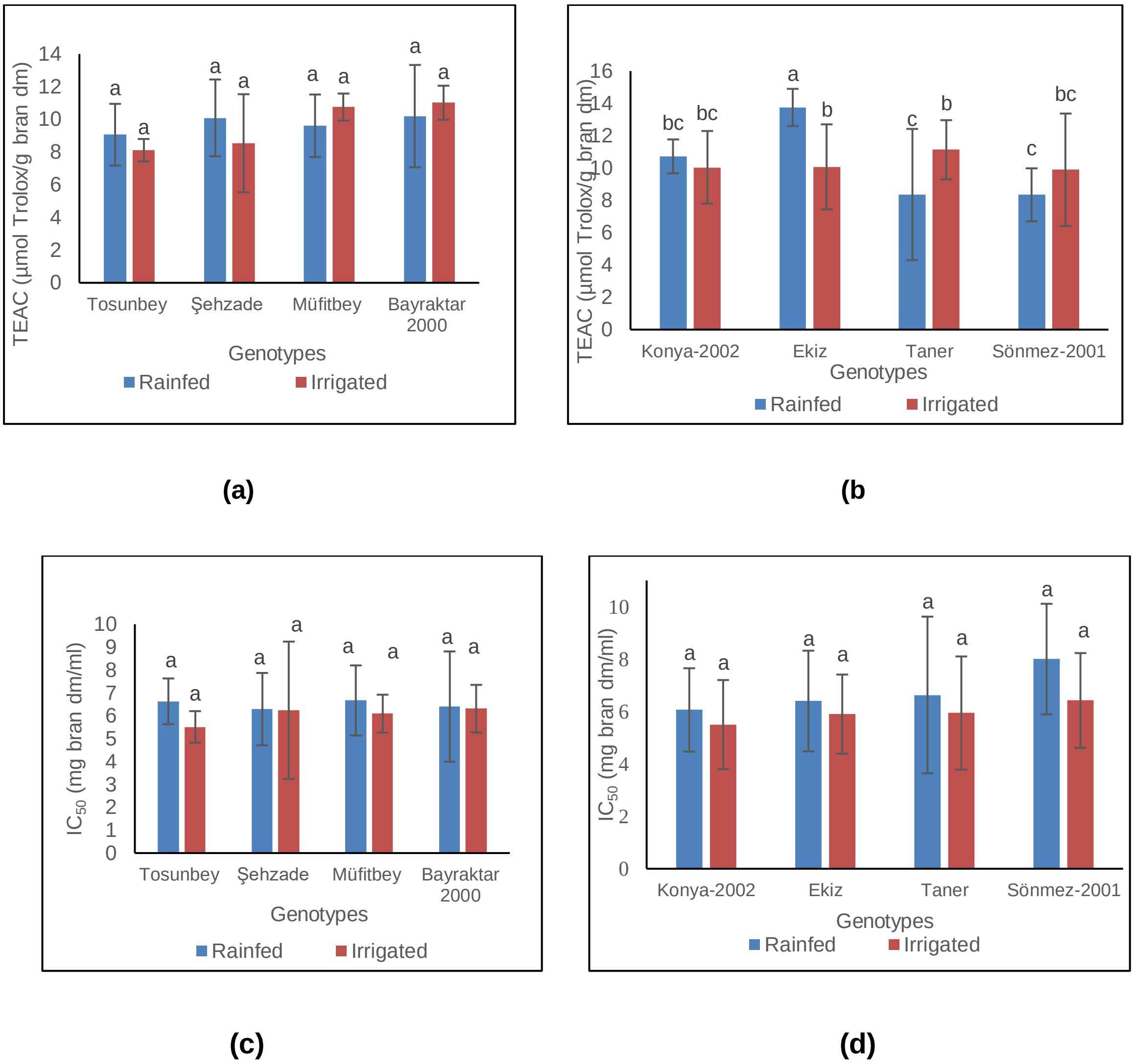


Figure 3. TEAC and IC_{50} values of white (a,c) and red (b,d) wheat brans grown under rainfed and irrigated conditions over 2 succeeding years

Table 4. Effects of G, C, Y and their interactions (G×C, G×Y) on quality traits in eight bread wheat varieties grown under rainfed and irrigated conditions over two succeeding years

White Wheat					
	G	**C**	**Y**	**GxC**	**GxY**
TKW	178.33**	3.67	93.50**	7.12	31.70**
TW	38.22**	5.60*	81.95**	4.62	7.42
PC	7.82**	0.00	0.11	0.11	3.77**
ZS	1891.34**	69.03**	148.78**	114.34*	252.09**
WG	308.68*	3.44	241.45*	99.84	1.44
PW	232.81**	9.24	147.55**	16.19	319.17**
Tint	11042.84**	921.95	5897.38**	606.50	5856.12*
TTint	37355.61**	1480.37	292.23	1611.74	6542.65

W	99400.75**	144.50	16290.13**	479.25	4633.63
P/L	6.23**	0.12	0.14	0.34	1.94**
Ie	295.57*	70.51**	111.38*	173.58**	786.01**
DDT	138.81**	20.91	2.72	101.18	94.14
WAC	643.13**	22.45**	21.13*	1.44	57.12**
E_{135}	7976.39**	7233.04**	728.67	419.71	9554.19**
R_{135}	25293.13	7875.13	13778.00*	3464.13	21438.25
Ext_{135}	3449.31*	1247.50*	181.45	778.42	5422.06**

Red Wheat					
	G	**C**	**Y**	**GxC**	**GxY**
TKW	261.48**	5.33	190.22**	32.98*	33.63*
TW	13.10**	25.29**	46.74**	22.07**	5.87**
PC	0.97	0.00	2.57*	1.04	2.56*
ZS	648.84**	11.28	34.03	77.84*	105.09*
WG	67.27	124.42	459.80**	15.87	37.70
PW	58.55**	8.38*	28.88**	12.40	9.22
T İNT	10185.64**	41.78	3175.89**	207.17	602.64
TT İNT	7162.58**	304.87	2479.38*	1061.21	3060.17
W	66684.09**	87.78	1471.53	3219.34	2457.09
P/L	3.28**	0.03	1.98**	0.55	0.22
Ie	1183.35**	0.72	0.18	101.73	106.42
DDT	30.67**	2.34	8.72*	8.18	12.98
WAC	61.62**	34.65**	112.88**	9.03	5.88
E_{135}	40331.25**	2688.27**	809.02	705.51	665.71
R_{135}	101744.34**	8745.03*	9556.53**	2451.34	6422.84
Ext_{135}	25587.21**	798.00	102.24	6609.71	835.04

G: Genotype, C: Condition, Y: Year, GxC: Interaction of genotype and condition, GxY: Interaction of genotype and year, TKW: Thousand kernel weight, TW: Test weight, PC: Protein content, ZS: Zeleny sedimentation value, WG: Wet gluten, PW: Mixograph peak width at the end of analysis, Tint: Mixograph peak area, TTint: Total area of mixograph curve, W: Alveograph dough energy P/L: Alveograph tenacity/extensibility (curve configuration) ratio, Ie: Alveograph elasticity index, DDT: Farinograph dough development time, WAC: Farinograph water absorption capacity, E_{135}: Extensograph energy value at 135 min., R_{135}: Extensograph resistance value at 135 min., Ext_{135}: Extensograph extensibility value at 135 min., CV: Coefficient of variation, LSD: Least significant differences, *: Significance at the level of 0.05, **: Significance at the level of 0.01.

3.3 Correlations between properties

Strong flours are generally obtained from hard wheat varieties characterized by PC and gluten content. These properties support the development of a strong gluten network, making such wheat varieties particularly suitable for bread production (Marti et al., 2015). To better understand wheat quality, correlations among various grain, flour, and dough characteristics were analyzed. The correlation data are presented in Table 5. A moderate positive correlation was observed between PC and ZS (r = 0.4634, $p < 0.01$). Furthermore, both PC and ZS were positively correlated with parameters such as Tint, TTint, W, P/L, WAC. Among the Farinograph parameters, WAC and DDT were positively correlated with WG, Tint, TTint, W, and PW, Tint, W, Ie, respectively.

In addition, Alveograph, a traditional dough-testing device, is generally used to evaluate the flour samples' quality and therefore predict end-product performance. Alveograph W and Mixograph PW, Tint, and TTint are indicators of the gluten strength of the wheat genotype (Li et al., 2013). In this study, a positive correlation was found between W value and PC, ZS, PW, Tint, TTint, P/L, Ie, WAC, DDT, E_{135}.

A high E_{135} value indicates dough with strong gas retention and good fermentation tolerance, while a higher R_{135} value reflects enhanced fermentation tolerance and improved dough processability (Yavuz et al., 2021). These values were positively correlated with PW, Tint, W, Ie, DDT and PW, Ie, DDT respectively.

These correlations are consistent with expected relationships among genotype traits.

The relationships among bran characteristics are summarized in Table 6. TDF content of wheat bran was positively correlated with bran TEAC value, and exhibited negative correlation the IC_{50} value. This suggests that increased TDF content may enhance the antioxidant capacity of wheat bran. This finding aligns with previous studies indicating that dietary fiber of wheat bran exerts additional physiological effects associated with the activities of antioxidant compounds (Sztupecki et al., 2023, Zhu et al., 2010). Although no significant correlation was found between TPC and antioxidant activity, a positive correlation was observed between TPC and PC. This result is consistent with earlier studies that also reported no correlation between TPC and the antioxidant activity of wheat bran (Cai et al., 2014, Yu et al., 2002). Contrasting findings in some studies (Li et al., 2005) may be attributed to differences in extraction methods, analytical techniques, and the phenolic content and antioxidant activity ranges (Ma et al., 2018).

Table 5. Correlations between conventional quality indices of grain, flour and dough.

Parametre	TKW	TW	PC	ZS	WG	PW	T İNT	TT İNT
TW	0.652**							
PC	0.0709	0.196						
ZS	0.1745	0.1816	0.4634**					
WG	0.2165	0.2577*	0.219	0.3714**				
PW	-0.03	0.1131	0.2334	0.1915	0.0345			
T int	0.0694	0.2614*	0.3835**	0.3886**	0.1114	0.7567**		
TT int	0.1026	0.1022	0.4192**	0.5656**	0.4654**	0.086	0.4519**	
W	0.003	0.2331	0.5328**	0.5537**	0.1676	0.5356**	0.7241**	0.5086**
P/L	0.2015	0.0486	0.4352**	0.3278**	0.2899*	0.1441	0.2444	0.5205**
Ie	-0.0563	0.1356	0.187	0.1218	-0.2927*	0.4975**	0.5075**	-0.1608
DDT	-0.2784*	-0.1234	0.026	0.0563	-0.2588*	0.326**	0.3665**	-0.1923
WAC	0.1742	0.1593	0.5027**	0.5555**	0.6015**	0.1149	0.2733*	0.7696**
E_{135}	-0.1233	0.1243	0.0801	-0.0325	-0.4123**	0.332**	0.2779**	-0.2371

R_{135}	-0.1972	0.0158	0.0169	-0.1812	-0.5262**	0.2499*	0.1483	-0.4223**
Ext_{135}	0.0542	0.0475	-0.0123	0.1465	0.0436	0.1377	0.0981	0.2238

Parametre	W	P/L	Ie	DDT	WAC	E_{135}	R_{135}
P/L	0.3594**						
Ie	0.5568**	-0.1701					
DDT	0.3487**	-0.3117*	0.4558**				
WAC	0.472**	0.6671**	-0.1902	-0.2134			
E_{135}	0.3336**	-0.2267	0.7181**	0.392**	-0.3093**		
R1$_{35}$	0.1597	-0.2545*	0.6416**	0.3725**	-0.4684**	0.9163**	
Ext_{135}	0.1515	-0.1227	0.1891	0.0766	0.1353	0.2552	-0.0149

TKW: Thousand kernel weight, TW: Test weight, PC: Protein content, ZS: Zeleny sedimentation value, WG: Wet gluten, PW: Mixograph peak width at the end of analysis, Tint: Mixograph peak area, TTint: Total area of mixograph curve, W: Alveograph dough energy, P/L: Alveograph tenacity/extensibility (curve configuration) ratio, Ie: Alveograph elasticity index, DDT: Farinograph dough development time, WAC: Farinograph water absorption capacity, E_{135}: Extensograph energy value at 135 min., R_{135}: Extensograph resistance value at 135 min., Ext_{135}: Extensograph extensibility value at 135 min.*: Significance at the level of 0.05, **: Significance at the level of 0.01.

Table 6. Correlations between functional properties of brans.

Parameter	PC	TPC	TEAC	IC_{50}
TPC	0.3689**			
TEAC	0.1665	0.1708		
IC_{50}	0.1900	0.0958	0.2282	
TDF	0.4292	-0.0112	0.0004*	-0.1123**

PC: Protein content, TPC: Total phenolic content, IC_{50}: The concentration of bran extracts to quench 50% of DPPH radicals in the reaction mixture, TEAC: Trolox equivalent antioxidant capacity, TDF: Total dietary fiber, LSD: Least significant differences, *: Significance at the level of 0.05, **: Significance at the level of 0.01.

4. Conclusion

Considering the widespread use of wheat in global nutrition and its potential to improve human health, it is important to develop potential approaches to improve the functional properties of wheat bran and quality of wheat flour by optimizing the growing conditions of selected wheat varieties. In the current study, we examined the effect of G, C and Y on red and white bread wheat varieties in terms of functional properties of their bran. The same varieties were also assessed in terms of flour quality. The results indicate that G has significant effect on PC, TPC, TDF in WWB and TPC, TEAC, TDF value in RWB. C could significantly influence PC and TDF in both WWB and RWB. The results reveal that both growing conditions and wheat genotypes significantly contribute to the observed variation in functional properties of wheat bran. Y significantly affected TPC, PC, antioxidant values (IC_{50} for WWB, IC_{50} and TEAC for RWB) in both WWB and RWB. Numerous factors influence the content of bioactive compounds in wheat bran. In this context, it is evident that the amount and distribution of precipitation across different years also play a role.

Furthermore, and the interaction between GxC and GxY had a lesser influence on the properties of the bran compared to G, C and Y alone. Also, significant G, C and Y effects were found for most of the wheat quality traits and flour characteristics. These findings suggest that the functional and quality traits of wheat can be influenced to some extent by the selection of appropriate wheat varieties and the determination of suitable growing conditions. Further research is needed to elucidate how wheat genotypes and growing conditions impact the functional properties of wheat bran.

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