ARAŞTIRMA MAKALESİ

WHEAT STUDIES

Evaluation of Yield, Quality, and Micronutrient Traits of Colored Wheat Genotypes

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Abstract

This study was conducted to determine the biofortification potential of purple pericarp and blue aleurone wheat genotypes in terms of yield, technological quality, and micronutrient content under irrigated Central Anatolian conditions. Ten colored wheat genotypes along with two commercial varieties (Altındane and Esperia) were tested at two locations (Konya Central and Gözlü) using a randomized complete block design with four replications. In addition to yield performance, technological quality traits (thousand kernel weight, test weight, protein content, Zeleny sedimentation, kernel hardness, total starch content, total phenolic content, dietary fiber, and alveograph energy) were analyzed. Micronutrient contents (Zn, Fe, Cu, Mg) were determined by ICP-MS in selected genotypes (Selçuklu Mavisi, Çatalhöyük Kırmızısı, Altındane, Esperia).

Analysis of variance revealed significant genotypic and locational effects on grain yield ($P<0.01$). The highest average yields were recorded for Esperia (672.3 kg da^{-1}), Altındane (620.2 kg da^{-1}), and Selçuklu Mavisi (580.0 kg da^{-1}). Selçuklu Mavisi stood out with high alveograph energy (249.7 J) and Zeleny sedimentation (41.0 mL). Correlation analysis revealed a negative relationship between protein content and total starch content ($r=-0.82$) and a positive relationship between protein content and total phenolic content ($r=0.68$). PCA analysis indicated that Esperia and Selçuklu Mavisi shared a similar technological quality profile.

Micronutrient analyses revealed that Selçuklu Mavisi had a zinc content of 46.6 mg kg^{-1}, approximately twice that of commercial varieties. In conclusion, the Selçuklu Mavisi genotype combines high yield, superior technological quality, and remarkable micronutrient content, offering significant potential as a genetic resource in colored wheat breeding.

Renkli Buğday Genotiplerinde Verim, Kalite ve Mikro Besin Elementi Özelliklerinin Değerlendirilmesi

ÖzetBu çalışma, mor perikarp ve mavi aleuronlu buğday genotiplerinin sulu Orta Anadolu koşullarında verim, teknolojik kalite ve mikro besin elementi içeriği bakımından biyo-zenginleştirme potansiyelini belirlemek amacıyla yürütülmüştür. Dört tekerrürlü tesadüf blokları deneme desenine göre iki lokasyonda (Konya Merkez ve Gözlü) on renkli buğday genotipi ile birlikte iki ticari çeşit (Altındane ve Esperia) değerlendirilmiştir. Verim performansının yanı sıra bin tane ağırlığı, hektolitre ağırlığı, protein oranı, Zeleny sedimentasyon değeri, tane sertliği, toplam nişasta içeriği, toplam fenolik madde içeriği, diyet lifi ve alveograf enerji değeri gibi teknolojik kalite özellikleri analiz edilmiştir. Mikro besin elementi içerikleri (Zn, Fe, Cu, Mg) ise seçilen genotiplerde (Selçuklu Mavisi, Çatalhöyük Kırmızısı, Altındane ve Esperia) ICP-MS yöntemiyle belirlenmiştir.

Varyans analizi sonuçları, tane verimi üzerinde genotip ve lokasyon etkilerinin önemli olduğunu göstermiştir ($P<0.01$). En yüksek ortalama verimler sırasıyla Esperia (672.3 kg da^{-1}), Altındane (620.2 kg da^{-1}) ve Selçuklu Mavisi (580.0 kg da^{-1}) genotiplerinden elde edilmiştir. Selçuklu Mavisi, yüksek alveograf enerji değeri (249.7 J) ve Zeleny sedimentasyon değeri (41.0 mL) ile öne çıkmıştır. Korelasyon analizi, protein oranı ile toplam nişasta içeriği arasında negatif ($r=-0.82$), protein oranı ile toplam fenolik madde içeriği arasında ise pozitif ilişki ($r=0.68$) bulunduğunu ortaya koymuştur. PCA analizi, Esperia ve Selçuklu Mavisi genotiplerinin benzer teknolojik kalite profiline sahip olduğunu göstermiştir.

Mikro besin elementi analizleri, Selçuklu Mavisi genotipinin 46.6 mg kg^{-1} çinko içeriğine sahip olduğunu ve bu değerin ticari çeşitlerin yaklaşık iki katı olduğunu ortaya koymuştur. Sonuç olarak Selçuklu Mavisi genotipi; yüksek verim, üstün teknolojik kalite ve dikkat çekici mikro besin elementi içeriğini bir arada bulundurarak renkli buğday ıslahı çalışmalarında önemli bir genetik kaynak potansiyeli göstermiştir.

1. Introduction

Wheat (*Triticum aestivum* L.) serves as the primary food source for approximately 40% of the world's population, providing 21% of daily caloric intake, 15% of iron (Fe) requirements, and 11% of zinc (Zn) requirements (Hakeem et al., 2025). As one of the most widely cultivated cereal crops globally, wheat constitutes a cornerstone of food security, particularly in developing countries (Shahzad et al., 2021). However, achieving the United Nations Sustainable Development Goal (SDG3) of "ensuring healthy lives and promoting well-being for all at all ages" appears unlikely without addressing micronutrient deficiencies (Lowe et al., 2022).

In contemporary consumer food preferences, not only the satisfaction of basic nutritional needs but also health-protective and disease-preventive functional properties play significant roles. In this context, interest in functional foods is progressively increasing, with biofortified products gaining prominence, especially in developing countries where micronutrient deficiencies are prevalent (Shahzad et al., 2021). Colored wheat genotypes occupy an important position in this functional food trend due to their high antioxidant capacity and mineral content. The problem of 'hidden hunger' arising from inadequate intake of essential micronutrients such as zinc (Zn) and iron (Fe) affects a substantial portion of the global population, further enhancing the value of colored wheats' biofortification potential (Hakeem et al., 2025; Lowe et al., 2022).

In this context, wheat breeding programs now target not only high yield and technological quality but also the development of varieties rich in health-beneficial components with functional food value (Garg et al., 2022; Akman et al., 2025). Colored wheat genotypes accumulating anthocyanins in different grain layers are particularly suitable for these objectives, owing to their distinctive appearance, high antioxidant capacity, and mineral content. Purple color results from anthocyanin accumulation in the pericarp and is controlled by Pp genes, while blue color originates from pigments accumulated in the aleurone layer and is controlled by Ba genes transferred to wheat from wild species (Zeven, 1991; Wang et al., 2020; Garg et al., 2022; Chumanova et al., 2025; Wu et al., 2025).

Globally, efforts to develop biofortified wheat varieties have accelerated. Varieties such as Zincol-2016 and Akbar-2019 in Pakistan, and Pusa Tejas (HI 8759) and HD 3171 in India have been registered and released for farmer cultivation (Ahmad et al., 2024; Lowe et al., 2022). The Akbar-19 variety, with a zinc content of 38.4 ppm and yield potential 10-15% higher than conventional varieties, covered 42% of the total cultivated area in Pakistan during the 2023-24 sowing season (Ahmad et al., 2024). These developments demonstrate that wheat breeding is an important tool against micronutrient deficiencies (Shahzad et al., 2021; Hakeem et al., 2025).

Regarding macronutrient composition and technological quality traits, colored wheats offer significant advantages. Akman et al. (2025) reported that protein content in colored wheat genotypes ranged from 13.8% to 17.3%, with the ranking according to color groups being purple > black ≈ blue > amber > red. Giordano et al. (2017), Fan et al. (2020), and Morgounov et al. (2020) similarly confirmed that colored wheats contain higher protein content. Regarding Zeleny sedimentation values, an indicator of protein quality, red bread wheats exhibited the highest values (66.8 mL), followed by purple (60.7 mL) and blue (55.0 mL) bread wheats (Fan et al., 2020; Akman et al., 2025). Colored wheat genotypes have also been reported to have higher total phenolic content and dietary fiber as functional properties (Köksel et al., 2023; Akman et al., 2025).

Regarding micronutrient content, numerous studies have demonstrated that colored wheats offer significant advantages over white wheat. Shi et al. (2025), in comprehensive analyses of 16 different colored wheat varieties, reported that colored wheat contained higher levels of anthocyanins, vitamins, iron, and zinc compared to white wheat, with Fe and Zn contents of 40.1 mg/kg and 38.9 mg/kg, respectively, representing increases of 36% and 16% over white wheat. Tian et al. (2018) reported that Zn, Fe, and Mg contents in colored wheat were 108.54-142.68%, 8.57-42.86%, and 5.31-40.63% higher, respectively, than those in normal wheat. Bartkiene et al. (2022) reported significant genotypic variations in zinc (Zn), iron (Fe), copper (Cu), and magnesium (Mg) concentrations among different colored wheat genotypes. Chumanova et al. (2025) also confirmed that colored wheat contains higher protein content and micronutrients such as Zn, Fe, Mg, and Cu compared to red and white wheat.

The relationship between yield and quality traits constitutes one of the most important and complex issues in wheat breeding. In general, a negative relationship exists between grain yield and protein content, leading to lower protein content percentages in high-yielding varieties (Maçãs et al., 2024; Akman et al., 2025). While Akman et al. (2025) confirmed this negative relationship between yield and protein content in colored wheat genotypes, they also demonstrated that some genotypes can combine high yield potential with good quality traits. Brković et al. (2025) similarly reported that genotypes with high yield stability do not always exhibit the highest yield but show reliable performance across different environmental conditions. In this context, examining genotype × environment interactions is critical for identifying stable and high-yielding genotypes (Morgounov et al., 2020; Yue et al., 2025). Under climate change conditions, selecting genotypes that perform consistently across different environments is gaining increasing importance for sustainable wheat production (Maçãs et al., 2024).

This study aimed to determine the biofortification potential of purple pericarp and blue aleurone wheat genotypes in terms of yield, technological quality, and micronutrient content.

2. Materials and Methods

2.1. Plant Material

The plant material consisted of grain wheat genotypes developed within the International Winter Wheat Improvement Program (IWWIP), along with two standard bread wheat varieties (*Triticum aestivum* L.) widely cultivated in the region, as plant material. Colored genotypes were selected using the single spike selection method and advanced through observation nursery, preliminary yield trial, yield trial, and regional yield trial stages to develop advanced breeding lines. The study included a total of 10 colored genotypes, comprising 5 blue (pigment accumulation in aleurone layer) and 5 purple (pigment accumulation in pericarp layer) genotypes (Table 1), along with 2 standard varieties (Altındane and Esperia) for comparison.

The standard varieties were selected among commercial varieties prominent for their high yield potential and superior technological quality traits, with widespread cultivation in the region:

Altındane (registered in 2006, Black Sea Agricultural Research Institute): Spring habit, white spike, white grain, awned wheat variety. Spikes bend downward during maturation; belongs to medium-early group in terms of heading time. Reaches 80–100 cm height under optimum conditions. Exhibits good threshing characteristics and resistance to grain shattering; responds well to nitrogen fertilization and irrigation. Variety yield ranges between 400–1150 kg da^{-1} depending on environmental conditions and management practices. Grain characteristics: test weight 80–82 kg/hl, thousand kernel weight 32–45 g, gluten index 98–99%, energy value 140–430 J, protein content 13–18%, SDS sedimentation 48–68 mL, flour yield 66%.

Esperia (registered in 2011; Tasaco Agriculture Industry and Trade Inc.): Winter habit, awned, medium-early wheat variety. Plant height is medium. Grain characteristics: red hard grain, test weight 80-82 kg/hl, thousand kernel weight 35-40 g, protein content 14.5%. Recommended cultivation areas include Central Anatolia, Western and Eastern Transition Zones, Inner Aegean, Thrace, northern Southeastern Anatolia Region, Eastern Anatolia, and highland areas of coastal regions.

Table 1. Grain color characteristics and pedigree information of colored wheat genotypes used in the trial

Genotip	Colour	Pedigri
Gen-1	Blue	BC1F2 (VILLA JUAREZ F2009/SOLALA//WBLL1*2/BRAMBLING/3/I:S29 PF)
Gen-2	Blue	BC1F2 (VILLA JUAREZ F2009/SOLALA//WBLL1*2/BRAMBLING/3/I:S29 PF)
Gen-3	Blue	BC1F2 (VILLA JUAREZ F2009/SOLALA//WBLL1*2/BRAMBLING/3/I:S29 PF)
Gen-4	Blue	BC1F2 (ELEMENT-22/I:S29 PF)
Gen-5	Purple	BC1F2 (VILLA JUAREZ F2009/SOLALA//WBLL1*2/BRAMBLING/3/I:S29 PF)
Gen-6	Purple	BC1F2 (VILLA JUAREZ F2009/SOLALA//WBLL1*2/BRAMBLING/3/I:S29 PF)
Gen-7	Purple	BC1F2 (VILLA JUAREZ F2009/SOLALA//WBLL1*2/BRAMBLING/3/I:S29 PF)
Gen-8	Purple	BC1F2 (VILLA JUAREZ F2009/SOLALA//WBLL1*2/BRAMBLING/3/I:S29 PF)
Selçuklu Mavisi	Blue	BC1F2 (ELEMENT-22/I:S29 PF)
Çatalhöyük Kırmızısı	Purple	BC1F2 (GERMANY-1/I:S29 PF)

2.2. Experimental site and agronomic practices

This research was conducted at two different locations in the Central Anatolia Region of Türkiye. One trial was established at the experimental fields of Bahri Dağdaş International Agricultural Research Institute in Konya central district (37°51′ N, 32°33′ E; 1092 m altitude), while the other was conducted at the Gözlü Agricultural Enterprise lands in Sarayönü district of Konya province (38°26′ N, 32°27′ E). Both locations represent typical wheat production areas of the region and are under the influence of continental climate characteristics.

The trials were established at both locations using a randomized complete block design with four replications. Plots were arranged as 1.2 m wide and 5 m long, with a plot area of 6 m². Sowing was performed in the first week of November at both locations using a drill seeder in accordance with regional production recommendations, with row spacing adjusted to 20 cm.

Cultivation practices were conducted under irrigated conditions, and plant water requirements were met through irrigation throughout the vegetation period.

For fertilization, 6 kg da^{-1} of pure phosphorus (P_2O_5) and 6 kg da^{-1} of pure nitrogen (N) were applied. All phosphorus and a portion of nitrogen were applied as base fertilizer at sowing, while the remaining nitrogen was applied as top dressing during the stem elongation stage.

Weed control was performed chemically during the stem elongation stage using a commercial herbicide containing 2,4-D 2-ethylhexyl ester + florasulam as the active ingredient.

Harvest was conducted in the third week of July when genotypes reached physiological maturity, using a plot combine harvester. Therefore, the experiments represent irrigated production conditions rather than moisture-limited stress environments.

2.2.1. Climatic conditions

Monthly mean, maximum, and minimum temperature and precipitation data for the 2024-2025 production season for Konya Central and Gözlü locations are presented in Table 2, compared with long-term (1929-2024) averages.

Table 2. Monthly mean, maximum and minimum temperature and precipitation data for Konya Central and Gözlü locations for the 2024–2025 production season and long-term (1929-2024) seasonal norms

KONYA Month /Years	air temperature (°C)			prec (mm)
	mean	max	min	
10 / 2024	13.10	30.16	-2.94	0.6
11 / 2024	5.85	20.57	-7.00	17.4
12 / 2024	3.73	16.64	-6.97	42.6
01 / 2025	2.96	13.65	-5.99	8.4
02 / 2025	0.29	14.30	-15.49	3.6
03 / 2025	9.69	29.43	-6.93	12.0
04 / 2025	10.72	27.36	-7.98	29.2
05 / 2025	17.46	33.07	2.79	28.8
06 / 2025	21.94	33.75	6.85	15.8
Mean/Sum	11.21	25.93	-3.07	165.8

KONYA Month /Years	air temperature (°C)			Prec (mm)
	mean	max	min	
10 / 1929-2024	12.9	20.1	6.0	29.3
11 / 1929-2024	6.5	13.1	0.9	29.3
12 / 1929-2024	1.8	6.7	-2.2	32.0
01 / 1929-2024	-0.2	4.7	-4.2	38.0
02 / 1929-2024	1.5	7.0	-3.3	28.6
03 / 1929-2024	5.6	11.8	-0.2	29.3
04 / 1929-2024	11.1	17.6	4.4	31.4
05 / 1929-2024	15.9	22.4	8.6	43.5
06 / 1929-2024	20.2	26.7	12.7	25.7
Mean/Sum	9.9	16.03	3.86	294.8

GÖZLÜ Month /Years	air temperature (°C)			prec (mm)
	mean	max	min	
10 / 2024	11.8	29.3	3.5	0.0
11 / 2024	4.5	18.6	-8.5	13.0
12 / 2024	3.0	15.0	-5.5	45.7
01 / 2025	2.6	14.0	-8.3	3.0
02 / 2025	-0.8	13.2	-14.5	5.0
03 / 2025	9.0	27.6	-7.0	11.0
04 / 2025	9.1	25.8	-9.2	49.5
05 / 2025	15.6	32.7	1.7	24.0
06 / 2025	20.5	33.1	7.2	12.5
Mean/Sum	8.4	23.3	-4.4	163.7

GÖZLÜ Month /Years	air temperature (°C)			Prec (mm)
	mean	max	min	
10 / 1929-2024	19.0	33.0	-0.9	29.3
11 / 1929-2024	13.0	28.0	-6.4	32.0
12 / 1929-2024	6.7	20.5	-11.0	42.3
01 / 1929-2024	2.3	14.6	-12.6	38.0
02 / 1929-2024	-0.4	12.9	-13.0	28.6
03 / 1929-2024	2.3	17.1	-7.2	29.3
04 / 1929-2024	6.2	22.2	-2.3	31.4
05 / 1929-2024	11.0	26.2	1.8	43.5
06 / 1929-2024	15.0	30.1	8.0	25.7
Mean/Sum	8.3	22.7	-4.0	300.1

At the Konya Central location, the mean temperature during the October 2024-June 2025 period was 13.8% higher than the long-term mean. The most pronounced increase in mean temperatures occurred in March (73%), while increases in May and June were 10.1% and 7.9%, respectively. Maximum temperatures in May and June were measured 47% and 26% above long-term values. Minimum temperatures fell significantly below long-term means, particularly in February (-15.49 °C) and April (-7.98 °C), with differences of 369% and 282%, respectively.

Regarding precipitation, total rainfall for the October-June period was 158.8 mm, 41.6% lower than the long-term mean. Precipitation amounts in October, January, and February remained at 2%, 22%, and 13% of long-term values, respectively, while May experienced a 33.9% reduction.

At the Gözlü location, the mean temperature in March reached 9.0 °C, approximately three times the long-term mean (2.3 °C), while a minimum temperature of -9.2 °C was recorded in April. Precipitation was recorded in November (13 mm) and December (45.7 mm), while January (3 mm) and February (5 mm) remained below long-term means. In April, precipitation of 49.5 mm occurred above the long-term mean.

2.3. Quality analyses

Analyses for determining grain quality traits were conducted using samples obtained from the Konya Central location, with analyses performed in two replications.

Thousand Kernel Weight (TKW) and Test Weight (TW) were determined according to AACC 55-31 and AACC 55-10/55-11 standard methods, respectively (American Association of Cereal Chemists [AACC], 2000).

Protein content (PC) was determined using the LECO FP-528 (Leco Inc., St. Joseph, MI, USA) instrument operating on the Dumas combustion principle according to AOAC 992.23 method. Total nitrogen (N) content was calculated as crude protein content (%) using the universally accepted conversion factor of 5.70 for wheat (AOAC, 2009).

Kernel hardness (SKCS) was determined using a calibrated Perten SKCS 4100 instrument according to AACC 55-31 standard (AACC, 2000). The Zeleny sedimentation test (ZSV) for gluten quality assessment was performed on ground flour samples according to AACC 56-61A standard method (AACC, 2000). For dough rheological properties, alveograph analysis was performed using a Chopin Alveo PC (Chopin Technologies, France) according to AACC 54-30 method, with dough strength (W) expressed in joules (J) (AACC, 2000).

For grain chemical composition, total starch content (SC) was analyzed according to AACC 76-13.01 standard using enzymatic hydrolysis, with results expressed as percentages (%) (AACC, 2000). Total phenolic content (TPC) was determined using the Folin–Ciocalteu spectrophotometric method, with results expressed as milligrams of gallic acid equivalent per 100 g (mg GAE 100 g^{-1}). Total dietary fiber content (TDF) was determined on the bran fraction of the grains, as dietary fiber is predominantly concentrated in the outer layers of the wheat kernel, using the AOAC 991.43 method, and results were expressed as percentage (%).

2.4. Micronutrient analyses

Micronutrient content determination was conducted on a limited number of genotypes. Accordingly, candidate colored wheat genotypes Selçuklu Mavisi and Çatalhöyük Kırmızısı, along with two standard bread wheat varieties (Altındane and Esperia) for comparison, were evaluated. Analyses were performed without replication, with standard varieties used as reference material. Zn, Cu, Fe, and Mg elements were determined by ICP-MS according to NMKL 186 analytical method, with results expressed in mg/kg.

2.5. Statistical Analysis

Data obtained from the research were subjected to analysis of variance (ANOVA). The LSD (Least Significant Difference) test at the 5% significance level was used to determine differences among genotype means. Correlation analysis was performed to determine relationships among the traits examined.

Principal Component Analysis (PCA) was applied to reveal multivariate relationships between genotypes and the traits examined. PCA was used to evaluate the variation structure among traits and to determine the distribution of genotypes according to the examined traits.

All statistical analyses were performed using JMP 11.2.1 (SAS Institute Inc., Cary, NC, USA) statistical software package. Prior to ANOVA, normality and variance homogeneity assumptions of error terms were checked to assess the validity of the statistical model.

3. Results

Analysis of variance results for yield values from the trial are presented in Table 3. Location and genotype effects were statistically significant (P<0.01), while the location × genotype interaction was non-significant. The coefficient of variation (CV) for the trial was calculated as 14.92%.

Table 3. Analysis of variance table for the 2024-25 production season bread wheat yield trial

Source	DF	MS	F Value
Location	1	2241742.0	63.24**
Genotip	11	54719.5	9.03**
Error 1	6	37492.0	6.19^{ns}
Location*Genotip	11	11524.2	1.90^{ns}
Error 2	82	6060.0	
C. Total	111		

*ns: not significant; ** P<0.01; CV: 14.92%*

Analysis of variance results for technological quality traits are presented in Table 4. Genotype effects were statistically significant (P<0.01) for thousand kernel weight, test weight, protein content, Zeleny sedimentation, SKCS hardness, and total starch content. Genotype effects were not statistically significant for total phenolic content, dietary fiber, or alveograph energy.

Table 4. Analysis of variance results for technological quality traits

Trait	Source	DF	SS	MS	F Value	P-value
TKW	Genotype	11	112.4	10.22	7.9	<0.01
	Replication	1	16.6	16.60	12.8	–
TW	Genotype	11	66.2	6.02	5.7	<0.01
	Replication	1	1.3	1.30	1.2	–
PC	Genotype	11	4.6	0.42	5.5	<0.01
	Replication	1	0.1	0.10	0.9	–
ZSV	Genotype	11	493.8	44.89	32.7	<0.01
	Replication	1	2.9	2.90	2.1	–
SKCS	Genotype	11	918.4	83.49	11.3	<0.01
	Replication	1	0.0	0.00	0.0	–
TSC	Genotype	11	56.0	5.09	7.2	<0.01
	Replication	1	0.0	0.00	0.0	–
TPC	Genotype	11	64001.9	5818.35	2.2	ns
	Replication	1	112.0	112.00	0.0	–
TDF	Genotype	11	68.4	6.22	1.6	ns
	Replication	1	3.6	3.60	0.9	–
W	Genotype	11	2944.2	267.65	1.4	ns
	Replication	1	21.9	21.90	0.1	–

Abbreviations: TKW, thousand kernel weight; TW, test weight; PC, protein content; ZSV, Zeleny sedimentation value; SKCS, Single Kernel Characterization System hardness; TSC, starch content; TPC, total phenolic content; TDF, total dietary fiber; W, alveograph energy; GY, grain yield; CV (%) for each trait: TKW 3.53, TW 1.35, PC 1.85, ZSV 2.95, SKCS 3.39, TSC 0.15, TPC 3.56, TDF 3.70, W 6.07.
ns: not significant (P > 0.05)

Mean yield values of genotypes at two locations are presented in Table 5. Average yield was 396.8 kg da^{-1} at the Konya location and 689.4 kg da^{-1} at the Gözlü location.

At the Konya location, the highest yield value was recorded for Esperia (570.2 kg da^{-1}), followed by Gen-4 (474.3 kg da^{-1}), Gen-1 (448.0 kg da^{-1}), Altındane (447.8 kg da^{-1}), and Selçuklu Mavisi (437.4 kg da^{-1}). The lowest yield values were observed for Gen-8 (270.0 kg da^{-1}) and Gen-6 (277.9 kg da^{-1}) .

At the Gözlü location, the highest yield values were obtained for Çatalhöyük Kırmızısı (792.7 kg da^{-1}) and Altındane (792.7 kg da^{-1}), followed by Esperia (774.4 kg da^{-1}), Gen-3 (749.6 kg da^{-1}), Gen-2 (744.9 kg da^{-1}), and Selçuklu Mavisi (722.5 kg da^{-1}). The lowest yield at this location was recorded for Gen-5 (586.9 kg da^{-1}).

Based on the two-location means, the highest yield values were determined for Esperia (672.3 kg da^{-1}), Altındane (620.2 kg da^{-1}), and Selçuklu Mavisi (580.0 kg da^{-1}). Çatalhöyük Kırmızısı, with an average yield of 517.8 kg da^{-1}, had the highest mean among purple aleurone genotypes.

Table 5. Mean yield values (kg da^{-1}) and multiple comparison results of genotypes at two locations

Genotype	Konya	Gözlü	Mean
Gen-1	448.0 bc	711.0 a-d	579.5 bc
Gen-2	406.1 bcd	744.9 abc	575.5 bc
Gen-3	404.7 bcd	749.6 abc	577.1 bc
Gen-4	474.3 b	629.9 cd	552.1 c
Gen-5	318.6 def	586.9 d	452.8 d
Gen-6	277.9 ef	634.2 cd	456.0 d
Gen-7	335.5 def	591.1 d	463.3 d
Gen-8	270.0 f	671.1 bcd	470.5 d
Selçuklu Mavisi	437.4 bc	722.5 abc	580.0 bc
Çatalhöyük Kırmızısı	370.3 cde	792.7 cd	517.8 cd
Esperia	570.2 a	774.4 ab	672.3 a
Altındane	447.8 bc	792.7 a	620.2 ab
Mean	396.8 b	689.4 a	557.8

Different letters in the same column indicate statistically significant differences between means (P<0.05).

Technological quality traits and physical analysis results of genotypes are presented in Table 6.

Thousand kernel weight ranged from 29.3 g (Altındane) to 35.3 g (Esperia). Esperia (35.3 g), Gen-4 (34.9 g), and Gen-6 (33.3 g) were the genotypes with the highest values.

Test weight ranged from 74.2 g (Gen-3) to 79.6 g (Gen-6). The highest values were recorded for Gen-6 (79.6 g), Gen-5 (78.7 g), and Gen-4 (77.7 g). Selçuklu Mavisi (77.7 g) and Çatalhöyük Kırmızısı (77.7 g) also ranked in the upper group.

Protein content ranged from 14.1% (Esperia) to 15.8% (Gen-8). The highest protein content was determined for Gen-8 (15.8%), Çatalhöyük Kırmızısı (15.3%), and Gen-4 (15.1%).

Zeleny sedimentation value ranged from 31.0 mL (Gen-6) to 45.5 mL (Altındane). The highest values were recorded for Altındane (45.5 mL), Esperia (45.0 mL), and Selçuklu Mavisi (41.0 mL).

SKCS hardness value ranged from 69.4 (Gen-8) to 90.7 (Gen-4). The highest hardness values were determined for Gen-4 (90.7), Selçuklu Mavisi (86.3), and Gen-7 (85.8).

Total starch content ranged from 53.2% (Gen-8) to 58.3% (Esperia). The highest values were recorded for Esperia (58.3%), Altındane (56.0%), and Gen-4 (55.6%).

Total phenolic content ranged from 1355.6 mg GAE/100g (Gen-4) to 1546.7 mg GAE/100g (Gen-8). The highest values were determined for Gen-8 (1546.7), Gen-3 (1460.9), and Gen-7 (1446.2). Çatalhöyük Kırmızısı ranked in the upper group with a value of 1443.9 mg GAE/100g.

Dietary fiber content ranged from 50.2% (Gen-8) to 56.3% (Gen-4). The highest values were recorded for Gen-4 (56.3%), Gen-2 (55.7%), and Selçuklu Mavisi (55.5%).

Alveograph energy value (W) ranged from 211.3 J (Gen-7) to 249.7 J (Selçuklu Mavisi). The highest values were determined for Selçuklu Mavisi (249.7 J), Altındane (240.5 J), and Esperia (226.4 J).

Table 6. Technological quality traits and physical analysis results of genotypes

Genotype	TKW	TW (kg/hl)	(PC) (%)	ZSV (ml)	SKCS	TSC (%)	TPC (mgGAE/100g)	TDF (%)	W (J)
Gen-1	31.2 c-f	74.6 fg	14.9 bc	37.0 ef	82.0 bc	54.4 bcd	1442.1	52.8	218.2
Gen-2	31.2 c-f	74.4 g	14.9 bc	39.5 bcd	85.3 abc	55.1 bc	1394.4	55.7	222.3
Gen-3	30.0 ef	74.2 g	15.0 bc	37.5 def	83.1 bc	54.2 cd	1460.9	52.7	222.6
Gen-4	34.9 ab	77.7 b-e	15.1 bc	35.5 f	90.7 a	55.6 bc	1355.6	56.3	221.4
Gen-5	31.1 c-f	78.7 ab	15.1 bc	36.0 f	81.1 bc	54.9 bcd	1419.8	54.3	219.2
Gen-6	33.3 abc	79.6 a	14.6 cd	31.0 g	79.9 cd	55.4 bc	1401.3	53.1	215.5
Gen-7	31.8 cde	75.8 c-g	14.7 bc	39.0 b-e	85.8 ab	54.3 cd	1446.2	52.9	211.3
Gen-8	33.1 cde	75.5 efg	15.8 a	38.5 cde	69.4 f	53.2 d	1546.7	50.2	222.9
Altındane	29.3 f	75.8 d-g	14.8 bc	45.5 a	73.7 ef	56.0 b	1423.1	52.2	240.5
Çatalhöyük Kırmızısı	30.8 def	77.7 a-d	15.3 ab	40.5 bc	80.7 bcd	54.0 cd	1443.9	54.6	225.3
Esperia	35.3 a	76.3 c-f	14.1 d	45.0 a	75.8 de	58.3 a	1367.4	53.1	226.4
Selçuklu Mavisi	31.2 c-f	77.7 abc	14.9 b	41.0 b	86.3 ab	54.9 bcd	1377.2	55.5	249.7
Mean	31.9	76.4	14.9	38.8	81.1	55.0	1423.2	53.6	226.3
CV (%)	3.53	1.35	1.85	2.95	3.39	0.15	3.56	3.70	6.07

Different letters in the same column indicate statistically significant differences (P < 0.05)
Abbreviations: TKW, thousand kernel weight; TW, test weight; PC, protein content; ZSV, Zeleny sedimentation value; SKCS, Single Kernel Characterization System hardness; TSC, starch content; TPC, total phenolic content; TDF, total dietary fiber; W, alveograph energy; GY, grain yield.

Pearson correlation coefficients among the examined yield and quality traits are presented in Table 7.

A strong negative correlation was determined between protein content (PC) and total starch content (TSC) (r = -0.82, P<0.01). A positive and significant relationship was found between protein content and total phenolic content (TPC) (r = 0.68, P<0.05).

Total phenolic content (TPC) showed strong negative correlations with total starch content (TSC) (r = -0.73, P<0.01), SKCS hardness value (r = -0.58, P<0.05), and total dietary fiber (TDF) (r = -0.78, P<0.01). A strong positive correlation was found between total dietary fiber (TDF) and SKCS hardness value (r = 0.82, P<0.01).

A positive correlation was detected between alveograph energy (W) and Zeleny sedimentation (ZSV) (r = 0.61, P<0.05).

Positive correlations were determined between grain yield (GY) and Zeleny sedimentation (ZSV) (r = 0.70, P<0.05) and total starch content (TSC) (r = 0.64; P<0.05).

Table 7. Pearson correlation coefficients among examined traits

Trait	TKW	TW	PC	ZSV	SKCS	TSC	TPC	TDF	W
TW	0.31								
PC	-0.24	-0.07							
ZSV	-0.19	-0.39	-0.24						
SKCS	0.03	0.11	-0.16	-0.35					
TSC	0.46	0.17	-0.82**	0.41	-0.04				
TPC	-0.32	-0.38	0.68*	-0.06	-0.58*	-0.73**			
TDF	0.09	0.33	-0.16	-0.11	0.82**	0.21	-0.78**		
W	-0.29	0.04	-0.02	0.61*	-0.11	0.21	-0.24	0.17	
GY	0.02	-0.44	-0.49	0.70*	-0.03	0.64*	-0.44	0.14	0.53

***P<0.01*; *P<0.05*

Abbreviations: TKW, thousand kernel weight; TW, test weight; PC, protein content; ZSV, Zeleny sedimentation value; SKCS, Single Kernel Characterization System hardness; TSC, starch content; TPC, total phenolic content; TDF, total dietary fiber; W, alveograph energy; GY, grain yield.

As a result of Principal Component Analysis (PCA), the first two principal components explained 62.7% of the total variation (PC1: 36.0%, PC2: 26.7%). Traits related to kernel physical properties, including total dietary fiber (TDF), SKCS hardness value (SKCS), thousand kernel weight (TKW), and test weight (TW), were positioned on the positive side of the PC1 axis, whereas total phenolic content (TPC) and protein content (PC) were located on the negative side. PC2 was mainly associated with Zeleny sedimentation value (ZSV) and alveograph energy (W), while protein content showed a moderate contribution to this axis.

In the PCA biplot, Esperia and Selçuklu Mavisi were positioned in the upper-right region, indicating closer association with technological quality traits such as ZSV and W, and therefore exhibiting similar quality profiles. Altındane was located in the upper-central region of the biplot, also showing proximity to these quality-related parameters. In contrast, Çatalhöyük Kırmızısı, together with Gen-1 and Gen-3, was positioned on the negative side of PC1, near the TPC vector, indicating association with higher total phenolic content. The opposite orientation and wide angle (>90°) between the TPC and TDF vectors visually confirmed the strong negative correlation between these traits (r = −0.78). This suggests that Çatalhöyük Kırmızısı may possess valuable compositional characteristics for functional food applications due to its elevated phenolic profile.

Gen-2 was positioned close to Selçuklu Mavisi and nearer to the vectors associated with TDF, SKCS, and TW, whereas Gen-4, Gen-5, Gen-6, and Gen-7 were distributed in the lower-central region of the biplot without showing a clear association with a specific trait. Based on vector lengths, TPC, TDF, SKCS, and ZSV were the traits contributing most strongly to the overall variation among genotypes.

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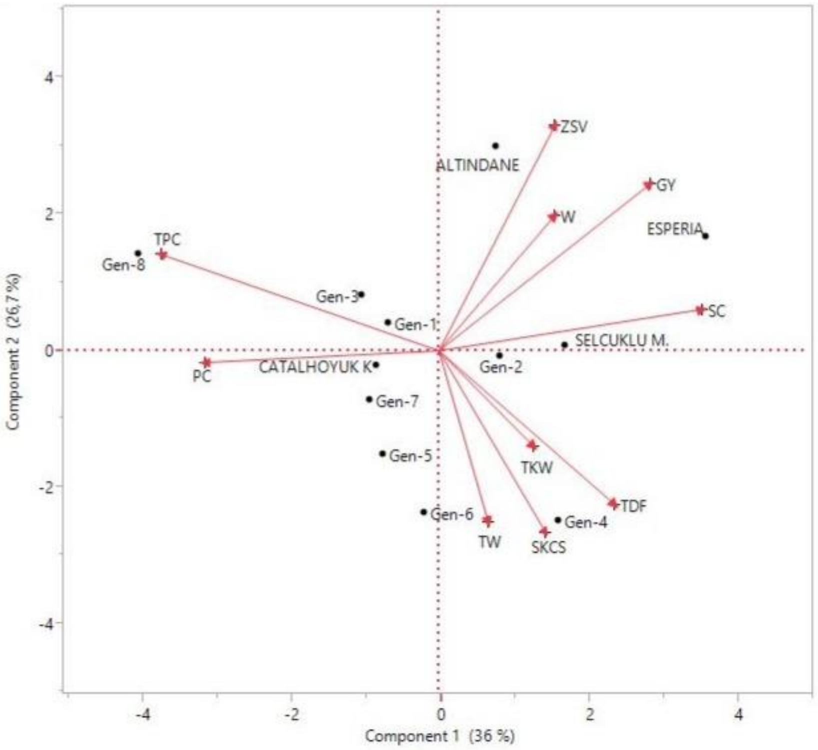

Figure 1. PCA biplot of 12 wheat genotypes based on yield, technological quality, and nutritional traits. PC1 and PC2 explained 36.0% and 26.7% of the total variation, respectively.

Abbreviations: TKW, thousand kernel weight; TW, test weight; PC, protein content; ZSV, Zeleny sedimentation value; SKCS, Single Kernel Characterization System hardness; TSC, starch content; TPC, total phenolic content; TDF, total dietary fiber; W, alveograph energy; GY, grain yield.

Micronutrient analysis results for the four selected genotypes (Çatalhöyük Kırmızısı, Selçuklu Mavisi, Altındane, Esperia) are presented in Table 8. Analyses were performed without replication, and results are presented as descriptive values.

Regarding zinc (Zn) content, marked differences were observed among genotypes. The highest zinc content was determined in Selçuklu Mavisi (46.6 mg kg^{-1}), which was 100% and 141% higher than Altındane (23.3 mg kg^{-1}) and Esperia (19.3 mg kg^{-1}), respectively. Çatalhöyük Kırmızısı also exhibited a zinc content of 40.0 mg kg^{-1}, approximately 88% above the average of standard varieties (21.3 mg kg^{-1}).

A similar situation was observed for copper (Cu) content, with the highest value recorded in Selçuklu Mavisi (4.702 mg kg^{-1}). This genotype had 8% and 37% higher copper content than Altındane (4.360 mg kg^{-1}) and Esperia (3.436 mg kg^{-1}), respectively. Çatalhöyük Kırmızısı (4.681 mg kg^{-1}) showed 20% higher copper content than the average of standard varieties (3.898 mg kg^{-1}).

Iron (Fe) content ranged from 32.5 mg kg^{-1} (Esperia) to 34.7 mg kg^{-1} (Çatalhöyük Kırmızısı), while the highest magnesium (Mg) content was determined in Altındane (1237 mg kg^{-1}) and the lowest in Selçuklu Mavisi (1031 mg kg^{-1}).

Table 8. Micronutrient contents of selected genotypes (mg kg^{-1})

Genotype	Zn (mg kg^{-1})	Fe (mg kg^{-1})	Cu (mg kg^{-1})	Mg (mg kg^{-1})
Çatalhöyük Kırmızısı	40.0	34.7	4.681	1075
Selçuklu Mavisi	46.6	34.3	4.702	1031
Altındane	23.3	33.0	4.360	1237
Esperia	19.3	32.5	3.436	1215

4. Discussion

In this study, purple pericarp and blue aleurone wheat genotypes were evaluated under irrigated field conditions in Central Anatolia ecological conditions for grain yield, technological quality traits, and micronutrient content. Analysis of variance results showed that both genotype and location effects on grain yield were statistically significant ($P<0.01$; Table 3). This reveals that yield formation is shaped by the combined effect of genetic structure and environmental conditions. Previous studies have also reported that yield in multi-environment wheat trials can vary significantly as a result of genotype × environment interactions (Morgounov et al., 2020; Maçãs et al., 2024; Brković et al., 2025).

The yield differences determined between locations revealed the determining role of environmental conditions on yield formation. While the average yield at the Gözlü location was 689.4 kg da^{-1}, this value remained at 396.8 kg da^{-1} at the Konya Central location (Table 5). Climatic conditions between locations are thought to be effective in creating this difference. The low total precipitation recorded during the vegetation period and low temperature values observed in some months at Konya Central may have limited plant development and grain filling. In contrast, it is considered that precipitation at the Gözlü location, particularly during heading and grain filling periods, may have contributed to yield formation by meeting plant water requirements. Previous studies have emphasized that the distribution of precipitation across critical phenological periods is more determinative of yield than total precipitation amount in water-limited environments; however, in this study, irrigation likely mitigated moisture stress effects (Maçãs et al., 2024; Yue et al., 2025).

When genotype performances were examined, Esperia, Altındane, and Selçuklu Mavisi genotypes stood out with high yield values (Table 5). Among colored wheat genotypes, Selçuklu Mavisi showed the highest average yield value (580.0 kg da^{-1}). The literature reports that colored wheat genotypes often have lower yield potential compared to modern commercial varieties. Morgounov et al. (2020) reported that purple-grained isogenic lines in most cases showed lower yield values than standard wheat varieties. Nevertheless, recent studies have revealed that some colored wheat lines can have high yield potential (Akman et al., 2025). In this study, Selçuklu Mavisi genotype exhibiting yield values close to commercial varieties such as Esperia and Altındane indicates that colored wheat genotypes can be competitive not only in terms of nutritional properties but also agronomic performance.

The different performance levels of other colored wheat genotypes evaluated in the study in terms of yield and quality traits reveal that there is significant phenotypic diversity among this material. While Gen-8 stood out with high protein content and total phenolic content, Gen-4 attracted attention with high kernel hardness and dietary fiber values (Table 6). This shows that colored wheat germplasm constitutes a valuable genetic resource for wheat breeding programs not only in terms of identifying superior genotypes but also in providing wide genetic variation (Giordano et al., 2017; Garg et al., 2022).

When technological quality traits were examined, Selçuklu Mavisi genotype drew attention with high alveograph energy (249.7 J) and Zeleny sedimentation (41.0 mL) values (Table 6). Alveograph energy value is an important rheological parameter reflecting dough elasticity and gas retention capacity and is directly related to breadmaking quality (Akman et al., 2025). The fact that Selçuklu Mavisi genotype had higher alveograph energy values than commercial varieties such as Esperia (226.4 J) and Altındane (240.5 J) indicates that this genotype may have a strong gluten structure. Regarding protein content, Çatalhöyük Kırmızısı (15.3%) and Selçuklu Mavisi (14.9%) genotypes showed relatively high values (Table 6). Previous studies have also reported that protein content is generally higher in colored wheat genotypes (Giordano et al., 2017; Morgounov et al., 2020).

Correlation analysis results (Table 7) showed a strong negative relationship between protein content and total starch content ($r=-0.82$, $P<0.01$). This relationship can be considered a reflection of the frequently reported yield-protein content trade-off in wheat (Akman et al., 2025; Maçãs et al., 2024). The balance between carbon and nitrogen metabolism during grain development determines protein content and total starch content accumulation (Feng et al., 2024). In contrast, the positive relationship determined between protein content and total phenolic content ($r = 0.68$, $P<0.05$) may be associated with increased phenolic metabolism, especially in colored wheats. Previous studies have reported that phenolic compounds are also present at high levels in anthocyanin-rich wheat genotypes (Wang et al., 2020; Garg et al., 2022). Regarding relationships among micronutrients, Thapa et al. (2022) reported a positive correlation ($r=0.52$) between grain Fe and Zn concentrations, indicating that these two traits can be improved simultaneously in breeding programs. A positive relationship between these two micronutrients was similarly observed in our study, suggesting that both elements can be targeted together in biofortification breeding. Furthermore, Thapa et al. (2022) reported a positive correlation between grain yield and grain Zn concentration ($r=0.19$) and a negative correlation with grain Fe concentration ($r = -0.63$). Selçuklu Mavisi's combination of high yield (580.0 kg da^{-1}) and high Zn content

(46.6 mg kg⁻¹) in our study is consistent with the findings of Thapa et al. (2022), demonstrating that mineral content can be increased in some genotypes without compromising yield. The zinc value of 46.6 mg kg⁻¹ determined in Selçuklu Mavisi is also compatible with the studies compiled by Garg et al. (2022). Indeed, it has been reported that colored wheat genotypes can show over 100% increases in zinc and iron content compared to white wheat (Tian et al., 2018; Guo et al., 2013). This reveals that Selçuklu Mavisi is a valuable genetic resource for biofortification programs against zinc deficiency, which is common in human nutrition.

Principal Component Analysis (PCA) was useful in visualizing quality and nutritional trait differences among genotypes (Figure 1). The first two components explained 62.7% of the total variation. The positioning of Esperia and Selçuklu Mavisi genotypes in the region associated with protein content, Zeleny sedimentation, and alveograph energy indicates that these genotypes have similar technological quality profiles. In contrast, the location of Çatalhöyük Kırmızısı genotype on the negative side of the PC1 axis, near the TPC vector and opposite to TDF, reflects the strong negative correlation between these two traits ($r = -0.78$). This suggests that Çatalhöyük Kırmızısı may possess compositionally valuable properties for functional food development, particularly due to its association with higher total phenolic content. PCA analysis has been reported in previous studies as an effective method for distinguishing wheat genotypes in terms of technological and nutritional traits (Brković et al., 2025).

The evaluated traits together represent grain physical quality, gluten strength, dough rheology, and functional nutritional properties of wheat. Thousand kernel weight and test weight reflect the physical properties and grain filling capacity of wheat grains and are closely related to milling yield and overall grain quality. Protein content, Zeleny sedimentation value, and kernel hardness are widely accepted indicators of gluten strength and technological quality in bread wheat. Furthermore, dough rheological behavior was characterized by alveograph analysis, with the dough strength parameter (W) providing important information about dough resistance and baking performance. Together, these parameters define the technological suitability of wheat for end-product quality. PCA analysis revealed a clear trade-off between technological quality and nutritional traits. On one side of the PC1 axis, technological quality traits such as Zeleny sedimentation, alveograph energy, and test weight were positioned, while on the other side, nutritional traits such as total phenolic content and dietary fiber were located. This reflects the physiological balance between quality and nutritional components frequently reported in wheat. However, the fact that Selçuklu Mavisi combines both high technological quality parameters and remarkable micronutrient content indicates that this trade-off can be overcome in some genotypes.

Beyond technological quality, nutritional and functional properties of wheat grain were also evaluated in this study. Total starch content represents the main carbohydrate component determining grain energy value and processing behavior (Kim & Kim, 2021), while total phenolic content and total dietary fiber contribute to the antioxidant capacity and health-promoting properties of wheat-based foods (Tosi et al., 2020). Therefore, the combined evaluation of these traits allows comprehensive examination of wheat genotypes in terms of both technological performance and nutritional quality.

Micronutrient analyses (Table 8) revealed significant differences among genotypes, particularly in zinc and copper contents. Selçuklu Mavisi genotype showed distinctly higher zinc content (46.6 mg kg⁻¹) than Altındane (23.3 mg kg⁻¹) and Esperia (19.3 mg kg⁻¹). Similarly, Çatalhöyük Kırmızısı genotype also attracted attention with a zinc content of 40.0 mg kg⁻¹. These results indicate that colored wheat genotypes carry significant potential for micronutrient richness. Some previous studies have also reported that zinc content in colored wheat genotypes can be higher compared to conventional wheat varieties (Tian et al., 2018; Shi et al., 2025). The zinc content of Selçuklu Mavisi was found to be above that of Akbar-19 (38.4 mg kg⁻¹), a variety developed in Pakistan (Ahmad et al., 2024). Similar superiority was observed in copper content, with Selçuklu Mavisi (4.702 mg kg⁻¹) and Çatalhöyük Kırmızısı (4.681 mg kg⁻¹) showing higher values than standard varieties (Bartkiene et al., 2022; Chumanova et al., 2025). These values are quite remarkable when compared with similar studies conducted in different geographies. Thapa et al. (2022), in multi-environment trials conducted in Nepal, reported that grain Zn concentration in biofortified wheat genotypes ranged from 19.1 to 48.7 mg kg^{-1}. The zinc content of 46.6 mg kg⁻¹ in Selçuklu Mavisi lies at the upper limit of this literature range and was also found above Akbar-19 (38.4 mg kg⁻¹), a widely cultivated variety developed in Pakistan (Ahmad et al., 2024). Similarly, Shi et al. (2025) reported mean Zn content of 38.9 mg kg^{-1} in colored wheat, while Tian et al. (2018) reported 108-142% higher Zn values compared to normal wheat. The value of 46.6 mg kg⁻¹ determined for Selçuklu Mavisi in our study is consistent with these literature findings and confirms the genotype's high biofortification potential. However, due to the non-replicated nature of the micronutrient analyses, the obtained values are preliminary in nature, and confirmation in future studies with larger samples and replicated analyses will contribute to stronger demonstration of the biofortification potential of these genotypes.

In recent years, increasing demand for nutrient-enhanced cereal products has increased interest in colored wheat breeding efforts. The biofortification approach aims particularly to increase micronutrients such as zinc and iron in cereal products, and this strategy is seen as an important tool in reducing global nutritional problems (Garg et al., 2022; Hakeem et al., 2025). One of the most important obstacles to colored wheats competing with commercial varieties is the yield reduction caused by linkage drag during the transfer of the blue aleurone trait from wild relatives (Garg et al., 2022). In this context, the fact that the Selçuklu Mavisi genotype in our study exhibited yield close to commercial varieties (Esperia, Altındane) is quite remarkable. This situation indicates that the undesirable genetic linkages causing yield reduction have likely been broken in this genotype, or that the genotype has a different genetic basis. As stated by Garg et al. (2022), developing new varieties that combine high yield and high anthocyanin/mineral content is one of the most critical breeding targets for the dissemination of colored wheats. Selçuklu Mavisi carries important genetic resource potential for achieving this target. Nevertheless, combining high yield, good technological quality, and rich nutrient content in the same genotype poses a significant challenge for wheat breeding. The results obtained in this study indicate that Selçuklu Mavisi and Çatalhöyük Kırmızısı genotypes exhibit balanced performance in terms of yield performance, quality traits, and micronutrient content. These genotypes attract attention not only for their agronomic performance but also as genetic resources representing the nutritional potential of colored wheat germplasm.

Marked differences in agronomic performance, technological quality, and nutritional traits were observed among the colored wheat genotypes examined in this study. The balanced performance of Selçuklu Mavisi and Çatalhöyük Kırmızısı genotypes in multiple traits reveals that colored wheat germplasm carries significant potential for wheat breeding programs aimed at simultaneous improvement of yield and nutritional quality traits.

5. Conclusion

This study revealed that purple pericarp and blue aleurone wheat genotypes exhibit significant variation in agronomic performance, technological quality traits, and micronutrient content under irrigated Central Anatolian conditions. The findings demonstrated that Selçuklu Mavisi and Çatalhöyük Kırmızısı genotypes, in particular, showed balanced and remarkable performance in terms of grain yield, quality parameters, and micronutrient content. This reveals that colored wheat genotypes constitute a valuable genetic resource not only for functional food potential but also for the development of agronomically competitive varieties.

The results obtained in this study demonstrate that high yield, appropriate technological quality, and rich nutrient content can be combined in the same genotype, and that colored wheat germplasm offers significant potential for biofortification and functional wheat breeding efforts. In this context, the fact that the Selçuklu Mavisi genotype, with a zinc content of 46.6 ppm, exhibits performance above registered biofortified varieties such as Akbar-19 (38.4 ppm) widely cultivated in Pakistan, suggests that local genetic resources are competitive with internationally recognized biofortified varieties. Furthermore, the Selçuklu Mavisi's yield values close to commercial varieties provide concrete evidence that the yield reduction problem (linkage drag), one of the most important obstacles to colored wheat breeding, can be overcome.

For future studies, it is recommended that (i) the performance of these superior genotypes under different ecologies be tested through multi-environment trials, (ii) anthocyanin profiles and antioxidant capacities be directly measured, (iii) the genetic basis of Selçuklu Mavisi's high zinc content be investigated with molecular markers, and (iv) new-generation biofortified varieties be developed by crossing these genotypes with commercial varieties. Therefore, evaluating especially Selçuklu Mavisi and Çatalhöyük Kırmızısı genotypes as parental material in advanced breeding programs could make significant contributions to the development of new wheat varieties with both enhanced nutritional value and strong agronomic performance.

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