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RESEARCH ARTICLE

Assessment of durum wheat (*Triticum durum* Desf.) genotypes for grain yield and quality in breeding programmes under rainfed conditions

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Abstract

The primary goal of durum wheat breeding is to develop new cultivars with high grain yield to feed the growing population and with high quality to meet the requirements of durum wheat end-products. The present study evaluated 24 durum wheat genotypes including 20 advanced lines and 4 cultivars grown in four locations under rainfed conditions. Grain yield and quality traits, namely, hardness index, test weight, kernel weight and diameter, color *L,a,b* values, vitreousness, protein content, SDS and modified SDS sedimentations were determined. Results showed significant variations in yield and quality traits. Test weight and grain yield varied more across the environments, while color values, hardness index and both SDS sedimentations showed greater variation among genotypes. Kernel diameter, weight, vitreousness and protein content also displayed similar variation among the genotypes and across the environments. Heritability ranged from 0.24 (vitreousness) to 0.99 (color *b* value). Correlation and biplot analyses identified significant trait relationships. Eight advanced lines exceeded 4,000 kg/ha grain yield in at least one location. Among the tested locations, Ikizce showed the highest average yield (3,601 kg/ha) making it the most suitable for wheat production.

Keywords: Durum wheat, breeding, quality, heritability, biplot

Introduction

Wheat supplies 20% of global calories and is the second most important staple grain after maize, with a production of 770.9 mt in 2021 (FAOSTAT 2023). Bread wheat makes up 95% of production, while durum wheat accounts for 5% (Saini et al. 2022). Durum wheat (*Triticum turgidum* L. var. durum), grown in specific conditions, is a key food source, especially in the Mediterranean region, where it is mostly used for producing pasta and bulgur. These products are affordable, easy to prepare and have a long shelf life (Kaplan Evlice 2022). In 2021, Türkiye was the second largest pasta exporter (1,293,209 tonnes to 149 countries) and the top bulgur exporter (2,38,627 tonnes to 111 countries) (Trade Map 2023).

Grain yield has long been the primary focus for wheat growers, with quality being secondary (Sanchez-Garcia et al. 2015). However, wheat quality has gained importance due to consumer, milling industry and breeder interest in end-product quality (Padalino et al. 2014). Test weight, yellow pigment content (YPC), kernel vitreousness and grain protein content are key durum wheat quality traits

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determining its commercial value (Fu et al. 2018). Bright yellow coloured pasta and bulgur are preferred by consumers. Protein content and gluten strength affect the cooking quality (Kaplan Evlice and ÖzKaya 2019). These factors are crucial in the competitive global pasta market (Saini et al. 2022).

It is well known that there is a negative relationship between wheat grain yield and quality. Therefore, one of the most challenging objectives in wheat breeding efforts is to achieve high-yielding genotypes with good-quality parameters (Tsenov et al. 2021). The quality of wheat is generally influenced by the genotype (G), environment (E), and their interactions (GxE) (Taheri et al. 2021). Understanding the influence of these factors on quality traits is essential for precise selection in breeding programmes aimed at improving wheat quality (Harisha et al. 2024). While quality traits like protein quality and colour are primarily determined by genotype and other traits, such as protein content and ash content, are significantly influenced by environmental conditions (Dencic et al. 2011; Schulthess et al. 2013). Heritability estimation is a common tool in breeding programmes to assess the impact of genetic and environmental factors on different traits, providing insights into how G, E, and GxE contribute to trait expression (Kaya and Akcura 2014). Further, wheat grain quality is determined by the interaction of multiple factors rather than a single one in breeding programmes (Guzman et al. 2016). Although the correlation coefficient is a useful method employed in breeding programmes, it provides only a partial understanding of the direct and indirect effects of the various factors involved (Zecevic et al. 2004). A more effective alternative method is biplot analysis, which is used to analyze different two-way data, such as genotype by trait (Yan and Holand 2010). Genotype by trait biplot analysis is widely applied in the selection process to develop new cultivars in breeding programmes (Branković et al. 2018). This method offers valuable insights by evaluating genotypes across multiple traits (Mohammadi 2019) and reveals the relationships between traits aligning with findings from correlation coefficients (Schulthess et al. 2013).

Wheat breeding is an ongoing process, and there is a need to develop new durum wheat cultivars with high quality and grain yield to address the demands of a growing global population and meet consumer expectations. A comprehensive understanding of the variability in grain yield and quality performances among advanced breeding lines could help our ongoing efforts to improve these traits in durum wheat. It could motivate the better selection of superior wheat cultivars in breeding programmes. Therefore, this study was conducted to evaluate the durum wheat genotypes based on quality and grain yield; to determine the heritability of the traits and to find out the relationships among the traits using biplot and correlation analyses.

Materials and methods

Materials

The research was carried out with a total of 24 durum wheat genotypes comprising 4 registered cultivars (Kızıltan 91, Eminbey, Vehbibey, and Çeşit-1252) and 20 advanced lines, sourced from the Durum Wheat Regional Yield Trial-2 at the Central Research Institute for Field Crops in Ankara, Türkiye. The material was grown during 2020-2021 under rainfed conditions across four diverse locations, namely, Ikizce-Ankara, Malya-Kirsehir, Polatli-Ankara, and Ulas-Sivas. The genotypes used in the experiment and their coded names and pedigrees are given in Table 1.

Conduct of experiment and recording of data

Grain yield (GY) was measured from a 6 m^2 plot (5 x 1.2 m) and reported in kilograms per hectare (kg/ha). Prior to physical analyses, wheat samples were cleaned using a dockage tester (Quator, Tripette & Renaud, France). Test weight (TW) was determined in kilograms per hectolitre (kg/hl) using a one-litter container (Seedburo Equipment Company, Chicago, IL). Hardness index (HI), kernel diameter (KD), and kernel weight (KW) were assessed using the single kernel characterization system (SKCS 4100, Perten Instruments, Sweden) in accordance with AACCI method No: 55-31 (AACC International 2010). Additionally, kernel vitreousness (KV) was evaluated following ICC Method No: 129 (ICC 2008).

To measure moisture and grain protein contents (GPC), a portion of the durum wheat sample was ground into a meal using a Perten 3100 laboratory mill (Huddinge, Sweden) after the physical analyses. Additionally, samples were milled into flour using a Brabender Quadrumat Junior (Duisburg, Germany) in accordance with AACCI Method No: 26-50 (AACC International 2010). The flour samples were stored at 4°C for two weeks before starting analyses. Moisture content was measured according to AACCI Method No: 44-15A, while protein content was determined using AACCI method No: 46-30 (AACC International 2010), with a conversion factor of 5.7 applied for protein calculation. SDS sedimentation (SDSS) and modified SDS sedimentation (MSDSS) analyses were performed following the methodology outlined by Koksel et al. (2009). The *L, a, b* colour values were measured using a Hunter Lab colourimeter (Gardner BYK, Colour View, USA).

A statistical analysis software (JMP 13.2.1) was used to perform an analysis of variance (ANOVA) and Pearson Correlation Coefficients (SAS Institute Inc., Cary, NC, USA). Broad-sense heritability (h^2b) was calculated using GGE-biplot software, as described by Yan and Holland (2010). To examine the relationships among traits and genotypes, a genotype-trait biplot was generated using the GenStat program (17th edition, VSN International Ltd., Hemel Hempstead, UK).

Table 1. The coded names and pedigree of genotypes used in the experiment

No	Coded names	Line pedigrees and cultivar names
1	1	Ank-013/073-44//Ank-013/073-44/3/Eminbey
2	2	Zenit//Ank-014/ Zf7113
3	3	Ydf2-3/Ank 98//Ank-98/3/Cali"S"/Ank-05/95
4	4	Ydf2/Sari//Ank-98/3/Ç-1252
5	Eminbey	Eminbey
6	6	Kızıltan 91/Mbvd-021
7	7	T539/3/Üvy162/61-130//13-6/4/Br180/ Dk60-120//Leeds/64-210/3/Berk469/5/İmren
8	8	Ç-1252/Eminbey
9	9	Ank-013/073-44//Sebou
10	Kiziltan	Kızıltan 91
11	11	Unknown/Ç-1252/2/Ç-1252/3/Ank-014/ Zf7113
12	12	61-130/Tela//Ç-1252
13	13	61-130/414-44//377-2/3/ Ank-014/4/08-09 Mbvd-018/5/ Kızıltan 91/6/Eminbey
14	14	61-130/Telemara//Unknown/3/İmren
15	Cesit	Çeşit-1252
16	16	Standart3/Berk// Ç-1252/3/Ank-014/ Zf7113
17	17	Standart3/Berk// Ç-1252/3/Ank-014/ Zf7113
18	18	Df9-71/3/Vz466//61-130/414-44/4/ Ergene/5/61-130/414-44//Çmk79
19	19	61-130/414-44//377-2/3/ Ank-014/4/08-09 Mbvd-018/5/ Kızıltan 91/6/Eminbey
20	Vehbibey	Vehbibey
21	21	Altın 40/98//Ank-013/073-44
22	22	Ank-015/ Ç-1252//Eminbey
23	23	Zf/Lds//185-1/3/61-130/4/ Ank-08/5/Kızıltan 91
24	24	Standart3/Berk// Ç-1252/3/Ank-014/ Zf7113

Results and discussion

Descriptive statistics for grain yield and quality parameters

The mean, maximum, minimum, standard deviation, and heritability values for grain yield and some quality parameters for 24 genotypes grown in 4 different locations are presented in Table 2. Kernel size plays a significant role in influencing various compositional and qualitative characteristics, as larger and heavier kernels typically contain a higher amount of starchy endosperm and lower proportions of external pericarp and aleurone layers. The KW and TW directly affect the semolina and flour yields, making them critical factors for the milling industry. Therefore, there is a strong preference, particularly within the milling sector, for wheat varieties with high KW and TW (Brandolini et al. 2011).

The variation in TW was slightly wider among environments than among genotypes, while the opposite result was observed for KW. However, KD showed comparable levels of variation for both genotypes and environments, with a mean value of 2.93 mm in the present study (Table 2). The literature presents varying findings regarding these parameters. For instance, Taghouti et al. (2010) reported that genotypic effects predominantly influence TW, while Subira et al. (2014) found that environmental factors play a more significant role in TW in Mediterranean regions. On the other hand, Guzman et al. (2016) observed substantial variability in both TW and kernel weight KW across genotypes and environments. These discrepancies may stem from differences in wheat species, cultivars, environmental conditions, and agronomic practices employed in the studies, all of which significantly impact KW, TW, and KD.

A defining characteristic of durum wheat is its hard and vitreous grain structure (Lafiandra et al. 2022). Among its key quality parameters, KV plays a critical role in the pasta industry, as it influences semolina yield, purity, and granulation, thereby determining the commercial value of durum wheat (Pinheiro et al. 2013). Additionally, KV impacts pasta cooking quality (Fu et al. 2018). In this study, the variation in HI was slightly broader among genotypes than across environments, whereas KV exhibited the same variations for both genotypes and environments (Table 2). The high heritability value for HI (0.89) aligns with expectations, as grain hardness is primarily controlled by genes at the Hardness locus (Ha), located on the short arm of chromosome 5D, which encode Puroindolines a and b (Bhave et al. 2009). However, KV had low heritability (0.24) (Table 2), likely due to its strong sensitivity to environmental conditions. These findings are consistent with previous studies, which reported high heritability for HI (0.90) (Guzman et al. 2016) and moderate heritability for KV (0.67) (Sieber et al. 2015).

Colour is a critical quality parameter in durum wheat, significantly influencing consumer preference. In the present study, the colour parameters(*L*: lightness/brightness, *a*: redness *b*: yellowness) presented wider variation among genotypes than across environments (Table 2). These findings align with those of Schulthess et al. (2013), who reported a wide range (18.6–22.6) in the b^* value among genotypes. The *L, a,* and *b* colour traits were primarily controlled by genetic factors, as evidenced by their high heritability values (≥0.78) (Table 2). Among these, the colour *b* value (yellowness) is a key selection criterion in durum wheat breeding programmes. High heritability values for the colour *b* value (≥0.90) were reported in the literature (Longin et al. 2013; Sieber et al. 2015), corroborating the results of this study.

Grain protein content (GPC) plays a crucial role in determining wheat quality, with higher protein levels generally required for achieving good cooking quality in durum wheat products (Saini et al. 2022). In this study, the range of GPC values was slightly wider among genotypes than across environments (Table 2), a finding consistent with those reported by Branković et al. (2018). It was stated that the variation and mean value in GPC tend to increase under heat and drought stress conditions compared to optimal growing conditions (Guzman et al. 2016). Since this study was carried out under rainfed conditions, the range of GPC across locations may be narrower compared to the variation observed among genotypes.

For producing high-quality pasta, a GPC exceeding 13% is desirable, as it enhances pasta quality and improves tolerance to overcooking (Saini et al. 2022). In the present study, the minimum GPC for genotypes was 12.5%, with a mean of 13.3% (Table 2). According to the Pasta Communique (2002/20) of the Turkish Food Codex (2002), the protein content of pasta must exceed 10.5% on a dry matter basis, corresponding to a minimum of 12% GPC to ensure product quality. The GPC values observed in this study fall within the range required for producing high-quality pasta, as specified by the Pasta Communique (2002/20).

Sedimentation tests assess both the quantity and quality of protein fractions, which determine the gluten characteristics. These tests are widely used by wheat

Table 2. The mean, minimum, maximum, and standard deviation of wheat grain yield and quality parameters across genotypes and environments

Values / Traits[a]	Genotypes (n = 24)			Environments (n = 4)			Mean (n = 96)	Heritability
	Min.	Max.	Std. D.	Min.	Max.	Std. D.		
TW (kg/hl)	79.1	83.0	0.9	78.4	83.5	2.1	81.2	0.89
KW (mg)	32.0	37.8	1.6	34.1	39.2	2.4	35.7	0.73
KD (mm)	2.81	3.05	0.06	2.86	3.05	0.09	2.93	0.79
HI	72.9	84.1	2.7	76.2	84.6	3.5	79.9	0.89
KV (%)	97	100	1.2	97	100	1.5	98.8	0.24
L	94.29	96.15	0.41	95.18	95.69	0.21	95.45	0.78
a	1.52	1.95	0.12	1.57	1.84	0.11	1.73	0.79
b	16.87	23.56	1.69	19.14	20.83	0.90	19.97	0.99
GPC (%)	12.5	14.0	0.4	12.7	14.1	0.6	13.3	0.53
SDSS (ml)	9	73	18	38	48	4	43	0.98
MSDSS (ml)	12	68	14	31	50	8	39	0.90
GY (kg/ha)	2,066	2,712	156	1,570	3,623	897	2,359	0.51

[a]Traits: Test weight (TW), Kernel weight (KW), Hardness index (HI), Kernel diameter (KD), Kernel vitreousness (KV), Color L value (L), Color a value (a), Color b value (b), Grain protein content (GPC), SDS sedimentation value (SDSS), Modified SDS sedimentation value (MSDSS), Grain yield (GY).
The results of TW and GPC were expressed on dry weight basis. The results of SDSS and MSDSS were expressed on 14% moisture basis.

breeders to select durum wheat genotypes (Clarke et al. 2010), since strong gluten and high protein content are essential for producing pasta with a firm texture and high cooking quality (Deng et al. 2017). In this study, both SDSS and MSDSS exhibited wider variation among genotypes across environments (Table 2). The SDSS values showed higher and wider variation compared to the findings of Branković et al. (2018) for genotypes. Both SDSS and MSDSS had high heritability values (≥0.90) (Table 2), indicating strong genetic control over these traits. Notably, the standard deviations for SDSS were four times greater among genotypes than across environments, highlighting significant genetic variability within the study material. This genotypic diversity is essential for developing cultivars with improved gluten quantity and quality.

In addition to determining protein quantity and quality, the MSDSS test is specifically used to assess suni-bug (*Eurygaster integriceps*) damage in wheat. A lower MSDSS value compared to the SDSS value indicated a deterioration in gluten quality caused by suni-bug damage (Koksel et al. 2009). Unfortunately, the results of both sedimentation tests in the present study revealed that the genotypes had suni-bug damage (Table 2). Therefore, rheological and end-product quality analyses could not be performed, since the gluten quality was negatively affected by the sun-bug damage.

The variation in GY was larger across environments than among genotypes, as expected. The standard deviation for GY was about 6 times higher across environments compared to genotypes (Table 2), indicating significantly higher variability due to environmental factors. These findings align with those of Vazquez et al. (2012), who concluded that environmental conditions primarily dictate GY variation. Similarly, Subira et al. (2014) found that 76.4% of yield variability could be attributed to environmental factors. In this study, a moderate heritability value (0.51) was calculated for GY further supporting the influence of environmental conditions on yield. This result is consistent with the low heritability values reported by Longin et al. (2013), reinforcing the idea that GY is more susceptible to environmental than genetic variation.

In wheat breeding programmes, GY is one of the most important parameters affecting the selection of genotypes based on multiple traits. Therefore, a more detailed account was given for GY compared to other parameters. Fig. 1 and Table 3 present the variations and mean values of GY across genotypes and environments. The mean GY in this study was 2,359 kg/ha. Although all genotypes presented the mean GY value or higher in at least one environment, particularly lines 2, 8, 10 (cv. Kiziltan), 11, 12, 13 16, 17, 20 (cv. Vehbibey), and 24 had yielded over 4,000 kg/ha in at least in one location. Among the locations, Ikizce exhibited the highest variability and mean GY, whereas Malya showed the lowest variability and mean GY. Despite the high variability in GY at İkizce, this location can be considered the most suitable environment for wheat production among those tested (Fig. 1).

The heritability of a trait determines the success of selection in breeding programmes (Dencic et al. 2011). Table 2 presents the heritability values for all traits examined in this study, which ranged from 0.24 for KV to 0.99 for the colour *b* value. Similar heritability values were reported for SDSS (0.79) and GPC (0.78) (Michel et al. 2017). Guzman et al. (2016) also documented high heritability values for TW (0.88), KW (0.97), HI (0.90), GPC (0.83), and SDSS (0.96). However, Mladenov et al. (2001) recorded relatively low heritability values for TW (0.29), GPC (0.35), and SDSS (0.50), attributing this to the significant influence of environmental factors on the phenotypic variation of these traits. Similarly, Heidari et al. (2016) found a relatively low heritability value for KW. Kaya and Akcura (2014) observed that heritability values varied widely, ranging from 0.32 for TKW to 0.52 for ZSV, which they linked to greater environmental variance. These differences highlight the complex interplay between genetic and environmental factors in shaping trait heritability.

Biplot and correlation analyses

Determining relationships among traits is essential when evaluating quality, especially when multiple traits are involved (Mladenov et al. 2001). In this study, associations among traits were examined using correlation and biplot analyses. Table 4 presents the Pearson correlation coefficients for the traits studied. Grain yield positively correlated with TW, KW, KD, and colour *L* value but negatively correlated with HI, colour *b* value, and GPC. Similarly, TW showed significant positive correlations with KW and KD, but negative correlations with HI, colour *b* value, SDSS, and MSDSS. The trait KW was positively correlated with KD and colour *b* value but negatively correlated with HI and GPC. Kernel diameter had a negative correlation with colour *L* value, but negative correlations with HI, colour *b* value, and GPC. Additionally, the colour *L* value was negatively correlated with the colour *b* value, GPC, and SDSS. The colour *a* value negatively correlated with KVbut positively correlated with colour *b* value, SDSS, and MSDSS. Colour *b* value exhibited negative correlations with KV and GPC while showing positive correlation with SDSS and MSDSS. SDSS showed positive correlations with GPC and MSDSS (Table 4).

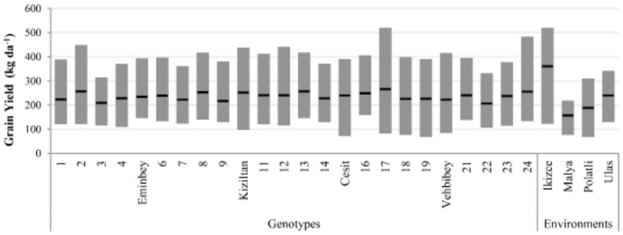


Fig. 1. The range and mean values of grain yield for both genotypes and environments

Table 3. Mean values of grain yield **(kg/ha)** for 24 genotypes grown at five environments

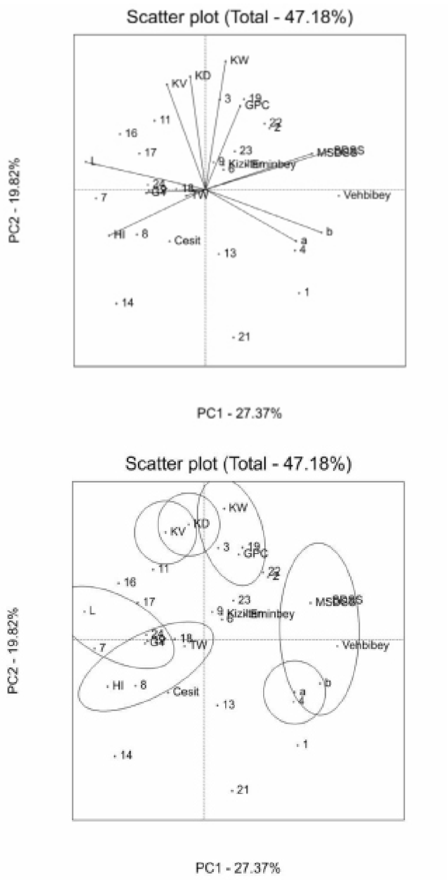
Genotypes	Environments				Mean value (kg/ha)
	Ikizce	Malya	Polatli	Ulas	
1	3,370±280^{df}	1,376±82de	1,959±253^{ac}	2,200±234^{ae}	2,226±212^{df}
2	4,132±165^{ab}	1,566±190^{ad}	2,156±235^{a}	2,400±127^{ae}	2,564±259^{ab}
3	2,543±447^{g}	1,552±139^{ad}	2,060±260^{ac}	2,197±279^{ae}	2,088±163^{f}
4	3,314±208^{df}	1,401±111^{ce}	2,021±222^{ac}	2,363±113^{ae}	2,275±194^{cf}
Eminbey	3,445±205^{cf}	1,691±46^{ac}	1,985±268^{ac}	2,227±135^{ae}	2,337±190^{bf}
6	3,642±165^{bf}	1,508±73^{ae}	2,172±197^{a}	2,217±227^{ae}	2,385±215^{ae}
7	3,259±216^{ef}	1,737±34^{a}	1,983±290^{ac}	1,898±190^{e}	2,219±181^{df}
8	3,781±181^{ae}	1,665±118^{ad}	2,077±163^{ac}	2,576±247^{ac}	2,525±220^{ac}
9	3,367±148^{df}	1,516±126^{ae}	1,829±166^{ac}	1,957±125de	2,167±194^{ef}
Kiziltan	3,862±251^{ae}	1,409±37^{be}	2,115±439^{ab}	2,674±311^{ab}	2,515±267^{ac}
11	3,748±195^{af}	1,519±133^{ae}	1,826±223^{ac}	2,521±193^{ad}	2,403±236^{ae}
12	3,883±261^{ad}	1,531±201^{ae}	1,759±175^{ac}	2,435±272^{ae}	2,402±258^{ae}
13	3,999±70^{ac}	1,566±75^{ad}	2,001±169^{ac}	2,687±149^{ab}	2,563±243^{ab}
14	3,474±108^{cf}	1,635±105^{ad}	1,778±193^{ac}	2,194±371^{ae}	2,270±211^{cf}
Cesit	3,721±90^{af}	1,670±67^{ad}	1,452±259^{c}	2,733±116^{ab}	2,394±243^{ae}
16	3,747±135^{af}	1,705±67^{ab}	2,118±202^{ab}	2,366±68^{ae}	2,484±206^{ad}
17	4,330±297^{a}	1,593±273^{ad}	2,092±236^{ac}	2,622±297^{ac}	2,659±293^{a}
18	3,602±149^{bf}	1,241±164^{e}	1,504±156^{bc}	2,660±130^{ab}	2,252±253^{cf}
19	3,307±216^{df}	1,655±189^{ad}	1,534±294^{ac}	2,536±107^{ad}	2,258±208^{cf}
Vehbibey	3,552±319^{bf}	1,424±231^{be}	1,760±253^{ac}	2,149±160^{be}	2,221±236^{df}
21	3,537±161^{bf}	1,654±110^{ad}	1,994±19^{ac}	2,402±108^{ae}	2,397±190^{ae}
22	3,158±113^{fg}	1,539±209^{ae}	1,503±208^{bc}	2,059±266^{ce}	2,065±195^{f}
23	3,650±74^{bf}	1,510±179^{ae}	1,588±78^{ac}	2,737±250^{a}	2,371±239^{be}
24	3,994±354^{ac}	1,790±205^{a}	1,808±76^{ac}	2,626±80^{ac}	2,554±250^{ab}
Mean Value	3,601	1,561	1,879	2,394	2,359
LSD	309.6	151.3	324.9	293.6	141.9
CV (%)	12.2	13.7	20.5	17.3	17.0
Significance	*	*	*	*	**

$^{a-g}$: Different superscripts within the same column indicate a statistically significant difference.
*, **: Significant at the %5 and %1 probability levels indicted by one and two asterisks, respectively.

A genotype with high KV is generally associated with high GPC. In this study, a positive relationship was determined between KV and GPC (Table 4), consistent with the findings of Sieber et al. (2015). However, Fu et al. (2018) found no clear relationship between KV and GPC, noting instances of high KV with low GPC and low KV with high GPC in durum wheat breeding programmes. They also observed that durum wheat genotypes with the same GPC exhibited a wide range of KV. These variations may arise from differences in genotypes, environmental conditions, and fertilizer applications across studies. GPC is a quantitative trait controlled by multiple genes and is heavily influenced by environmental factors and agronomic practices (Branković et al. 2018). Besides, similar to the results of this study, positive correlations were reported between GY and KW (Sasani et al. 2020; Khalid et al. 2023), between GY and TW (Taheri et al. 2021), and between GPC and SDSS (Sasani et al. 2020). Conversely, negative correlations between GPC and GY (Longin et al. 2013; Sieber et al. 2015; Taheri et al. 2021), and between GPC and TW (Taheri et al. 2021) were also reported. Our results are consistent with these previous reports. The negative relationship between GPC and GY or TW might be due to the impact of protein content since low protein content could be a result of high grain yield. The negative relationship between GPC and GY or TW may be attributed to the dilution effect, where high grain yield can lead to lower protein content due to the increased proportion of non-nitrogen compounds during the grain-filling stage (Branković et al. 2018). Similarly, Guzman et al. (2016) noted that TW and KW had a negative relationship with GPC, which they attributed to the dilution or concentration-effect depending on grain size. These results highlight the complex interplay between yield, protein content, and other quality traits in durum wheat.

The biplot method is a powerful tool for analyzing and ranking wheat genotypes based on their performance across multiple traits and environments (Kendal and Sener 2015). In this study, biplot analysis was employed alongside Pearson correlation coefficients to evaluate relationships between traits and compare genotypes, facilitating the identification of lines with desirable characteristics. The first two principal components (PC1 and PC2) collectively explained approximately 47.18% of the variability among genotypes and traits, with PC1 accounting for 27.37% and PC2 for 19.82% (Figs. 2a, b). In a biplot, vectors representing traits that form acute angles indicate positive correlations, obtuse or straight angles suggest negative correlations and vertical angles imply no correlation. Additionally, the proximity of genotypes reflects their similarity (Yan and Holland 2010).

A strong relationship was observed between colour a and b values. SDSS and MSDSS were grouped closely, indicating a significant relationship between them. GPC, KW, KD, and KV were positioned at the top of the chart, suggesting strong positive associations among these traits (Fig. 2a). These findings align with those of Branković et



Grain yield (GY), Test weight (TW), Kernel weight (KW), Hardness index (HI), Kernel diameter (KD), Kernel vitreousness (KV), Color *L* value (*L*), Color *a* value (*a*), Colour *b* value (*b*), Grain protein content (GPC), SDS sedimentation value (SDSS), Modified SDS sedimentation value (MSDSS).
The numbers belong to the lines.

Figs. 2a and b. Biplot analysis for genotypes and traits according to (a) the option of connecting trait scores with origin and (b) the option of mega environment

Table 4. Correlations coefficients among traits

Traits[a]	GY	TW	KW	HI	KD	KV	L	a	b	GPC	SDSS
TW	0.375**										
KW	0.571**	0.552**									
HI	-0.262*	-0.546**	-0.557**								
KD	0.561**	0.556**	0.901**	-0.498**							
KV	-0.022	0.105	0.171	-0.156	0.154						
L	0.345**	0.127	0.262**	0.134	0.225*	-0.091					
a	0.154	-0.127	-0.018	0.137	-0.111	-0.255**	-0.136				
b	-0.205*	-0.268**	-0.084	-0.037	-0.223*	-0.313**	-0.234*	0.475**			
GPC	-0.426**	-0.062	-0.261**	-0.159	-0.209*	0.411**	-0.540**	-0.128	-0.270**		
SDSS	-0.137	-0.268**	-0.021	-0.072	-0.153	-0.051	-0.229*	0.188*	0.353**	0.277**	
MSDSS	0.070	-0.312**	0.079	0.086	-0.069	-0.141	0.012	0.293**	0.386**	0.176	0.812**

[a]Traits; Grain yield (GY), Test weight (TW), Kernel weight (KW), Hardness index (HI), Kernel diameter (KD), Kernel vitreousness (KV), Color *L* value (*L*), Color *a* value (*a*), Color *b* value (*b*), Grain protein content (GPC), SDS sedimentation value (SDSS), Modified SDS sedimentation value (MSDSS).
*, **: Significant at the %5 and %1 probability levels, respectively.

al. (2018), who also reported positive relationships among KV, GPC, and SDSS. GY and TW were located near each other, while HI and colour b values were positioned farther apart from the other traits (Fig. 2a). These results suggest that achieving higher GY, protein content, and gluten quality simultaneously in a single genotype is challenging, as indicated by the biplot analysis. This observation is consistent with the findings of Kaya and Akcura (2014), who also reported a negative relationship between GY and GPC. The relationships between traits observed in the biplot analysis generally aligned with the correlation coefficients in this study. However, some discrepancies were noted, as the biplot captures the interrelationships among all traits simultaneously, reflecting the overall structure of the data. These differences arise because the biplot provides a holistic view of trait interactions, whereas correlation analysis focuses on pairwise relationships.

Regarding the genotypes, particularly, genotypes 3 and 19 were grouped around KW and GPC. The cv. Vehbibey was positioned near SDSS, MSDSS, colour *b* and values, suggesting its favorable performance for these quality parameters. Genotype 4 was close to colour *b* and *a* values, while genotypes 7, 12, and 24 were grouped near colour *L* value and GY. Additionally, genotypes 8, 12, 18, and 24 were located close to GY, TW, and HI (Fig. 2b). Colour and SDS are among the most important quality parameters in durum wheat breeding programmes. Genotype selections in early generations are often based on these traits due to their high heritability values (Longin et al. 2013). When GY and these two quality traits were evaluated together in the biplot, none of the genotypes were positioned close to all three parameters simultaneously. However, cv. Vehbibey was located between SDSS and colour *b* value, indicating its balanced and desirable performance for both quality traits across the tested environments. Genotypes grouped together in the biplot exhibited similar performance patterns across various quality parameters, as noted by Kaya and Akcura (2014). This clustering provides valuable insights for selecting genotypes with desirable trait combinations in breeding programmes.

The development of durum wheat cultivars depends on regional or national priorities. Countries such as Italy and Türkiye prioritize cultivating high-quality durum wheat to meet the demand for premium products in the market. The findings of this study revealed significant variability among genotypes and environments for GY and all grain quality parameters. Notably, HI, colour *L,a,b* values, SDSS, and MSDSS showed wider variation across genotypes than across environments. This genotypic variability offers wheat breeders an opportunity to select and develop new, superior cultivars with improved quality. Both biplot and correlation analyses identified significant relationships among traits, providing valuable insights for targeted breeding efforts.

Authors' contributions

Conceptualization of research (AKE, TŞ, AP, AS, SY, BÖ); Designing of the experiments (AKE, AP, AS, SY); Contribution of experimental materials (AS, SY, BÖ, MEA, GK, MİA, FBS); Execution of field/lab experiments and data collection (AKE, AP, TŞ, FÜC, RA, ŞK, AS, SY, BÖ, MEA, GK, MİA, FBS); Analysis of data and interpretation (AKE, AP); Preparation of the manuscript (AKE, AS, MİA).

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