https://doi.org/10.61308/NDZW8081

Analysis of the technological quality and agronomic traits of the PWD1216/ MvTD10-98 winter durum wheat mapping population

Gyula Vida*, Katalin Puskás, Mónika Cséplő
HUN-REN Centre for Agricultural Research, Agricultural Institute, 2462 Martonvásár, Hungary
*Corresponding author: *vida.gyula@atk.hun-ren.hu*
Gyula Vida ORCID ID: https://orcid.org/0000-0002-5244-5170
Mónika Cséplő ORCID ID: https://orcid.org/0009-0002-8951-5424

Citation: Vida, G., Puskás, K., & Cséplő, M. (2025). Analysis of the technological quality and agronomic traits of the PWD1216/MvTD10-98 winter durum wheat mapping population. *Bulgarian Journal of Crop Science, 62*(6) 29-40

Abstract: To investigate the inheritance of the Minolta b* value related to yellow pigment content, a biparental winter durum wheat mapping population was created. The line 'PWD1216' was chosen as the parent with high yellow pigment content, and 'MvTD10-98' as the low one. The Minolta b* values of the parents and lines were evaluated for a total of 13 years. Measurement of gluten and thus gluten index were performed in 5 years. The Minolta b* value of the semolina of the line with the highest yellow pigment content exceeded 24 in 12 years, while the minimum values did not reach the value of 20 in most years. The gluten strength of the lines in the population varied within a wide interval. The gluten index of the lines with the strongest gluten structure significantly exceeded that of both parents. The gluten index of the line with the weakest gluten was between 1.18 and 9.93. The effect of years and genotypes was analyzed using a linear mixed model. In our experiment, other traits (wet gluten content, plant height, heading time and cold tolerance under phytotron conditions) were also observed in several years, so we could analyze the correlation of these traits with the Minolta b* value and the gluten index. In this population the Minolta b* value and the gluten index proved to be genetically well-determined traits, but in addition to these two more traits, the heading time and plant height were also controlled to a decisive extent by the genetic background.

Keywords: *Triticum turgidum* ssp. *durum*; Minolta b* value; gluten index; inheritance; repeatability

INTRODUCTION

Durum wheat is the second largest cultivated *Triticum* species in the world. Its cultivation area in Hungary exceeded 50,000 ha in 2024 (Eurostat, 2025), which is expected to increase due to favorable market opportunities. The country's climatic conditions are favorable for the cultivation of winter varieties, as these genotypes are able to utilize winter precipitation and, due to their earlier grain-filling period and ripening, their yield can be several times higher than that of spring-sown varieties. Winter durum wheat represents a special group among durum wheat genotypes, its cultivation is mainly concentrated to Eastern and Central-Eastern European countries (Palamarchuk, 2005). Durum wheat cultivation began in Hungary in the 1980s (Beke and Barabás, 1981) and has only been steadily exceeding 10,000 ha since 2009 (Eurostat, 2025). The first winter durum wheat varieties from Martonvásár were registered in 1996 (Szunics et al., 1998), and the primary goal during their breeding was to improve cold tolerance. Additional years were needed for the technological quality of the winter varieties to be competitive with those of the spring varieties. The yellow pigment content and gluten quality of

the new varieties now meet the requirements of the processing industry.

The development of the yellow color of dry pasta made from durum wheat is influenced by two main factors: the genetically determined quality of the raw material and the technology used by the processing industry (Irvine and Winkler, 1950; Irvine and Anderson, 1953). Among the genetically determined traits, the yellow pigment content ranks first (Borrelli et al., 1999), which plays a special role in the technological classification of durum wheat. The methods developed for determining the yellow pigment content are based on spectrophotometric measurements, the versions of which are still widely used today, and on chromatographic measurements. A group of measurement methods is not based on the chemical analysis of the compounds forming the pigment, but on the determination of the strength and depth of the yellow color in the visible or near infrared range. From a practical point of view, the results of these measurements are the easiest to interpret, since the consumer also chooses a product based on the visible color and not on the lutein content. Another advantage of direct color measurement is that it eliminates possible errors during extraction of sample preparation, and also takes into account that other factors (particle size, refractive index, lipoxygenase and peroxidase enzyme activity) play a role in the formation of color intensity (Matz and Larsen, 1954; Borrelli et al., 2008). After demonstrating the correlation between optically measured values and carotenoid content (Johnston et al., 1980), the method was clearly found suitable for use in durum wheat breeding programs, as it allows selection to increase the yellow pigment content quickly and without the use of hazardous chemicals.

Yellow pigment content is a highly heritable trait, with h^2 values ranging from 0.66 to 0.96 in most of the studied spring durum wheat populations (Braaten et al., 1962; Lee et al., 1976; Santra et al., 2005; Clarke et al., 2006). Several biparental mapping populations of spring durum wheat were created until the mid-2010s to identify the chromosomal regions determining yellow pigment content (Elouafi et al., 2001; Pozniak et al., 2007; Blanco et al., 2011; Alsaleh et al., 2015), but no similar study has been conducted in winter durum wheat.

A valuable technological quality property of durum wheat is the strong gluten matrix, which is able to keep the starch molecules in a bound form during processing and cooking (Feillet, 1984), and as a result, the dough will retain its shape during cooking. Reserve proteins, and within these, gluten-forming proteins, play a prominent role in the development of the technological quality of bread and durum wheat. Durum wheat is a tetraploid species, thus in its natural form it carries only the genes found on the A and B genomes. The diversity is still extraordinary. Melnikova et al. (2012) examined the gliadin composition of 700 durum wheat varieties from 45 countries and revealed the presence of 16 Gli-A1, 41 Gli-A2, 19 Gli B1, 55 Gli-B2 and 1 Gli-B5 alleles. When examining glutenins, Sissons et al. (2005) identified 9 HMW and 14 LMW subunits in a durum wheat population consisting of 229 Canadian and 139 Australian genotypes. Several prolamin alleles also have a statistically proven effect on the quality of durum wheat (Martinez et al., 2005). The role of HMW glutenin subunits, which are of paramount importance in shaping the baking quality of wheat (*Triticum aestivum*), is less significant in shaping the quality of dry pasta (Branlard and Marion, 2011). Among the gliadins, the first report was about the effect of γ-gliadin subunits 42 and 45. According to the results of Damidaux and Feillet (1978), the average R value measured by viscoelastograph of varieties carrying the γ-gliadin subunit 45 exceeded those carrying the gliadin protein subunit 42. Results of Payne et al. (1984) and Pogna et al. (1988), on the other hand, proved that gliadin proteins can only be considered as markers and that the real effect on the viscoelastic properties and strength of gluten is exerted by the LMW glutenin subunits (LMW-1 and LMW-2) encoded by genes located on the short arm of chromosome 1B. The genes responsible for the production of HMW glutenin subunits located on the long arms of chromosomes 1A and 1B are also found in durum wheat. Bran-

lard et al. (1989) identified 7 subunits encoded by chromosome 1A and 11 by chromosome 1B in 502 durum varieties.

The strength of gluten can be determined by several rheological testing methods. The measurement of the gluten index (GI) is well-suited for durum wheat breeding programs, the methodological basis of which was developed by Harald Perten (1990). A modified version of the gluten index method was developed by Cubadda et al. (1992), who first used to investigate durum wheat wholemeal and semolina. The gluten index is a highly heritable genetic trait, and its heritability value was between 0.84 and 0.93 in the experiment of Clarke et al. (2000). Their results were later confirmed using a wider range of varieties (Clarke et al., 2009).

An outstanding goal in the winter durum wheat breeding program in Martonvásár is to increase the yellow pigment content. For a detailed molecular investigation of the genetic background determining the trait, we created a biparental mapping population by crossing the PWD1216 high Minolta b* value line and MvTD10-98 line with low Minolta b* value. In addition to the Minolta b* value and the gluten index, we also observed several morphological and phenotypic traits of these lines and analyzed the correlation between the traits. In our publication, we present the results of this work.

MATERIALS AND METHODS

Location

The experiments were set up between 2001 and 2014 on the same field (Martonvásár, 47°18'N/18°49'E). The forest residue chernozem soil was sufficiently homogeneous. The soil was neutral in pH (6.99) and loamy in physical form. Based on its humus content (2.4 m/m%), it had a medium nitrogen supply, the phosphorus content was medium (120 mg kg^{-1}), while the potassium supply was uniformly good (>300 mg kg^{-1}). The precrop of the experiments was oil radish. The nutrient supply in the experiments was carried out by applying 60:60:60 kg ha^{-1} N:P:K in the autumn, which was followed by a single 60 kg ha^{-1} nitrogen top dressing in early spring. The sowing was carried out with a HEGE-90 type plot drill (Hans-Ulrich Hege GmbH und Co., Waldenburg, Germany). During the growing season, weed control (MCPA, clopyralid, triasulfuron, tribenuron-methyl + fluroxypyr, if necessary fenoxaprop-P-ethyl active ingredient) and insecticide (lambda-cyhalothrin, esfenvalerate) were applied. The plots were harvested with a Wintersteiger plot combine harvester (Wintersteiger AG, Reid, Austria) at full maturity. The meteorological characteristics of the vegetation periods are presented in Table 1. The plots were 2 m in length, with a row distance of 20 cm, the tests were carried out in two replicates.

Phenotypic studies

For determining the chromosome regions controlling Minolta b* value and gluten, a biparental mapping population was created. Breeding lines with extremely high and low Minolta b* values were selected as parents. The high yellow pigment parent was the durum wheat line 'PWD1216' (Saatzuch Donau GmbH, Probstdorf, Austria), and the low one was the 'MvTD10-98'from Martonvásár. After the crossing, a total of 240 lines were generated from the F_1 generation. The first technological quality test was performed in the F_3 generation (samples of $F_{2:3}$ families) in 2001. From the F_5 generation (2003), the population was treated as consisting of recombinant inbred lines. From then on, the Minolta b* value of the samples was measured every year until 2014, in accordance with the purpose of the mapping population. The gluten index of the lines constituting the population proved to be diverse as well, therefore this trait was also determined over five years. In addition to these two technological quality traits, we examined the wet gluten content of the lines (according to the ICC158 standard, from semolina (ICC, 1995)) and among the phenotypic data, we observed the heading time (7 years, UPOV, 1988), the plant height (6 years, measured in cm together with the awns according to UPOV, 1988) and the phytotron cold toler-

Table 1. Meteorological characteristics of the vegetation periods between 2000/2001 and 2013/2014 in Martonvásár, Hungary

Vegetation period	Precipitation (mm)		Mean temperature (°C)		No. of heat days[3]	Day of the year		Relevant meteorological stress factors
	Σ[1]	GFP[2]	Σ	GFP		sowing	harvest	
2000/2001	450.2	93.2	9.23	18.76	5	269	188	Dry grain filling period
2001/2002	188.8	45.0	9.14	19.91	11	271	179	Cold December, preharvest heat stress
2002/2003	231.0	39.0	7.00	21.37	27	283	178	Cold winter, hot & dry grain filling
2003/2004	484.4	130.6	7.35	18.46	8	282	194	Cold January
2004/2005	458.4	49.2	6.96	18.69	10	280	177	Wet harvest
2005/2006	421.6	118.4	7.30	19.01	17	283	191	Cold January, preharvest heat stress
2006/2007	167.8	86.6	10.64	20.71	30	285	173	Drought, preharvest heat stress
2007/2008	361.4	88.8	7.97	19.91	14	285	184	Above average amount of precipitation
2008/2009	320.0	85.5	8.32	18.06	6	283	183	Dry April & grain filling period
2009/2010	629.5	186.5	8.06	19.96	14	281	195	Excessive amount of precipitation
2010/2011	238.1	54.5	7.26	19.29	3	287	192	Cold December, preharvest heat stress
2011/2012	210.2	78.2	7.39	18.73	9	284	180	Drought, preharvest heat stress
2012/2013	381.8	68.2	7.63	17.96	7	279	183	Strong cold snap in mid-March
2013/2014	304.9	87.7	9.22	17.78	6	276	183	Dry January, mild winter

Notes: [1]Σ = period from sowing to harvest; [2]GFP = Grain filling period; [3]Daily maximum temperature ≥ 30°C

ance of the lines (2 years, according to the method published by Tischner et al., 1997).

Technological quality testing

The gluten index of the winter durum wheat samples was determined from semolina according to the ICC158 (ICC, 1995) standard, using a Perten Glutomatic 2200 and a Perten 2015 Centrifuge (Perten Instruments AB, Hägersten, Sweden). The Minolta b* value was measured between 1996 and 2016 with a Minolta CR-300, and from 2017 onwards with a Minolta CR-400 chromameter (the data measured by the two devices were compared when the type was changed, the values were the same). The tests were performed on semolina in all cases.

Semolina was produced until 2010 on a Brabender Junior laboratory mill (Brabender GmbH & Co. KG, Duisburg, Germany), which was adapted for milling durum wheat samples as recommended by Vasiljevic et al. (1977). At this time, the coarse bran fraction was separated on a Retsch KS 1000 sieve (Retsch GmbH, Haan, Germany). The 160–315 μm fraction was then purified on a Chopin Semolina Purifier (Chopin Technologies, Villeneuve-la-Garenne, France). Since 2010, durum wheat samples have been ground on a Chopin CD2 laboratory mill. Semolina was purified on the previously used Chopin Semolina Purifier, so the particle size of the semolina produced before 2010 and on the new mill was the same. Separation of HMW glutenin subunits was performed on SDS polyacrylamide gel (Jackson et al., 1996).

Statistical analyses

Statistical analyses were performed on the data of the durum wheat lines used for mapping

and the two parental varieties. Phenotypic data were analyzed using the SPSS 16.0 (SPSS Inc., Chicago, IL, USA) program with the linear mixed model (REML analysis) module. The fixed model was represented by the Constant + Genotype factor, and the random model was represented by Year. In the case of six traits for which we had data from multiple years, we determined the variance components (σ^2_G = genotypic variance; σ^2_{GY} = Genotype × Year interaction variance; σ^2_e = residual variance; σ^2_p = phenotypic variance) using the method of Longin et al. (2013). REML analysis (based on a random model), was performed, and then the repeatability (genotypic/phenotypic variance = h^2) values were calculated. Pearson's correlation coefficients were used for demonstrating the relationships between phenotypic traits.

The lines forming the population can be divided into two groups based on a morphological difference. The statistical reliability of the difference between the phenotypic mean values of the groups separated by the color of the awn was checked with a *t*-test (Microsoft Excel 2013; Microsoft Corporation, Redmond, WA, USA). Depending on the result of the *F*-test, the *t*-test was performed for equal or unequal standard deviations. Descriptive statistics of the molecular data were prepared using SPSS 16.0.

RESULTS AND DISCUSSION

Based on previously published results, it can be stated that the environment and genotype significantly influence both the Minolta b* value and the gluten index in winter durum wheat populations (Vida et al., 2022). In plant breeding, knowledge of the genetic factors encoding traits can make the targeted selection of offspring more efficient and faster. Following in the footsteps of DNA-level research initiated in wheat, the first results in spring durum wheat, were published within a short time. However, information in this regard was not available in winter durum wheat around the turn of the millennium. During this period, the low yellow pigment content of the winter genotypes significantly impaired the marketability of newly produced varieties. Therefore, two breeding lines with extremely high and low Minolta b* values were used as parents to create a mapping population. An Austrian line 'PWD1216' (Prostdorfer Saatzuch, currently Saatzucht Donau GmbH) was chosen as the parent with high yellow pigment content, and the line 'MvTD10-98' from Martonvásár as the parent with low yellow pigment content. Our primary goal was to identify the chromosome regions linked to yellow pigment content, and we measured the Minolta b* value of the parents and the offspring lines for a total of 13 years. We performed gluten washing and thus gluten index measurement for 5 years, so we were able to identify the genetic factors determining this trait on the linkage map. We used molecular data from 179 lines to compile the genetic map, and the published phenotypic data, also refer to this population and the two parents.

Descriptive statistics of the population and data on the parent lines broken down by year are included in Table 2.

Average values of the lines and parents did not differ significantly from each other (the result of the paired *t*-test: Minolta b*: 1.841^{ns}; gluten index: 1.669^{ns}). However, in the case of the two traits, a remarkable difference is visible between the values of the two parents and the extreme values of the population. The average Minolta b* value of the parents 'PWD1216' and 'MvTD10-98' differed significantly ($t = 20.815^{***}$). Among the lines the lowest Minolta b* value approached the value of the parent 'MvTD10-98', and the highest one was similar to the value of the parent 'PWD1216'. The Minolta b* value of the semolina of the line with the highest yellow pigment content exceeded 24 in 12 years – except for the 2011 – which corresponds to a high-quality raw material for the pasta industry, and in fact, in the most favorable year (2004) a value above 30 was measured. The minimum values did not reach the Minolta b* value of 20 in most years. The size of the range exceeded 7 in every year (the difference between the extreme values was 8.727 on average over 13 years), the largest difference was measured in 2005 between the two lines with extreme Minolta b* values (11.08).

Table 2. Descriptive statistics of the durum wheat lines forming the biparental population 'PWD1216/ MvTD10-98' and the Minolta b* value and gluten index of the parents

Year	Lines				Parents		
	Mean	**Minimum**	**Maximum**	**Standard deviation**	**PWD1216**	**MvTD10-98**	**Mean**
*Minolta b**							
2001	23.42	19.74	27.19	1.33	25.86	18.59	22.23
2003	22.42	18.59	26.03	1.27	26.03	20.32	23.18
2004	25.59	21.26	30.20	1.64	29.39	21.09	25.24
2005	21.98	16.65	27.73	2.05	25.28	18.42	21.85
2006	21.51	17.40	26.26	1.62	25.23	18.93	22.08
2007	24.67	19.63	29.57	1.92	28.27	21.67	24.97
2008	22.88	18.36	28.03	1.78	27.87	20.03	23.95
2009	21.60	16.80	26.20	1.81	24.80	18.88	21.84
2010	19.98	16.55	24.70	1.40	23.81	17.37	20.59
2011	18.97	15.43	23.78	1.55	24.17	16.64	20.41
2012	20.11	16.80	24.41	1.49	21.87	17.86	19.87
2013	20.23	16.50	24.34	1.66	24.45	18.03	21.24
2014	20.81	16.15	24.87	1.49	24.14	18.74	21.44
Mean	21.86	17.93	25.47	1.32	25.47	18.96	22.22
Gluten index							
2007	57.55	1.53	90.91	21.87	50.90	81.38	66.14
2011	62.93	1.64	95.94	19.94	61.65	59.50	60.57
2012	32.71	2.72	67.94	17.81	32.55	39.51	36.03
2013	22.80	1.12	76.26	21.64	25.97	30.65	28.31
2014	50.92	1.18	94.22	23.85	52.44	54.50	53.47
Mean	45.38	3.21	78.77	17.75	44.70	53.11	48.90

The gluten index of the two parents did not differ significantly on average over the years ($t = 1.514^{ns}$), despite this, the gluten strength of the lines of the population varied within a wide interval (average difference based on the 5-year data was 83.416). The gluten index of the lines with the strongest gluten structure significantly exceeded that of both parents. The gluten index of the line with the weakest gluten (G22) varied between 1.18 and 9.93, and the gluten structure was extremely soft regardless of the year. However, the data of the line with the highest gluten index (G136) had a larger variance (60.23–92.12). The gluten index of this line belonged to the "very good" to "excellent" category in four out of 5 years based on the Cubadda et al. (1992) classification system, only the 2012 sample was "above average". Considering the fact that the average gluten index in 2012 was 32.68, this line had the strongest gluten in this year as well.

The effect of years and genotypes was analyzed using a linear mixed model (REML analysis). The genotype was treated as a fixed factor, and the years as a random factor (Table 3). Variance components and the repeatability (h^2) values for the examined traits were determined (Table 4). Other traits (wet gluten content, plant height, heading time and cold tolerance) were also observed in several years, so the relationship of these traits with the Minolta b* value and the gluten index could be analyzed (Table 4).

Based on the results of the REML analysis, a difference can also be detected between the Minolta b* value and the gluten index of the genotypes (*F*-value significant at $p < 0.001$ level). However, the 'year' factor only affected the Minolta b* value, and the differences were not statistically proven during the analysis of the gluten index.

The values reported in Table 4 refer to the entire population (179 mapping lines and the two parents combined). All traits varied within a wide interval between the genotypes examined. The difference observed in the Minolta b* and gluten index data was already analyzed based on Table 2, but the difference recorded in the population was 13.3% in wet gluten content between the genotypes with the lowest and highest values, more than two weeks in heading time, nearly 26 cm in plant height and 50% in phytotron survival rate. In terms of genetic determination, the majority of the significant variance in the case of wet gluten content, heading time, plant height and cold tolerance was determined by the genotype itself (σ^2_G is a multiple of σ^2_{GY}), however, in the analysis of Minolta b* and gluten index, σ^2_{GY} was also significant. Repeatability (h^2) represents the ratio of genotypic to phenotypic variance, based on which a conclusion can be drawn about the genetic determination of the trait. Based on our calculations, we proved in this population that the Minolta b* value and gluten index are genetically well-determined traits, but in addition to these two traits, heading time and plant height were also largely determined by the genetic background. The same

Table 3. Analysis of the effect of genotype and year using REML analysis based on the data of the 179 lines and parents, Martonvásár, Hungary, 2001–2014

Factor	Minolta b*		Gluten index	
Fixed factor	*F*		*F*	
Genotype	46.385	***	18.841	***
Random factor	*Wald Z*		*Wald Z*	
Year	2.448	*	1.412	
Residual	47.503		28.504	

*Notes: F = Wald statistics/degrees of freedom; *,*** the effect of the factor was significant at. p < 0.05 or < 0.001 level, respectively*

Table 4. Descriptive statistics, variance components, repeatability of technological quality and phenotypic traits of durum wheat lines, and the correlation of Minolta b* value and gluten index with the other traits tested

	Minolta b*		Gluten index		Wet gluten %		Heading time		Plant height		Cold tolerance	
No. of years	13		5		5		7		6		2	
Mean	21.864		45.356		39.778		143.036		87.111		13.166	
Minimum	17.934		3.212		33.535		140.857		75.667		0.000	
Maximum	25.473		78.770		46.855		156.429		101.33		50.000	
St. deviation	1.356		17.656		2.461		1.369		5.349		10.380	
σ^2_G	1.763	***	279.264	***	3.947	***	0.933	***	25.243	***	72.643	***
σ^2_{GY}	0.913	***	142.987	***	0.561	***	0.057	***	9.071		6.548	
σ^2_e	0.157		38.751		3.333		1.033		17.754		189.875	
σ^2_P	1.839		311.736		6.056		1.036		28.235		0.675	
Repeatability (h^2)	0.959		0.896		0.651		0.900		0.894		0.675	
$r_{\text{Minolta b*}}$			0.104	**	0.096	**	-0.051		-0.668	***	-0.021	
$r_{\text{gluten index}}$	0.104	**			-0.111	**	0.263	**	-0.157	**	-0.005	

*Notes: σ^2_G = genotypic, σ^2_{GY} = genotype × year interaction, σ^2_e = residual, σ^2_P = phenotypic variance; **,*** value is significant at p < 0.01 or < 0.001 level, respectively*

cannot be said for wet gluten content and cold tolerance.

The correlation between the Minolta b* value and three other traits, gluten index, wet gluten content and plant height, was significant. However, the correlation with gluten index ($r = 0.104^{**}$) and wet gluten content ($r = 0.096^{**}$) is weak. Based on the correlation coefficient of -0.668** calculated between the Minolta b* value and plant height, a moderately strong, negative relationship existed between the two traits, i.e., the yellow pigment content of lower plants was higher compared to higher ones. The gluten index correlated with four other traits, but the strength of the relationship was weak in all cases ($-0.157 \leq r \leq 0.263$).

The studied durum wheat lines can be divided into two groups based on an easily identifiable morphological trait. All lines had white ears, but many of them had black awns (79, type 'PWD1216'), while the others had white ones (100, type 'MvTD10-98'). Calculations were performed to determine whether the awn color was associated with any of the technological quality or phenotypic traits examined. The variance of the two groups was determined with an *F*-test. Apart from heading time, the standard deviations of all traits were the same in the two groups. The statistical similarity of the group means – taking into account the identity or difference of the standard deviations – was tested with a *t*-test (Table 5).

There were no statistically significant differences in 5 of the 6 traits in the two groups separated by awn color. The only exception was the gluten index ($t = 3.141^{**}$), which was significantly higher in the black awned lines (49.878) than in the white awned ones (41.775). However, there was a large overlap between the ranges of lines with the two awn types (black: 17.399–78.770; white: 3.212–76.812), so lines with strong gluten were also found among the white awned lines (gluten index of 9 white awned lines exceeded the value of 65).

The two parental lines were located close to the extreme values of the population based on the Minolta b* value. At the time of the creation of the mapping population, 'PWD1216' was one of the lines with the highest Minolta b* value in the entire breeding program based on yellow pigment content, while 'MvTD10-98' was among the worst ones. By creating the population, we planned to identify the chromosomal regions determining the Minolta b* value. During subsequent studies, we observed that the gluten index of the lines in the population is also extremely diverse. This result was unexpected, since the gluten index of the two parents was average and the difference between them was not significant. In the population, we demonstrated high level of diversity for the two traits that made it suitable for performing QTL analysis.

Our studies conducted in the biparental mapping population demonstrated a strong correlation between HMW glutenin subunits and gluten index values. Since Payne et al.'s publication

Table 5. Mean and variance of lines (including parents) with different awn types, and comparing the means of groups by *t*-test

	Black awned lines		**White awned lines**					
No. of lines	80		101		***F***		***t***	
	Mean	Variance	Mean	Variance				
Minolta b*	21.894	1.909	21.840	1.801	1.060		0.266	
Gluten index	49.878	273.103	41.775	316.063	0.864		3.141	**
Wet gluten %	40.038	5.660	39.573	6.331	0.894		1.266	
Heading time	142.946	0.886	143.108	2.662	0.333	***	-0.837	
Plant height	86.646	28.619	87.480	28.576	1.002		-1.043	
Cold tolerance	12.791	112.283	13.463	105.066	1.069		-0.432	

*Notes: **,*** value is significant at p < 0.01 or < 0.001 level, respectively*

in 1979, it has been known that high molecular weight subunits significantly determine gluten strength in bread wheat. In durum wheat, a primary role was attributed to LMW subunits (Payne et al., 1984; Pogna et al., 1988; Sissons et al., 2005). However, some research groups have also demonstrated a relationship between HMW glutenins and gluten strength. Branlard et al. (1989) demonstrated the presence of 11 alleles (three of which were previously unknown) at the most significant locus Glu1-B1 in durum wheat, indicating that genetic variability is present in this species on chromosome arm 1BL. Brites and Carrillo (2001) and Sissons et al. (2005) have also described the beneficial effect of HMW subunit combinations on gluten strength. The 10 lines with the highest and 10 lowest gluten indices were examined by SDS polyacrylamide gel electrophoresis to determine which subunits could have caused the difference in the gluten indices of the lines. The results of the study are included in Table 6.

The lines with extreme gluten index were clearly distinguishable based on their HMW glutenin subunit composition. The 7+8 pattern characteristic of the parent 'MvTD10-98' was identified in all lines with high gluten structure, while the subunit composition identical to the parent 'PWD1216' was present in all lines with low gluten index.

The data from the biparental population also proved that the two technological quality traits highly genotype-determined, well-heritable traits. The repeatability (h^2 = 0.978) reported earlier (Vida et al., 2022) based on the data from the broad genetic range of varieties differed by less than 2% from that calculated from the data from the mapping population (h^2 = 0.959). The repeatability of the gluten index differed to a greater extent. Using the data from the genotypes of the broad genetic range of varieties, an h^2 value approaching 0.95, was calculated while this remained just below 0.9 for the lines of the mapping population. Our results are consistent with those calculated by other research groups after examining durum wheat genotypes (Braaten et al., 1962; Clarke et al., 2000; 2006; 2009; Santra et al., 2005; Taneva et al., 2019), as well as with previous data on winter durum wheat populations (Longin et al., 2013; Vida et al., 2014). Other research groups have also calculated high h^2 values for heading time and plant height (in spring durum wheat Abinasa et al., 2011; Wolde et al., 2016; Moreno-Amores et al., 2020; in winter durum wheat Longin et al., 2013). In the experiment

Table 6. HMW glutenin subunit composition of the lines (based on 5-year average) with 10 highest and 10 lowest gluten index values of the biparental mapping population

High gluten index group				*Low gluten index group*			
Line	Gluten index	Glu1-A1	Glu1-B1	Line	Gluten index	Glu1-A1	Glu1-B1
G58	75.17	0	7+8	G22	3.21	0	13+16
G135	71.68	0	7+8	G48	3.59	0	13+16
G136	78.11	0	7+8	G74	11.73	0	13+16
G137	71.90	0	7+8	G78	17.40	0	13+16
G138	71.81	0	7+8	G88	17.66	0	13+16
G155	75.79	0	7+8	G89	17.77	0	13+16
G157	73.07	0	7+8	G146	17.98	0	13+16
G171	76.81	0	7+8	G216	17.79	0	13+16
G180	70.36	0	7+8	G217	9.90	0	13+16
G223	73.91	0	7+8	G218	17.40	0	13+16
Mean	73.86				13.44		
MvTD10-98	53.11	0	7+8	PWD1216	44.70	0	13+16

of Longin et al. (2013), the repeatability of wet gluten content of winter durum wheat varieties and lines was 0.62, which was also supported by our own observations (h^2 = 0.651). There is no information available regarding the genetic determination of cold tolerance. In a high-altitude experiment (set up in free-standing boxes at 700 m above sea level), Longin et al. (2013) reported an h^2 value of 0.88 after testing "frost tolerance". This is significantly higher than what was determined in the phytotron test (0.675). However, the two methods do not produce the same response, so the results cannot be compared. While in the box experiment the hardening process and the determination of cold tolerance take place under natural temperature and light conditions, phytotron testing is carried out according to a strictly defined program (Tischner et al., 1997).

Based on the results of the correlation analysis, although we calculated several significant *r*-values, they did not reach the medium strength with one exception. The exception was the relationship between Minolta b* and plant height (r = -0.668**). Several research groups have examined the relationship between the two traits. In winter durum wheat, Longin et al. (2013) reported a correlation coefficient value of r = 0.38**, which is significant in the group of cold-tolerant genotypes, but with our own measurements, it was of the opposite sign, and r = 0.02 for non-cold-tolerant varieties. The same research group (Sieber et al., 2015) determined the relationship to be r = -0.12 after examining another group of varieties. In the experiment of Amallah et al. (2015), the plant height of Mediterranean landraces correlated with the Minolta b* value with a strength of r = 0.346. In light of previously reported results, the moderately strong, negative correlation observed between Minolta b* value and plant height is difficult to explain and is presumably typical of the population we examined.

In the case of gluten index, the effect of the Glu1-B1 locus on chromosome arm 1BL is clear, as was also demonstrated by SDS-PAGE separation of HMW glutenin subunits of extremely high and low value lines. The 7+8 subunit combination characteristic of the 'MvTD10-98' parent differed from the 14+15 composition genotypes, which had the best effect based on the study of Brites and Carrillo (2001), only in the SDS sedimentation value, while the mixographic dough development time and stability were not statistically different. The 7+8 subunit combination also favorably influenced the gluten index value in the experiment of Sissons et al. (2005).

CONCLUSIONS

A unique mapping population was created to identify QTLs determining Minolta b* by crossing winter durum wheat lines. The population later proved to be suitable for studying the genetic control of gluten index. In this case, the h^2 values of both traits also supported strong genetic determination (Minolta b* = 0.959; gluten index = 0.896). Gluten index was clearly associated with the locus on chromosome arm 1BS. We later demonstrated that this locus was linked to the gene encoding Glu1-B1 HMW glutenin subunits.

Due to the successful breeding work of the past decades, winter durum wheat is now a real choice for farmers. Our studies with the lines of the mapping population prove that in this range of genotypes, targeted selection definitely can help to approach the technological quality of spring durum wheat varieties, which may lead to the expansion of the sowing area of this species in the Central and Eastern European region.

Acknowledgements

This research was carried out as part of the project TKP2021-NKTA-06, supported by the National Research, Development, and Innovation Fund of the Ministry of Innovation and Technology, financed through the TKP2021-NKTA grant program.

REFERENCES

Abinasa, M., Ayana, A. & Bultosa, G. (2011). Genetic variability, heritability and trait associations in durum

wheat (*Triticum turgidum* L. var. *durum*) genotypes. *African Journal of Agricultural Research, 6*(17), 3972-3979.

Alsaleh, A., Baloch, F. S., Derya, M., Azrak, M., Kilian, B., Özkan, H. & Nachit, M. (2015). Genetic linkage map of Anatolian durum wheat derived from a cross of Kunduru-1149 × Cham1. *Plant Molecular Biology Reporter, 33,* 209-220.

Amallah, L., Taghouti, M., Rhrib, K., Gaboun, F. & Hassikou, R. (2015). Genetic variability in agro-morphological and quality traits of Mediterranean durum wheat landraces. *Cereal Research Communications, 43*(1), 123-132.

Beke, B. & Barabás, Z. (1981). The first Hungarian durum wheat varieties. *Cereal Research Communications, 9*(2-3), 115-117.

Blanco, A., Colasuonno, P., Gadaleta, A., Mangini, G., Schiavulli, A., Simeone, R., Digesù, A. M., De Vita, P., Mastrangelo, A. M. & Cattivelli, L. (2011). Quantitative trait loci for yellow pigment concentration and individual carotenoid compounds in durum wheat. *Journal of Cereal Science, 54*(2), 255-264.

Borrelli, G. M., De Leonardis, A. M., Platani, C. & Troccoli, A. (2008). Distribution along durum wheat kernel of the components involved in semolina color. *Journal of Cereal Science, 48*(2), 494-502.

Borrelli, G. M., Troccoli, A., Di Fonzo, N. & Fares, C. (1999). Durum wheat lipoxygenase activity and other quality parameters that affect pasta color. *Cereal Chemistry, 76*(3), 335-340.

Braaten, M. O., Lebsock, K. L. & Sibbitt, L. D. (1962). Intergeneration relations of physical properties of dough and carotenoid pigment content in durum wheat. *Crop Science, 2*(4), 277-281.

Branlard, G., Autran, J. C. & Monneveux, P. (1989). High molecular weight glutenin subunit in durum wheat (*T. durum*). *Theoretical and Applied Genetics, 78,* 353-358.

Branlard, G. & Marion, D. (2011). Proteins and lipids for the 21st century. In: *The World wheat book, Volume 2: a history of wheat breeding* (Bonjean A.P., Angus W.J., van Ginkel, M. eds.). Lavoisier, Paris, 981-1023.

Brites, C. & Carrillo, J. M. (2001). Influence of high molecular weight (HMW) and low molecular weight (LMW) glutenin subunits controlled by *Glu-1* and *Glu-3* loci on durum wheat quality. *Cereal Chemistry, 78*(1), 59-63.

Clarke, J. M., Clarke, F. R., McCaig, T. N., Knox, R. E. & Ames N. P. (2000). Evaluation of predictors of quality for use in early generation selection. Options Méditerranéennes, Série A: Séminaires Méditerranéens 40, 439-446.

Clarke, F. R., Clarke, J. M., McCaig, T. N., Knox, R. E. & DePauw, R. M. (2006). Inheritance of yellow pigment concentration in seven durum wheat crosses. *Canadian Journal of Plant Science, 86*(1), 133-141.

Clarke, F. R., Clarke, J. M., Pozniak, C. J., Knox, R. E. & McCaig, T. N. (2009). Protein concentration inheritance and selection in durum wheat. *Canadian Journal of Plant Science, 89*(4), 601-612.

Cubadda, R., Carcea, M. & Pasqui, L. A. (1992). Suitability of the gluten index method for assessing gluten strength in durum wheat and semolina. *Cereal Foods World, 37*(12), 866-869.

Damidaux, R. & Feillet, P. (1978). Relation entre les propriétés viscoélastiques du gluten cuit, la teneur en protéines et la qualité culinaire des blés durs (*T. durum*). *Annales de Technolgie Agricole, 28*(4), 799-808.

Elouafi I., Nachit, M. M. & Martin, L. M. (2001). Identification of a microsatellite on chromosome 7B showing a strong linkage with yellow pigment in durum wheat (*Triticum turgidum* L. var. durum). *Hereditas, 135*(2-3), 255-261.

Eurostat (2025). Crop production in EU standard humidity. https://ec.europa.eu/eurostat/ databrowser/view/ apro_cpsh1/default/table

Feillet, P. (1984). The biochemical basis of pasta cooking quality, its consequences for durum wheat breeders. *Sciences des Aliments, 4,* 551-566.

ICC (International Association for Cereal Science and Technology) (1995). ICC Standard No. 158: Gluten index method for assessing gluten strength in durum wheat (*Triticum durum*). Approved: 1995.

Irvine, G. N. & Winkler, C. A. (1950). Factors affecting the color of macaroni. II: Kinetic studies of pigment destruction during mixing. *Cereal Chemistry, 27,* 205-218.

Irvine, G. N. & Anderson, J. A. (1953). Variation in principal quality factors of durum wheat with a quality prediction test for wheat or semolina. *Cereal Chemistry, 30,* 334-342.

Jackson, E. A., Morel, M.-H, Sontag-Strohm, T., Branlard, G., Metakovsky, E. V. & Redaelli, R. (1996). Proposal for combining the classification systems of alleles of *Gli-1* and *Glu-3* loci in bread wheat (*Triticum aestivum* L.) *Journal of Genetics and Breeding, 50*(4), 321-336.

Johnston, R. A., Quick, J. S. & Donnelly, B. J. (1980). Note on comparison of pigment extraction and reflectance colorimeter methods for evaluating semolina color. *Cereal Chemistry, 57*(6), 447-448.

Lee, J., Kaltsikes, P. J. & Bushuk, W. (1976). The inheritance of lipoxidase activity and pigment content in durum wheat. *Theoretical and Applied Genetics, 47,* 243-250.

Longin, C. F. H., Sieber, A. N. & Reif, J. C. (2013). Combining frost tolerance, high grain yield and good pasta quality in durum wheat. *Plant Breeding, 132*(4), 353-358.

Martinez, M. C., Ruiz, M. & Carrillo, J. M. (2005). Effects of different prolamin alleles on durum wheat quality properties. *Journal of Cereal Science, 41*(1), 123-131.

Matz, S. A. & Larsen, R. A. (1954). Evaluating semolina color with photoelectric reflectometers. *Cereal Chemistry, 31*, 73-86.

Melnikova, N. V., Kudryavtseva, A. V. & Kudryavtsev A. M. (2012). Catalogue of alleles of gliadin-coding loci in durum wheat (*Triticum durum* Desf.). *Biochimie, 94*(2), 551-557.

Moreno-Amores, J., Michel, S., Miedaner, T., Longin, C. F. H. & Buerstmayr, H. (2020). Genomic predictions for *Fusarium* head blight resistance in a diverse durum wheat panel: an effective incorporation of plant height and heading date as covariates. *Euphytica, 216,* 22.

Palamarchuk, A. (2005). Selection strategies for traits relevant for winter and facultative durum wheat. In: *Durum wheat breeding: current approaches and future strategies* (Royo, C., Nachit, M., Di Fonzo, N., Araus, J.L., Pfeiffer, W.H., Slafer, G.A. eds.). Food Products Press, New York. 599-644.

Payne, P. I., Corfield, K. G. & Blackman, J. A. (1979). Identification of a high-molecular-weight subunit of glutenin whose presence correlates with bread-making quality in wheats of related pedigree. *Theoretical and Applied Genetics, 55*(3-4), 153-159.

Payne, P. I., Jackson, E. A. & Holt, L. M. (1984). The association between γ-gliadin 45 and gluten strength in durum wheat varieties: A direct causal effect or the result of genetic linkage? *Journal of Cereal Science, 2*(2), 73-81.

Perten, H. (1990). A rapid measurement of wet gluten quality by the gluten index method. *Cereal Foods World, 35,* 401-402.

Pogna, N., Lafiandra, D., Feillet, P. & Autran, J. C. (1988). Evidence for a direct causal effect of low molecular weight subunits of glutenins on gluten viscoelasticity in durum wheats. *Journal of Cereal Science, 7*(3), 211-214.

Pozniak, C. J., Knox, R. E., Clarke, F. R. & Clarke, J. M. (2007). Identification of QTL and association of a phytoene synthase gene with endosperm color in durum wheat. *Theoretical and Applied Genetics, 114*(3), 525-537.

Santra, M., Santra, D. K., Rao, V. S., Taware, S. P. & Tamhankar, S. A. (2005). Inheritance of β-carotene concentration in durum wheat (*Triticum turgidum* L. ssp. *durum*). *Euphytica, 144*, 215-221.

Sieber, A.-N., Würschum, T. & Longin, C. F. H. (2015). Vitreosity, its stability and relationship to protein content in durum wheat. *Journal of Cereal Science, 61*, 71-77.

Sissons, M. J., Ames, N. P., Hare, R. A. & Clarke, J. M. (2005). Relationship between glutenin subunit composition and gluten strength measurements in durum wheat. *Journal of the Science of Food and Agriculture, 85*(14), 2445-2452.

Szunics, L., Bedő, Z., Szunics, Lu., Láng, L. & Veisz, O. (1998). Results of durum wheat breeding in Martonvásár. *Acta Agronomica Hungarica, 46*(2), 135-148.

Taneva, K., Bozhanova, V. & Petrova, I. (2019). Variability, heritability and genetic advance of some grain quality traits and grain yield in durum wheat genotypes. *Bulgarian Journal of Agricultural Science, 25*(2), 288-295.

Tischner, T., Kőszegi, B. & Veisz, O. (1997). Climatic programmers used in the Martonvásár phytotron most frequently in recent years. *Acta Agronomica Hungarica 45*(1), 85-104.

UPOV (1988): TG/120/3: Guidelines for the conduct of tests for distinctness, homogeneity and stability: Durum wheat (*Triticum durum* Desf.). International Union for the Protection of New Varieties of Plants, 34 p.

Vasiljevic, S., Banasik, O. J. & Shuey, W. C. (1977). A micro unit for producing durum semolina. *Cereal Chemistry, 54*(3), 397-404.

Vida, G., Szunics, L., Veisz, O., Bedő, Z., Láng, L., Árendás, T., Bónis, P. & Rakszegi, M. (2014). Effect of genotypic, meteorological and agronomic factors on the gluten index of winter durum wheat. *Euphytica, 197*, 61-71.

Vida, G., Szunics, L., Veisz, O. & Cséplő, M. (2022). Breeding for improved gluten strength and yellow pigment content in winter durum wheat. *Bulgarian Journal of Crop Science, 59*(6), 16-33.

Wolde, T., Eticha, F., Alamerew, S., Assefa, E. & Dutamo, D. (2016). Genetic variability, heritability and genetic advance for yield and yield related traits in Durum wheat (*Triticum durum* L.) accessions. *Sky Journal of Agricultural Research, 5*(3), 42-47.

Received: November, 11, 2025; *Approved:* December, 02, 2025; *Published:* December, 2025