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ASSESSMENT OF THE EVOLUTION OF *DURUM* WHEAT END-USE QUALITY FROM DOMESTICATION TO BREEDING ACHIEVEMENTS

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Abstract

The quality characteristics of durum wheat are important parameters to consider in developing grain products. Here we assessed the end-use quality of a collection of 294 durum wheats from several genetic resources including Mediterranean landraces, Moroccan varieties, and international lines using various standardized methods. To achieve this goal, sample seeds for each genotype were subjected to the most important features determining the commercial value of *durum* wheat, according to standardized methods; gluten strength (SDS), grain protein content (PC), yellow pigment concentration (YP), yellow index (b), brightness (L), test weight (TW), 1000-kernel weight (TKW), and kernel vitreousness (VIT) were assessed. There were decreases over time in yellow pigment content and protein levels from landraces to Moroccan cultivars, via international lines. These findings might be directly used by farmers interested in cultivating traditional varieties for specialized food markets. Genotype selection based on multiple traits is a key issue in plant breeding; breeders practice selection on target traits to improve productivity but need to consider unfavorable associations among key traits of similar economic interest.

INTRODUCTION

There has been a generally successful global drive to *ex situ* conserve crop genetic resources during the last 70 years. As a consequence, hundreds and thousands of samples have been kept in germplasm banks across the world. Approximately 150,000 wheat and related species accessions are stored in the Germplasm Bank of the International Maize and Wheat Improvement Center (CIMMYT) [1]. Traditional bread and durum wheat landraces make up around a third of this collection [1]. To enhance and facilitate their usage in research and breeding programs, many have been genotyped and phenotyped for a variety of characteristics [2-1]. These investigations have revealed that some of these durum wheats require additional characterization for various characteristics in order to be fully utilized in breeding efforts [1].

Over the last few years, large breeding projects have targeted on increasing durum wheat productivity characteristics, such as grain yield and tolerance to biotic and abiotic stress [3-4]. Recently, there has been a movement in research aimed at improving wheat quality and nutritional value evaluated using multiple measures including protein content and water absorption, and flour color has become a priority [3]. Consequently, durum varieties have been tested for quality in order to reach the desired semolina flour.

To accomplish this, analytical methods have been designed for assessing various end-use characteristics, establishing their physicochemical, and determining the capacity of durum wheat to be processed into these end-products [5]. Such phenotyping investigations of durum wheat genetic resources would give complete knowledge and a better understanding of durum wheat's suitability for various uses [5]. In exchange, the genetic resources might be better utilized as a source of innovation for future durum wheat uses [5].

There are two types of quality assessment tests. The first consists of quality prediction tests that examine the raw material, which is referred to as the semolina value [6]. This depicts a collection of wheat grain physicochemical properties: 1000 grain weight, test weight, vitreousness, and yellow pigment content [6]. The second category comprises tests that predict end product or dough quality features, such as protein quantity and quality, which influence gluten strength and extensibility [6].

A possible alternative to traditional dough quality and end-use product testing is physicochemical assays that indirectly evaluate wheat quality characteristics [6]. In real-world practice, a single test is unlikely to suffice; rather, a mix of tests is required [6]. The quantity of protein, as well as its functional quality and composition, are known to influence the quality of durum wheat dough and pasta [6-7]. The viscosity and extensibility of the dough are determined by monomeric proteins, mostly gliadins, whereas dough strength is determined by polymeric proteins, primarily glutenins [6].

While additional approaches to select wheat breeding material for higher quality have been highlighted [8], no other technique is likely to completely substitute phenotyping end-use quality, at least in the later phases of line advancement and before varietal release [8]. Typically, for the evaluation of protein content, which is more affected by the environment than genetics [9], marker selection will not necessarily be more efficient to improve the trait in question [8].

The present work had two main objectives: first, to characterize the properties of a Moroccan durum wheat collection (landraces, international lines, and Moroccan cultivars) and second, to assess the evolution of durum wheat genetic resources from landraces to modern genotypes and the impact of breeding programs on the quality end-use value.

MATERIALS AND METHODS

Plant Materials

The plant materials used in this study consisted of a set of 294 durum wheat accessions (*Triticum turgidum* L. var. *Durum*, 2n = 4x = 28, AABB genome): 49 landraces (LAND) of Mediterranean origin, of which 33 genotypes were collected from farmers in different regions of Morocco and 16 durum wheat landraces originating from Mediterranean countries; 23 Moroccan cultivars (MV) registered in the official national catalog; and 222 international advanced lines (IAL), including 127 IAL from the International Maize and Wheat Improvement Center (CIMMYT) and 95 IAL from the International Center for Agricultural Research in the Dry Areas (ICARDA). The plant materials studied are available at the National Institute for Agronomic Research (INRA) in Rabat, Morocco and at ICARDA genebank. Table S1 summarizes the list of *durum* wheat accession codes and origins.

Field Experimental Design

The quality traits assessment was conducted in trials at Allal Tazi (34°31'N, 6°19'W; INRA's research station) using an augmented block design. Each entry was sown in four rows 2.5 m long and spaced at 0.3 m, only the two rows in the middle were harvested. Soil preparation, fertilization, and weeding were performed according to standard agronomic management, and the fertilizer used was 19-38-0 (N-P-K) complex applied at 150 kg/ha and amino nitrate (33.5 % N) applied at 100 kg/ha.

Quality Trait Assessment

For quality analysis, seeds samples from each genotype were harvested and analyzed separately. Whole grain flour samples were obtained with a whole–meal grinder (Udy-Cyclone 0.5mm screen). The quality parameters evaluated were: (1) gluten strength (SDS), determined by the SDS sedimentation test as described previously [10] (2) yellow pigment concentration (YP), assayed using the AACC 14-50 modified method [11]; (3) grain color, evaluated by measuring brightness (L) and yellow index (b) parameters with a Chroma Meter CR-400 reflectance colorimeter (Konica Minolta); (4) grain protein concentration (PC), determined using a INFRANEO NIR spectrophotometer; (5) test weight (TW), determined using an Aqua-TR (Tripette and Renaud Chopin); (6) 1000-kernel weight (TKW) and (7) grain vitreousness percentage (VIT), determined by counting the number of vitreous grains after cutting a random sample of 100 grains per accession. All physicochemical tests were measured in triplicate and the results were averaged.

Statistical Analysis

Descriptive statistics mean (96% confidence interval) or median (interquartile range), minimum (min), maximum (max), standard error, or frequency were utilized to summarize the data [12]. Kruskal–Wallis test (one-way ANOVA on ranks test) was used to compare the three groups of durum wheats based on each trait [12-13]. Fisher's LSD multiple-comparison test was used for pairwise comparison [14]. To control the false positive rate Benjamini-Hochberg method was utilized for the adjustment of multiple comparisons [15].

Pearson correlation coefficients (r) were used to measure the strength and direction of the relationship between various continuous variables [16].

In order to better cluster the 294 durum wheat accessions regarding their quality characteristics, principal component analysis (PCA) was performed [17] using a correlation matrix, and then Varimax with Kaiser's normalization was applied. A rotation converged in 4 iterations. Kaiser's rule selects all PCs for which Kaiser's Eigenvalues are greater than 1 [18-19].

Statistical analyses were performed in SAS software version 9.1 (SAS 9.1 Institute Inc., Cary, NC) and XLSTAT software version 2020.3.1.18 (Addinsoft, New York, USA).

Sample Size Calculation and Power Analysis

A one-way design with three groups has sample sizes of 49 landraces (LAND), 222 international advanced lines (IAL), and 23 Moroccan varieties (MV). The null hypothesis is that the standard deviation of the group means is 0.0 and the alternative standard deviation of the group means is 0.4. The total sample of 294 subjects achieves a power of 100% using the Kruskal-Wallis Test with a target significance level of 0.050 and an actual significance level of 0.055 [20-21].

RESULTS AND DISCUSSION

Tables 1 and 2 summarize the descriptive analysis of pasta-making quality parameters of durum wheat collection according to their type. Variance analysis (Table 3) revealed a highly significant difference between the 294 accessions based on the evaluated quality parameters except for TKW as demonstrated by Kruskal-Wallis One-Way test (Table 3) and the Fisher's LSD Multiple-Comparison Test and (Table 4).

Table 1. Pasta-making quality parameters of the tested durum wheat collection

Measurement	Count/Missing	Mean ± SD	Min-Max
TKW (g)	292/2	33.68 ± 5.92	17.28 - 64.28
TW (kg/hl)	290/4	82.26 ± 4.65	64.64 - 93.63
b	292/2	19.62 ± 1.92	14.34 - 24.22
L	292/2	82.31 ± 8.92	39.32 - 92.7
YP (ppm)	291/3	6.58 ± 1.5	3.02 - 10.42
SDS (mL)	292/2	47.12 ± 8.24	18.5 - 68
VIT (%)	242/52	64.71 ± 26.58	7.33 - 99.33
PC (%)	272/22	14.36 ± 1.64	11.59 - 21.97

TKW: Thousand kernel weight, TW: Test weight, b: Yellow index, L: Brightness, YP: Yellow pigment content, SDS: SDS sedimentation test, VIT: Vitreousness, PC: Protein content, SD: Standard Deviation

Table 2. Descriptive analysis of pasta-making quality parameters of durum wheat collection according to their type

Measurement	LAND		IAL		MV	
	Count/Missing	Mean ± SD	Count/Missing	Mean ± SD	Count/Missing	Mean ± SD
TKW (g)	45/2	32.76 ± 4.9	222/0	33.78 ± 6	25/0	34.44 ± 6.83
TW (Kg/hl)	45/2	79.08 ± 5.62	220/2	82.96 ± 4.17	25/0	81.77 ± 4.44
b	45/2	21.13 ± 1.33	222/0	19.44 ± 1.82	25/0	18.42 ± 2.16
L	45/2	85.11 ± 2.47	222/0	81.47 ± 9.68	25/0	84.8 ± 7.96
YP (ppm)	45/2	7.58 ± 1.06	221/1	6.48 ± 1.44	25/0	5.61 ± 1.78
SDS (mL)	46/1	43.91 ± 8.32	221/1	48.18 ± 7.99	25/0	43.63 ± 8.04
VIT (%)	22/25	91.94 ± 3.8	208/14	60.24 ± 25.86	12/13	92.29 ± 13.32
PC (%)	36/11	15.39 ± 2.07	213/9	14.05 ± 1.32	23/2	15.62 ± 2.28

IAL: International Lines, LAND: Landraces, MV: Moroccan varieties, TKW: Thousand kernel weight, TW: Test weight, b: Yellow index, L: Brightness, YP: Yellow pigment content, SDS: SDS sedimentation test, VIT: Vitreousness, PC: Protein content, SD: Standard Deviation

Table 3. Kruskal-Wallis one-way ANOVA on ranks

Variable	Type (Median)				
	IAL	MV	LAND	*p*-value	Sig Diff
TKW (g)	33.64	33.13	33.65	0.76578	H0
TW (kg/hl)	82.99^{a}	82.83^{a}	81.14^{b}	0.00032	H1***
b	19.45^{b}	18.73^{c}	21.2^{a}	0.00000	H1***
L	83.29^{b}	86.42^{a}	85.05^{a}	0.00206	H1**
YP (ppm)	6.61^{b}	5.41^{c}	7.61^{a}	0.00000	H1***
SDS (mL)	49.05^{a}	44.6^{b}	46.9^{b}	0.00015	H1***
VIT (%)	66.67^{b}	98.33^{a}	91.83^{a}	0.00000	H1***
PC (%)	13.88^{b}	14.84^{a}	15.09^{a}	0.00000	H1***

IAL: International Lines, LAND: Landraces, MV: Moroccan varieties, TKW: Thousand kernel weight, TW: Test weight, b: Yellow index, L: Brightness, YP: Yellow pigment content, SDS: SDS sedimentation test, VIT: Vitreousness, PC: Protein content. H0: All medians are equal. H1: At least two medians are different, *,**and*** : Significant at probability level less than P = 0.05, P = 0.01 and P = 0.001, respectively

Table 4. Fisher's LSD multiple-comparison test

Group Types/Variables	TKW	TW	b	L	YP	SDS	VIT	PC
IAL	_	LAND	LAND, MV	LAND	LAND, MV	LAND, MV	LAND, MV	LAND, MV
LAND	_	IAL, MV	IAL, MV	IAL	IAL, MV	IAL	IAL	IAL
MV	_	LAND	IAL, LAND	_	IAL, LAND	IAL	IAL	IAL

b: Yellow index, IAL: International Lines, L: Brightness, LAND: Landraces, MV: Moroccan varieties, TKW: Thousand kernel weight, TW: Test weight, YP: Yellow pigment content, SDS: SDS sedimentation test, VIT: Vitreousness, PC: Protein content

SDS Sedimentation Test

The SDS sedimentation value is an effective parameter for predicting the rheological properties of durum wheat genotypes in breeding programs. The test measures how the swelling capacity of gluten proteins in whole-meal durum wheat affects the sedimentation rate of a meal suspension in SDS medium. According to the International Association for Cereal Science and Technology (ICC), better-quality gluten gives rise to slower sedimentation and higher SDS values [22]. The sedimentation volume value has been shown to be a good predictor of the gluten strength and the viscoelasticity of cooked pasta and bread-making quality of durum wheat [23-25]. Although the germplasm of LAND, MV and IAL were quite diverse, only slight variability in the sedimentation volume was apparent between the studied genotypes, with the average volume ranging from 44.6 to 49.05 mL. Median value was relatively higher in IAL than LAND and MV (Table 3 and Figure S1). This result suggests that the majority of breeders within CIMMYT and ICARDA integrated breeding for quality purposes in their strategy and included gluten strength as the main selection criterion in their crosses. This was successful due to the high heritability potential of this trait basis [26-28]. However, there has yet to be a detailed characterization of the genetic control of sedimentation volume [9].

In terms of rheological quality, these values were low compared to the standards reported by Williams et al. [29]; for wheat to be of average strength, it must have a sedimentation volume >50 mL. However, some authors have stated that durum wheat, unlike soft wheat, has relatively lower SDS volumes [30]. By comparing the SDS sedimentation volume obtained in previous research, the studied genotypes showed fairly high gluten strength, implying higher extensibility and dough strength values within the germplasm [31-34].

Yellow Pigment Content

Semolina and pasta color are the result of yellow (desirable) and brown (undesirable) pigments [3]. Pasta color is an important esthetic factor associated with consumer preference for a bright yellow color [35]. This parameter is principally determined by the accumulation of carotenoids in the endosperm, mainly of the hydroxylated carotenoids α- and β-carotene. During pasta processing, lipoxygenase results in the oxidative degradation of the carotenoid pigments, while peroxidase and polyphenol activities contribute to the browning of the meal [26].

In addition to their commercial value, carotenoids are considered a significant source of nutrients/antioxidant compounds [3]. Indeed, they are known precursors of vitamin A, generating health advantages such as antioxidant properties, reinforcing the immune system, decreasing the risk of degenerative and cardiovascular ailments, having anti-obesity/hypolipidemic properties, and protecting the macula region of the retina [3, 4, 36].

The yellow pigment content and yellow index (b) decreased significantly within MV and IAL compared to LAND. Yellow pigment levels (ß-carotene concentrations) varied between 5.61 and 7.61 ppm, while the standard range is 6.58 ± 1.5 ppm (Table 3). As well being recognized as being a strong heritability factor independent of environmental conditions and cultural practices, which is supposed to facilitate the success of breeding programs [3, 26, 27, 37], the carotenoid concentration was higher in durum wheat LAND compared to MV. These results will be very helpful for efficiently exploiting landrace genotypes in breeding programs aiming to improve semolina color.

Protein Content

Protein content (PC) is one of the major quality traits in both bread and durum wheats and is strongly associated with end-use performance [9, 38]. As stated by Dexter [39], durum wheat PC can account for 30–40% of the variability in pasta cooking quality [40]; in fact, in addition to their nutritional value, proteins are the basis of secondary processes such as pasta making, bread making, and biscuit making. In general, the higher the PC, the firmer and less sticky the pasta. Pasta made from high-protein semolina has good physical strength, elasticity, firmness, is not very sticky, is resilient when cooked, and retains its texture even when overcooked [7, 41, 42].

While the relationship between PC and pasta firmness is well documented, the impact is complex and is influenced by many factors including genotype, environment, and pasta processing conditions, particularly drying temperature [41-42].

NIRS protein measurements showed a decrease in PC from LAND (15.09%) to IAL (13.88%). In MV (14.84%), the PC remained high (Table 3). This decrease is intuitive, since the objectives of the development of the MV were essentially aimed at improving yield.

However, this decrease in protein levels was relative, not falling below 14% in any of the tested *durum* wheats and exceeding the minimum value necessary for the "pasta processing industry" (12.5%) [43]. This can be explained by the fact that the variation in PC is highly influenced by the environment, nitrogen manuring, than genetic control [28, 38, 44]. According to Häner and Brabant [45], varietal choice accounts for 33% of PC variability and is thus the easiest factor to control when influencing the PC of *durum* wheat. However, PC remains very difficult to achieve, as it is a low heritability trait under the control of several genes and highly affected by environmental conditions [43, 44, 46].

Test Weight

The test weight (TW) varied from 64.64 to 93.63 kg/hl, with an overall average of 82.26 kg/hl (Table 1). The IAL and MV genotypes had the highest TW averages of 82.99 and 82.83 kg/hl, respectively, while the LAND had the lowest values (81.14 kg/hl) (Table 3).

TW increased progressively over time from LAND, IAL, to MV, confirming the efficiency of breeding for yield-related traits. Moreover, TW, important trait for primary processing industry, is one of the best predictors of semolina yield and should therefore be included as a selection index to improve semolina yield [44, 47]. Consequently, the pure international lines (IAL) studied offer great opportunities to achieve, by selection, appreciable gains for both yield and semolina extraction rate.

These results agree with several other published studies [44, 48]. However, it has also been reported that modern cultivars are characterized by low values of TW compared to old genotypes, which might be due to variations in the genotypes studied or the environmental conditions [49].

Vitreousness

Because of its influence on semolina milling performance and end-use quality, kernel vitreousness (VIT) is a key grade indicator of durum wheat [35]. According to the Canadian Official Grain Grading Guide, vitreous kernels have a natural transparent hue or "glassy" look as an externally apparent indicator of grain hardness [35]. Kernels with an externally visible starchy area of any size are termed non-vitreous (entirely starchy or piebald) [35].

On average, VIT was high, compared to the overall average (64.71 ± 26.58%; Table 1), for LAND (91.83%) and MV (98.33%) compared to IAL (66.67%) as shown in Table 3.

VIT significantly decreased from IAL to LAND, but this reduction was partially compensated for in MV, suggesting that vitreousness did not suffer significant changes over time. Taneva et al. [23] reported low heritability of vitreousness revealing the predominance of non-additive gene actions. Hence, the influence of environmental conditions in the inheritance of this character is dominant, efficient genotype-by-phenotype selection in the early generation will be impossible [23, 31, 50].

Therefore, MV seem to be resistant to yellow-berry, confirming the highly significant effect of the genotype on VIT. Debbouz *et al*. [51] concluded that the loss of vitreousness was associated with severely weather-damaged samples and was reflected by a decrease in semolina yield. The resulting production would be used for breadmaking instead of semolina; indeed, flour of the *Marzak* variety is used to make bread ('*Batbout*', '*Chiar*', and even '*Msemen*') without adding other flours.

Principal Component Analysis

In order to describe the dispersion of the 294 genotypes in the collection (LAND, IAL, and MV) and to identify characteristics contributing to their structure based on all the physicochemical parameters, PCA was carried out to visualize the genetic variability (Fig. 1).

First, factor analysis was performed with one as the Eigenvalue to improve the strength of the factors. Then, two factors were extracted when the rotation converged in their iterations. According to Component Score Coefficient Matrix after Varimax rotation, out of the eight variables (quality traits: YP, b, L, SDS, PC, VIT, TW and TKW), the first four were categorized as semolina quality traits (YP, b, TW and TKW), while the remaining four could be considered as pasta cooking quality parameters (SDS, PC, VIT, L) (Fig. 1).

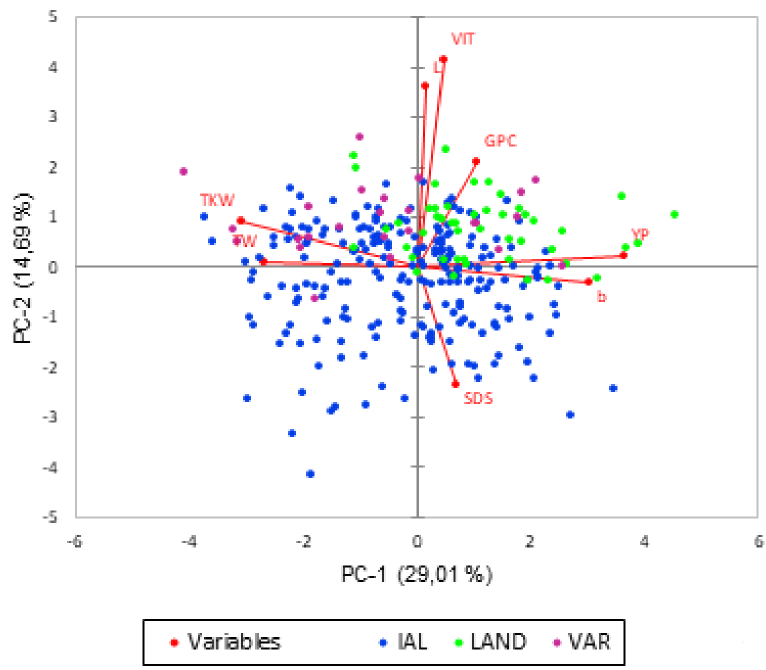

Figure 1. Distribution of the three genetic resources of durum wheat according to their quality traits (variables) as showed by PCA analysis (43.70% of the variation). b: Yellow index, IAL: International Lines, L: Brigthness, LAND: Landraces, VAR: Moroccan varieties, GPC: Protein content, TKW: Thousand kernel weight, TW: Test weight, SDS: SDS:sedimentation test, YP: ß:carotenes content, VIT: Vitreousness

The analysis extracted a two-factor solution, each with eigenvalues above one, which explained 43.7% of the total variance (Table 5). The KMO was 0.610 indicating a good level based on Kaiser's and the Bartlett's test for sphericity was significant ($\chi^2 = 294.670$, df = 28, $p = 0.0001$).

The scatter plot in Fig. 1 shows some clustering and distinction of LAND genotypes from IAL genotypes. There are also two other juxtaposed groups, one representing the genotypes of the very heterogeneous IAL and the other representing the MV, which are confusing since they have accessions located mainly in the IAL group. Some accessions were mixed with LAND genotypes.

In the first axis of Fig. 1, which contrasts LAND and IAL, the dominant active modalities for IAL were TKW, TW, and SDS tests. IAL were mainly characterized by low protein levels. Within this group of IAL, two other groups were also superimposed in relation to axis 2, one representing genotypes characterized by very high TKW and SW, and the other representing accessions with very high gluten strength and yellow pigment content.

The variables that most contributed to the LAND group were protein content and vitreousness. LAND was characterized by vitreous and protein-rich grains, whereas some accessions from MV were distinguished by high TKW and TW and others were distinguished by grains rich in protein and yellow pigment.

To quantify the associations or variations between variables (physicochemical parameters), a Pearson's correlation matrix was developed on the basis of the eight quantitative variables (Table 6). Eight coefficients were significantly different from zero. There were both positive and negative correlations among the variables that varied from weak to strong. Most of the correlation coefficients were significant at $p < 0.05$.

Table 5. Correlations between variables and factors (PC-1, PC-2) after Varimax rotation

	PC-1	**PC-2**
TKW	- 0.342	0.168
TW	- 0.271	0.139
b	0.304	0.161
L	- 0.033	0.353
YP	0.363	0.126
SDS	0.140	- 0.322
VIT	- 0.019	0.565
PC	0.040	0.460

TKW: Thousand kernel weight, TW: Test weight, b: Yellow index, L: Brightness, YP: Yellow pigment content, SDS: SDS sedimentation test, VIT: Vitreousness, PC: Protein content

Table 6. Pearson correlation coefficients (*r*) between the different quality parameters based on the entire sample of 294 genotypes

	TKW	**TW**	**b**	**L**	**YP**	**SDS**	**VIT**	**PC**
TKW	**1**							
TW	**0.41*****	**1**						
b	**-0.29*****	**-0.22*****	**1**					
L	-0.03	0.02	-0.10	**1**				
YP	**-0.51*****	**-0.38*****	**0.66*****	0.10	**1**			
SDS	**-0.17****	-0.03	-0.01	0.01	0.10	**1**		
VIT	0.00	-0.04	0.05	0.11	0.09	-0.09	**1**	
PC	-0.07	**-0.15***	**0.12***	0.08	0.11	0.03	0.06	**1**

TKW: Thousand kernel weight, TW: Test weight, b: Yellow index, L: Brightness, YP: Yellow pigment content, SDS: SDS sedimentation test, VIT: Vitreousness, PC: Protein content. *,**and*** : Significant at probability level less than P = 0.05, P = 0.01 and P = 0.001, respectively

The two variables TKW and TW had statistically significant positive correlation, $r = 0.41$, $p < 0.001$). This correlation is consistent with earlier research [44, 45, 52].

There was a very highly significant correlation, $r = 0.66$; $p < 0.001$, between yellow pigment concentration and yellow index b, as previously reported [26, 53]. Consequently, the yellow index b may be a useful, fast, and safe method for screening genotypes for high yellow pigment contents in breeding programs compared to the chemical test.

There was also a low correlation between the yellow index b and protein levels ($r = 0.12$; $p < 0.05$). However, the relationship between yellowness and protein content is still controversial. Some researchers reported a negative correlation between these traits [42, 54]. Others found no significant correlation [35].

There were no other significant correlations between protein content and quality (determined by SDS sedimentation volume). Similar results were reported in several previous studies [25, 33, 46]. In fact, the PC is controlled by both the environment and genetics, unlike the SDS sedimentation volume expressing the gluten strength, which has a particular genetic basis [9, 28]. This wide variability in gluten strength, which is a characteristic controlled mainly by allelic variations at the Glu-A1, Glu-B1, Glu-A3, Glu-B3, and Glu-B2 loci, could give an idea of the genetic diversity at these loci [55-56].

CONCLUSION

The comparison of mean quality parameter values between different *durum* wheat genotypes showed a consistent increase over time from LAND to MV through IAL for semolina yield (TKW, TW) and dough quality (SDS sedimentation test). However, these improvements were to the detriment of some quality characteristics reflecting the nutritional value, such as yellow pigment and protein content, which were lower in IAL. Overall, the durum wheat landraces were still characterized by high yellow pigment and protein contents, which may explain why these wheat are still appreciated by consumers and maintained by farmers in several regions of the country. It would be interesting for breeders to take advantage of LAND genotypes in breeding programs to combine their adaptive characteristics, prospective technological uses, and nutritional value with the high potential yield of IAL and MV.

Furthermore, the industry should further investigate the physicochemical characteristics of available *durum* wheat genetic resources to expand their large-scale commercial use.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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