

Novel quality features to expand durum wheat applications

Meriem Aoun^{a*} and Fatma Boukid^{b*}

Abstract

Durum wheat represents a staple food in the human diet owing to its nutritional and technological features. In comparison to common wheat, durum wheat has higher tolerance to biotic and abiotic stresses. However, its production and culinary uses are limited compared to common wheat. Therefore, significant attention was attributed to upgrading the key quality of durum wheat (i.e., hardness, protein, starch and color). This review intends to put the spotlight on the modification of these properties to create new functionalities suiting a wider range of food applications based on critical compilation of scientific publications. Targeting specific genes has been shown to be a valuable strategy to design novel wheat varieties with higher nutritional value (e.g., high amylose), improved technological properties (e.g., higher glutenin content), attractive appearance (e.g., colored wheat) and new uses (e.g., soft durum wheat for breadmaking). Further efforts are still needed to find efficient ways to stabilize and maintain these properties.

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Keywords: hardness; pigmented durum wheat; high amylose; waxy durum wheat; protein; allergy

INTRODUCTION

Wheat is a staple food worldwide, providing essential elements in the human diet such as energy, proteins, vitamins and minerals, among other health beneficial compounds.¹ There are several classifications of wheat species/varieties in relation to their history of breeding such as ancient species (einkorn, emmer and spelt), landraces, and old and modern varieties.² Durum wheat (*Triticum turgidum* subsp. *durum*) and common wheat (*Triticum aestivum*) are classified among the modern species. Globally, 95% of wheat crops are of common wheat, and it is used primarily in bread and biscuits, and pastries. Durum wheat production presents only 5–8% of global wheat production and it is mostly concentrated in the Mediterranean region, with the European Union being the largest producer.³ Durum wheat is widely used in Mediterranean cuisine (e.g., couscous, bulgur, bread, flatbreads and freekeh),^{4–6} while globally its culinary uses are primarily pasta and couscous. The main motives behind the restricted global production/application of durum wheat are the high grain hardness and moderate gluten strength/extensibility compared to common wheat.^{7,8}

In wheat breeding, improved durum wheat quality involves key features – i.e., hardness, starch content/composition, protein content/composition and color. Grain hardness is closely related to processing properties (yield of flour, degree of starch damage and energy inputs of milling) and the performance of products (rheological, techno-functional and technological properties).⁹ Starch and protein are the main components of wheat grain, and they are closely related to wheat quality (technological and nutritional) and wheat performance, once included in a food.¹⁰ Wheat color is associated with the presence of natural pigments – i.e., carotenoids and anthocyanins¹¹ – which is also related to several health benefits owing to their anti-inflammatory, antioxidant, anticancer and antidiabetic properties.¹²

Selecting new durum wheat varieties with large variations in terms of hardness, protein, starch and color will create a portfolio of novel wheat types with unique functionalities to fit new applications such as meat analogues, dairy alternatives and egg substitutes.^{13–15} In this review, biochemical and genetic bases of the main durum wheat features (hardness, color, protein and starch) are discussed (Table 1). Furthermore, genetic strategies aiming to modify these features were addressed based on a critical compilation of scientific publications.

GRAIN HARDNESS

Grain hardness or grain texture is a key factor which determines wheat milling and end uses. The hardness of grain is related to wheat texture; thus there are four classes: namely, soft and hard common wheat, very hard durum wheat and a fourth class called 'Super Soft' wheat.^{16,17} Soft grains are white or floury when cut and have opaque endosperm, while hard grains are horny and translucent when cut in half and have a vitreous interior.¹⁶ Durum wheat is characterized by glassy vitreous kernels.^{16,18} Milling (size reduction and separation) of durum wheat results in the production of semolina, with particle size ranging from 112 to 500 µm.¹⁶ Coarse semolina is primarily used for couscous making;

* Correspondence to: M Aoun, Department of Entomology and Plant Pathology, Oklahoma State University, Stillwater, OK 74078, USA. E-mail: meriem.aoun@okstate.edu; or F Boukid, ClonBio Group Ltd, 6 Fitzwilliam Place, Dublin D02 XE61, Ireland. E-mail: fboukid@clonbioeng.com

^a Department of Entomology and Plant Pathology, Oklahoma State University, Stillwater, Oklahoma, USA

^b ClonBio Group Ltd, Dublin, Ireland

Table 1. Novel durum wheat grain features to expand its applications

Trait	Modifications	Applications
Grain hardness	Soft durum and extra-soft durum	Improved pasta quality, acceptable bread quality and cookies
Color	Pigmented durum	Natural colorant, high antioxidant properties and lower glycemic index
Starch	Waxy durum	Antistaling agent in breads and possibly new food applications such meat analogues
	High-amylose durum	Food with increased resistant starch: high-fiber and low-carbohydrate pasta
Protein	Higher protein concentration and gluten strength	Increased dough strength, improved breadmaking quality and meat analogues
	Hypoallergenic gluten	Food products for individuals genetically predisposed to gluten-related disorders

it is preferred for pasta, while medium-coarse and medium semolina is usually mixed with common wheat for making leavened and non-leavened flatbreads in Mediterranean countries. Soft common wheat is characterized by soft kernels requiring less power to mill and produces flour with lower levels of starch damage, smaller particle size and lower water absorption compared to common hard wheat.¹⁸ In bakery products, hard wheat is used for making yeast-leavened breads, whereas soft wheat is used for making crackers, cookies, cakes, steam breads and some Asian-style noodles.¹⁸

Grain hardness is largely controlled by the *Hardness (Ha)* locus, located on chromosome arm 5DS. The *Ha* locus carries two tightly linked genes: *puroindoline a (Pina)* and *b (Pinb)*.^{19,20} The presence of wild-type genes (*Pina-D1a* and *Pinb-D1a*) resulted in soft wheat kernels. Mutations in the *Pin* genes results in hard wheat kernels, whereas the lack of the *Ha* locus results in a very hard texture in durum wheat.^{16,18,20,21} The quantification of grain hardness is commonly performed using the single-kernel characterization system (SKCS), near-infrared reflectance and the particle size index.²² This quantification showed that although the puroindolines are the main genetic factors distinguishing the different wheat classes, there is quantitative variation within each wheat class due to the presence of other genes/quantitative trait loci (QTL).²¹

Soft durum wheat

Grain hardness and gluten strength are the major limitations in durum wheat for culinary use. Durum wheat milling results in the production of semolina. Attempts to further reduce the particle size of semolina result in unacceptably high starch damage and excessive dough water absorption. Durum wheat lacks the D genome and thus the puroindoline genes. Soft durum wheat was created using *ph1b*-mediated translocations from bread wheat.^{18,23,24} This translocation allowed the replacement of ~20 million base pairs (Mbp) of chromosome 5BS with ~28 Mbp of chromosome 5DS. Soft-textured durum wheat recombinant

line 'Langdon 1-674' was used to develop the soft durum variety 'Soft Svevo',¹⁸ which was used to create soft durum germplasm.²⁴ Soft Svevo and its soft derived lines showed significantly softer endosperm and reduced gain hardness compared to hard Svevo and within the range typical of soft common wheat.^{18,25} Milling process was improved as soft durum wheat requires less energy to a level similar to that of common wheat and less than typical durum wheat.^{25,26} Particle size was reduced to a mean size value of 0.75 µm. The break flour yield increased from ~17% in durum wheat to >40% in soft durum wheat.²⁷ The flours showed lower starch damage (1.5–2%) and ash (0.41%) than those obtained from hard durum and similar to common wheat.^{25,26} Solvent retention capacities (water, sodium carbonate and sucrose) were lower and similar to common wheat.^{24,27,28} However, sodium dodecyl sulfate sedimentation volume and lactic acid solvent retention capacity of soft durum flours were found to be more similar to the Svevo hard durum, indicating that the introduction of *Pina-D1a* and *Pinb-D1a* did not affect protein strength.²⁸ These changes in functional features imparted new features when included in food soft applications.^{26,27,29}

Soft Svevo-derived soft durum lines were used to make cookies,³⁰ having a diameter similar to that of common wheat. In the case of bread, these soft durum wheat flours produced dough with decreased water absorption, gluten strength and tenacity in comparison with hard Svevo. These soft durum lines can be considered an intermediate category having medium gluten strength. Furthermore, they preserved the yellow color and protein characteristics of durum wheat.^{27,28} Breads made with soft durum had higher volumes compared to durum wheat but lower volumes compared to common wheat.²⁸ Soft durum wheat was used to make extruded snacks and resulted in a satisfactory expansion ratio.³¹ Soft durum wheat dry pasta had a superior quality compared to hard durum wheat, showing a low cooking loss, high firmness and low stickiness.²⁹ Fresh pasta made with soft durum wheat was also used to make fresh pasta, exhibiting low cooking water uptake (115–122%), low cooking loss (~3–4%), high firmness and low stickiness compared to durum wheat pasta. The yellow index and luminosity of raw and cooked pasta were comparable to durum semolina-based pasta. Thus, soft durum wheat might offer a new variety of high-quality pasta.²⁶

Extra-soft durum wheat

During the development of soft durum wheat, SKCS hardness index values were found as low as 5 among progeny of a cross involving cv. Svevo durum wheat and a cv. Langdon *Ha* translocation line (5DS-5BS), and this super-soft kernel phenotype was proven to be independent of the *Puroindolines*.¹⁸ Reduced kernel hardness in soft durum to below zero was identified in a recombinant inbred line population developed from a cross between the soft durum wheat 'Soft Strongfield' and 'Kamut' (*T. turgidum* ssp. *turanicum*) Khorasan wheat. This created an 'extra-soft' durum wheat.³² QTL associated with extra-soft kernel texture was mapped on chromosomes 4B and 1B.³² Extra-soft durum wheat has not been commercialized and the effects of extra-soft kernel texture on milling, flour and end-product qualities have not yet been studied.^{18,33} Studying the application of extra-soft durum wheat in pastries and confectionery products is warranted.

COLOR

The grain color of durum wheat is attributed to the presence of natural pigments – i.e., anthocyanins and carotenoids. Durum

Table 2. Commercial food products made with pigmented durum wheat

Food categories	Yellow	Purple	Red		Blue	Black
			Red flour	Red bran		
Bakery	240	87	70	20	0	23
Snacks	44	27	35	4	0	5
Breakfast cereals	58	16	0	6	0	6
Meals and meal centers	1373	10	49	0	0	14
Dairy	3	0	0	5	0	3
Processed meat products	62	2	3	0	0	0
Baby food	188	50	3	0	0	3
Soup	177	0	6	0	0	0
Side dishes	2141	3	92	0	0	6
Sauces and seasonings	25	3	4	0	0	0
Desserts and ice creams	10	0	1	0	0	0
Chocolate confectionery	6	0	0	0	0	0
Fruit and vegetables	6	0	0	0	0	0
Sugar confectionery	4	0	0	0	0	0
Drink	4	2	0	5	0	2
Total	4381	200	263	40	0	62

The market search was carried out by consulting the Mintel Global New Product Database (GNPD; Mintel Group Ltd, London, UK). The searches were conducted by considering as categories: food and drinks, keywords and type of colored wheat, without restriction on the date of product launches.

wheat owes its amber yellow color to carotenoids. The typical yellow endosperm color is determined mainly by two loci: *Psy1* and *Psy2*.³⁴ *Psy1* was located on chromosomes 7A and 7B of durum wheat, while *Psy2* is located on group 5 chromosomes of durum wheat.³⁵ The yellow color is related to the presence of lutein, zeaxanthin and β -cryptoxanthin, providing health benefits due to their antioxidant capacity.³⁶ A bright-yellow color of semolina and pasta is an important criterion for the durum wheat industry.

Red, purple or blue grain colors are associated with anthocyanins located in the aleurone or pericarp.³⁷ The high anthocyanin content in these colored wheat grains make these varieties an attractive avenue for the production of nutritious food products with a peculiar natural color feature. Red color is controlled by *Pp3*, *Pc*, *Pls* and *Plb* genes, located on chromosomes 2A, 7A and 7B.³⁸ The red color is related to the presence of catechins and proanthocyanidins, which are synthesized through the flavonoid biosynthesis pathway.³⁹ Purple grain color is caused by anthocyanins in the pericarp, controlled by the *Pp* gene, which is located on chromosome 7B.⁴⁰ Blue color is caused by anthocyanins in the aleurone layer,^{12,41} which is determined by the genes *Ba1* and *Ba2*.⁴² Black wheat results from the combination of genes for blue aleurone and purple pericarp.⁴³ Pasta using purple durum wheat showed similar sensory properties to that of commercial whole meal pasta, with a lower *in vitro* glycemic index.⁴⁴ Red wheat-based pan and pita were reported to be bitter, with sour aftertastes and dark color, limiting consumer acceptance.⁴⁵ As illustrated in Table 2, the use of colored wheat is limited compared to yellow durum wheat. Formulating foods with colored grain products, can be challenging at high levels of inclusion due to the bitter taste and dark color.

STARCH COMPOSITION

Starch is the major component of wheat (up to 80%), made of amylose (linear biopolymer composed of mainly α -D-(1,4)-glucosyl units with very few α -D-(1,6)-glucosyl units) and amylopectin

(branched biopolymer with α -D-(1,6)-glucosyl linkages).^{9,46,47} The technological (e.g., water holding and gelling capacities) and nutritional (starch digestibility) qualities of starch are strongly related to the ratio of amylose to amylopectin.⁴⁷ The amylose/amylopectin ratio determines the functional properties and nutritional value of starches and their derived products (Fig. 1). Available genetic resources with mutants associated with amylose and amylopectin synthesis provided an opportunity to generate wheat genotypes with novel starch properties to meet the demand of consumers and the food industry.⁴⁸

Waxy durum wheat

Amylose is synthesized by granule-bound starch synthase (GBSS) having two isoforms GBSSI and GBSSII, which is encoded by two homologous waxy genes positioned on chromosomes 7A (*Wx-A1*) and 4A (*Wx-B1*).^{49–51} Waxy wheat lacking GBSSI (waxy protein) had starch granules without amylose (<2%).⁵⁰ Silencing one or two of the waxy genes (*Wx-A1* and *Wx-B1*) usually results in reduced amylose 'partial waxy' wheat, whereas silencing the two genes produces 'complete waxy' wheat. Partial waxy wheat shows changes in the starch granule size and chain length, depending on the silenced gene.^{48,51} Complete waxy wheat exhibits rapidly digestible starch, and hence has a high glycemic index.⁵²

Semolina produced from complete waxy durum wheat was not suitable for making pasta because of its lower firmness, higher cooking loss and increased stickiness compared to durum wheat.⁵³ Sharma *et al.*⁵⁴ reported that partial waxy durum wheat had a minor impact on reducing pasta quality. Although waxy durum is not suitable for making pasta, the softening properties of waxy dough may allow new food applications such as meat analogues for thickening purposes. Waxy durum wheat showed higher starch peak viscosities and swelling power compared to non-waxy lines (30% amylose).⁵¹ It was also reported that waxy durum wheat flour blended with common flour improved loaf

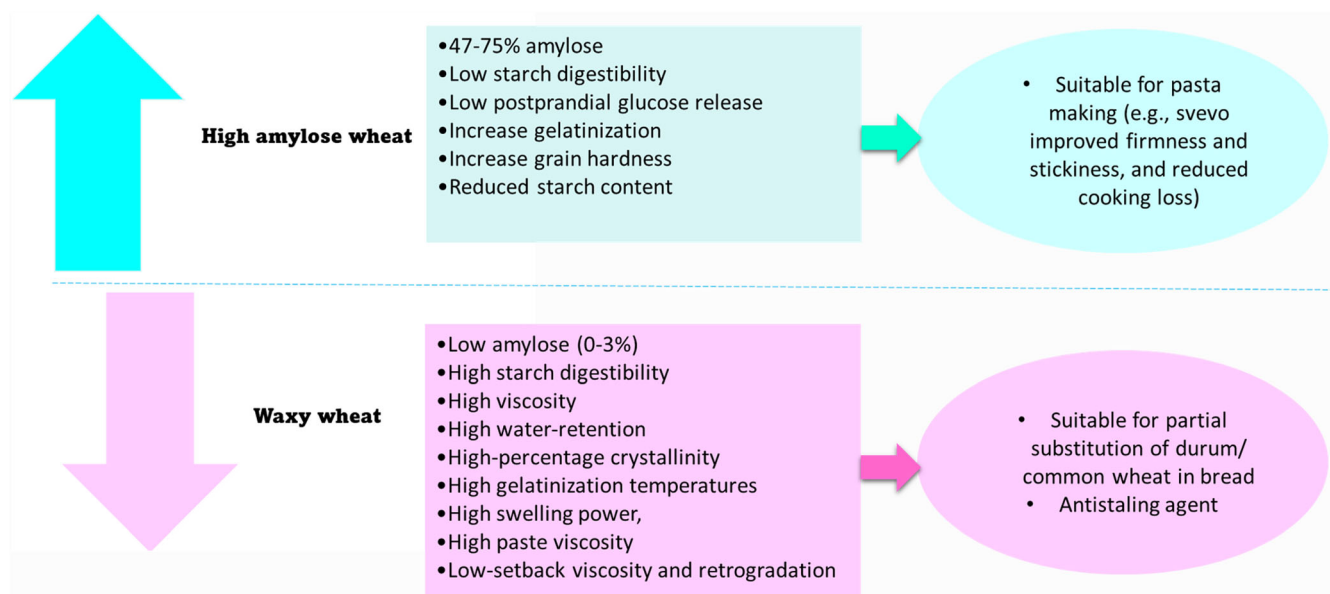


Figure 1. Changes in starch composition and their effects on quality features.

expansion and reduced loaf firmness of bread, which is attributed to higher gelatinization temperatures and swelling ability of waxy starch.⁵⁵ In a previous study, waxy durum wheat flour did not affect bread volume.⁵⁶ Bread made with 20% waxy wheat flour showed extended shelf life due to the antistaling properties of waxy flour.⁵⁵ In the Mediterranean region, durum wheat is used to make different types of breads and pastries, and waxy durum wheat can be used for partial substitution as an antistaling agent.⁵⁷

High-amylose durum wheat

To achieve higher amylose content in durum wheat, two main approaches have been reported. First, amylose can be increased by increasing the expression of GBSS. Second, amylopectin biosynthesis could be decreased by silencing starch synthases of class IIa (SSIIa) and finally by suppressing starch branching enzyme (SBE), IIa or/and IIb (SBEIIa and SBEIIb).^{48,58}

Through non-transgenic downregulation of SBEIIa, amylose content was increased up to 47–55%.^{58,59} Mutations on the A and B genomes altered SSIIa and increased amylose content from 23% to 44%,⁴⁸ while a single mutation on A genome SSIIa increased amylose content from 29% to 44%.⁵⁹ The silencing of starch synthases IIa and starch branching enzymes IIa in Svevo (33% amylose content) increased amylose content to 43% (Svevo SSIIa) and 58% (Svevo SBEIIa), respectively, and resistant starch from 0.73% to 2.06% (Svevo SSIIa) and 7.36% (Svevo SBEIIa), respectively.⁶⁰ Durum wheat with increased resistant starch that is less susceptible to breakdown by digestive enzymes has many health benefits.⁶¹ Through RNAi gene silencing, the suppression of SBEIIa resulted in raising the amylose content from ~25% to ~75%.⁶²

High-amylose wheat exhibited an increase in grain hardness^{63,64} and a reduction in starch content,⁵⁸ and modifications of size and morphology starch granules (A and B).⁶⁵ High-amylose wheat is associated with increased resistant starch (RS2, RS3 and RS5).^{66–68} As such, high-amylose wheat is less digestible in the gastrointestinal tract and the postprandial glucose release is limited depending on the amount of resistant starch.^{60,68,69} This can be related to the dense structure of high-amylose starch,

resulting from the interconnection of amylose–amylopectin crystallites and amylose–lipid complexes limiting digestive accessibility.⁷⁰ High amylose was reported to enhance fermentation due to the health benefits of resistant starch fermented into short-chain fatty acids that are beneficial for gut health.⁷¹ Thus, adopting high-amylose wheat flour might increase the daily intake of dietary fiber and bridge the fiber gap. In addition, it can impart several health benefits that can be claimed on product labels and thus attract health-conscious consumers seeking high-fiber and low carbohydrate foods.⁷² Raising awareness about high-amylose wheat flour will boost its uses.⁶⁵

Nevertheless, there are limited studies on the application of high-amylose durum wheat flour for food product development. High-amylose pasta has improved nutritional values – i.e., increased fiber, resistant starch, and protein and reduced carbohydrates.^{60,73–75} Cooked pasta made with high-amylose wheat was soft and less sticky but cooking loss was higher compared to hard Svevo spaghetti.⁶⁰ This can be related to the increase in protein and fiber, resulting in a firmer structure and less swollen pasta. Previous studies showed that pasta made with high-amylose semolina from SBEII had higher firmness and cooking loss and deteriorated color.^{75,76} In another study, pasta prepared from silenced SSIIa showed lower water absorption, cooking time and yellowness, but increased cooking loss and firmer texture compared with the wild-type genotype.⁷⁶

PROTEIN COMPOSITION

Gluten is the major protein component of wheat (~80% of the total proteins). Glutenins and gliadins are the main components of gluten conferring its functionality in wheat end-use quality. The glutenins are subdivided into two subfamilies – high-molecular-weight glutenin subunits (HMW-GSs) and low-molecular-weight glutenin subunits (LMW-GSs) – while gliadins are made of α -, β -, γ -, δ - and ω -gliadins. The relative amount and composition of gluten depend on several genetic and environmental factors, which in turn impact its end-use quality. There are hundreds of genes encoding gluten proteins in wheat.

Breadmaking quality is related to protein content and gluten strength, which are important targets for wheat breeding. Hard wheat, which typically has a higher content of protein and higher elasticity, is necessary for high-quality bread and pasta, as compared to soft wheat, which typically has a lower protein content, desired for cakes and pastries.⁹ HMW glutenins are major determinants of gluten strength, which is responsible for the formation of a protein/starch network suitable for breadmaking.⁷⁷ This is due to the *Glu-D1* locus, which is present in common wheat but absent in durum wheat. The lack of *Glu-D1* locus in durum wheat explains its weak gluten and limited use in bakery products.⁷⁸ During the last decade, the selection of durum wheat genotypes focused on changes in protein composition, mainly increased B-type LMW-GS, which is associated with reduction in the gliadin-to-glutenin ratio to increase gluten index.⁷⁹ It was reported that the introduction of the *Glu-D1* alleles from common wheat in durum wheat increased dough strength.⁸⁰ Increasing protein content by introducing *Gpc-B1* allele from wild emmer (*Triticum turgidum* subsp. *dicoccoides*) also improved dough strength and breadmaking quality.⁸¹

Vital wheat gluten is also an ingredient recovered from wet extraction of starch and it has a long history of use as a dough strengthener of weak flours.⁸² Gluten is also widely used in food products as binder, filler and extender to improve consistency, mouthfeel and sensory traits.^{83,84} In the frame of the transition of plant-based diets, gluten is gaining much interest in the formulation of meat analogues because it can form a three-dimensional network. Gluten is commonly blended with oilseed and pulse proteins and then extruded to obtain textured proteins with various features that can fit different types of meat analogues, such as sausages, patties and meatballs.⁸⁵ Gluten could contribute to the formation of fibrous structure and provide the essential texture in meat analogue products. Making new wheat with gluten having tailored features suiting these emerging applications would be a booster for a wider use of durum wheat.

On the other hand, wheat proteins can be related to health disorders (gastrointestinal and respiratory). Gluten 'epitopes' can trigger gastrointestinal immune responses in susceptible individuals expressing human leukocyte antigen alleles *DQ2* and/or *DQ8*. This is due to epitopes belonging mainly to α - and ω -gliadins,⁸⁶ as well as LMW and HMW glutenins and γ -gliadins from wheat.^{87,88} Celiac disease, wheat allergy and non-celiac gluten sensitivity are the major gluten-related disorders.⁸⁹ The ω -5 gliadins, HMW-GSs, α -amylase/trypsin inhibitors and nonspecific lipid transfer proteins are associated with wheat-dependent exercise-induced anaphylaxis and baker's asthma.^{90,91} Several genetic interventions (conventional and genetic editing) have attempted to develop wheat with hypoallergenic gluten. Conventional breeding cannot produce hypoimmunogenic varieties due to the complexity of the polymorphism of gluten.⁹² In durum wheat, α -gliadin-coding genes are located on chromosome 6, while γ -gliadin, ω -gliadin and LMW glutenin genes are located on chromosome 1. Bread wheat is more complex as it is an allohexaploid in which A, B and D genomes contain gluten gene families.¹⁰ The use of genetic editing showed great efficiency in silencing genes coding gluten, but negatively impacted the quality of wheat-based products.^{93–95}

CONCLUSIONS

The use of classical and innovative biotechnological tools has enabled the modification of the technological and nutritional

characteristics of durum wheat. The softening of durum wheat kernels resulted in new properties that can fit bread and baked goods formulations. Colored durum wheat offers a portfolio of different ingredients with high antioxidant properties to be included in different products to play a dual role, a natural colorant and functional ingredient. Available approaches for modulating amylose/amylopectin ratio impart low- and high-amylose durum wheat result in different technological and nutritional features that can fit several applications. Proteins are key features in wheat utilization. Modulating gluten strength can enlarge durum wheat uses from extender, binder and thickener to be more of a key ingredient in the new generation of meat analogues. Expanding the culinary uses of durum wheat can revolutionize durum wheat production to many growing areas to address food insecurity. As durum wheat is known to be more tolerant to biotic and abiotic stresses compared to common wheat, expanding its production can contribute to more sustainable solutions. Nevertheless, more efforts are still needed to maintain these properties and create a stable quality. New trends in the food industry may direct future research towards creating novel durum wheat varieties in response to consumer demand.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Meriem Aoun and Fatma Boukid wrote the main manuscript text. Both authors reviewed the manuscript.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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