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Yellow berry in wheat: genetics, impact on grain protein content, technological quality, and value-added applications

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ABSTRACT

Objective: To highlight the importance of wheat grain quality in the food industry, with emphasis on the presence of the disorder known as yellow berry (YB).

Design/Methodology/Approach: This review analyzes the importance of wheat grain quality, focusing on YB, its physiological and nutritional causes, and its relationship with nitrogen availability. It also addresses advances in genetics and breeding aimed at increasing the stability of grain protein content, along with potential value-added applications for affected wheat.

Results: Wheat (*Triticum* spp.) is a staple crop in the human diet and one of the most consumed cereals. Grain quality, especially its protein content, is a key attribute for nutrition and food security. However, the presence of YB represents a significant limitation, as it is associated with a reduction in protein concentration and an increase in starch content. This disorder has been primarily linked to nitrogen deficiencies in the soil. Affected grains exhibit a floury, opaque, chalky-looking endosperm, accompanied by a heterogeneous protein matrix.

Study Limitations/Implications: Genetic improvement strategies are needed to mitigate the effects of YB; nevertheless, studies on this topic are scarce.

Findings/Conclusions: Optimizing management practices, such as nitrogen fertilization, is essential to balance crop yield and grain quality. This contributes to ensuring economic viability and promoting environmental sustainability in wheat production.

Keywords: protein, starch, bread, durum, nitrogen.

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INTRODUCTION

Wheat (*Triticum* L.), as the predominant staple crop, is essential for global food security, supplying more than 20% of calories and protein, and contributing more than 30% of the energy consumed by humans (Wan *et al.*, 2023), in addition, it is one of the main cereals in the global economy due to its high productive potential and technological value. The most widely cultivated variety is *Triticum aestivum*, known as common wheat (Biel *et al.*, 2021), considered one of the most consumed cereals in the world, along with rice

and maize (Nardino *et al*., 2022). On the other hand, durum wheat (*Triticum turgidum* L. var. *durum*) is the tenth most prominent and cultivated cereal globally, with an average annual production of 40 million tons. Wheat plays a significant role in nutrition, as today wheat grains contribute greatly to the human diet by providing major nutrients such as carbohydrates, proteins, dietary fiber, minerals, vitamins and as well as phenolic acids known for their antioxidant potential (Mariem *et al*., 2020).

Nonetheless, the quality of this important food can be compromised by various factors, and sometimes, the harvested grain may exhibit quality deviations, primarily due to a high incidence of the physiological defect known as yellow berry (YB), which prevents it from meeting industry standards (Solís Moya & Díaz De León Tobías, 2001), considered a serious disorder in the grains of bread wheat, durum wheat, and triticale. This problem arises mainly due to nitrogen (N) deficiency in the soil (Zárate Márquez *et al*., 2015) and is manifested by the appearance of areas with starchy spots in generally vitreous grains, which results in a less compact structure, with numerous open spaces and a physically variable protein matrix in the grains (Taranto *et al*., 2023); so that this character is closely associated with a reduction in the protein content in the grain (Rodríguez *et al*., 2011) significantly affecting the quality of flour in bread wheat and pasta in durum wheat (Zárate Márquez *et al*., 2015).

Although YB has been detected in both durum wheat and bread wheat; in the case of the manufacture of durum wheat products, large, vitreous grains with high protein content, yellow pigment, and strong gluten are needed. The physiological alterations associated with YB extend beyond the grain level; the reduction in vitreousness and protein content directly comprises both technological performance and commercial value. The proportion of vitreous grains is an indicator of quality, as it is related to semolina yield and protein content. In contrast, an increase in "YB grains" deteriorates quality, reducing protein content by up to 1% for every 10% of these grains (Solís *et al*., 2009). In this context, YB grain is characterized by its opacity and floury texture, which reduces the vitreous properties of durum wheat and results in a higher commercial penalty compared to bread wheat (Castro, 2022). In this regard, the amount of wheat grain protein sets up the price paid to producers and is subject to the amount of N in the canopy at anthesis and the absorption capacity of available N during grain filling (Longmire *et al*., 2023).

The technological and nutritional quality of durum wheat semolina fundamentally depends on the type of proteins that constitute gluten and their quantity (Graziano *et al*., 2019); the rheological properties of gluten are indispensable not only for the manufacture of bread but also for a wider variety of foods that are made exclusively from wheat, such as noodles, pasta, breads, cakes, cookies and other food products (Žilić *et al*., 2011). Quality is therefore a key factor in wheat improvement, as its genetic origin is less affected by the environment and has a significant impact on the commercial value of a cultivar. Consequently, if a cultivar has a specific combination of alleles at important loci, it is likely to present valuable qualitative traits with respect to the quality of the final product and this applies to both durum wheat and bread wheat germplasm (Varzakas *et al*., 2014).

On the other hand, alternatives have recently been proposed for the potential use of wheat grain with YB, over its high starch content and low protein concentration.

Although this imbalance is undesirable in other industries, it can be unbelievably valuable in beer brewing, since starch is an essential substrate to produce of this beverage (García *et al.*, 2023).

Concerning the above-mentioned aspects, the content of this review aims to highlight the importance of wheat grain quality in the food industry, with special emphasis on the physiological defect YB and its impact on wheat grain quality, including protein content, technological properties, and nutritional properties. It synthesizes current knowledge on the genetic, physiological, and agronomic determinants of YB and outlines their implications for quality improvement and industrial valorization.

Importance of wheat crop

Wheat is the most widely cultivated cereal in the world in terms of grain yield and cultivated area. Today, the most important wheat varieties are hexaploid soft wheat (*Triticum aestivum* L.) and tetraploid durum wheat (*Triticum durum* Desf.) (Rossi *et al.*, 2024), which are two species strongly related with potentially different adaptations and few different technological properties that make semolina and wheat flour destined to produce of pasta and bakery products, respectively (Mastrangelo & Cattivelli, 2021). Around 80 million farmers depend on wheat for their livelihood; between 90% and 95% of the wheat grown worldwide is common or bread wheat, which is used for the production of refined or whole wheat flours in the production of a wide variety of bakery products (Giraldo *et al.*, 2019). Of the total wheat production, 5% is represented by durum wheat, with a planting area of 16 million hectares worldwide (Beres *et al.*, 2020). Foods made from durum wheat vary greatly between producing countries; although pasta is the most recognized product worldwide and an icon of Italian cuisine, couscous is the most common durum wheat-based food in North Africa. In southern Italy, Spain, Turkey, and the Mid-East Mediterranean regions, durum wheat breads have traditional importance (Laddomada *et al.*, 2021).

Nutritional value of wheat

Wheat grain is essentially made up of starch, proteins, and cell wall polysaccharides, constituting approximately 90% of its dry weight. In addition, it contains other components in smaller quantities, such as lipids, terpenoids, phenolic compounds, B-complex vitamins, and minerals (Shewry *et al.*, 2013). The Table 1 shows the main nutritional components of wheat.

Wheat is a carbohydrate-rich food composed mainly of starch, a main source of energy to maintain metabolic balance, which involves a complex linkage of several factors, such as nutrient intake, hormonal regulation, and metabolic processes (El Houssni *et al.*, 2024). Starch granules hold approximately 30% linear amylose molecules and 70% branched amylopectin molecules. In these granules, amylopectin adopts a double helix structure, which gives the system a high capacity to retain water and a rapid expansion capacity (Hidalgo *et al.*, 2016). Likewise, cereals are a rich source of dietary fiber, such as non-starch polysaccharides, with the predominant components of wheat grain being arabinoxylans and β-glucans (De Santis *et al.*, 2018).

Table 1. Nutritional composition of wheat and nutrient reference values.

Macronutrients	Content (%)	Mineral	Content (mg/100 g)	NRVs-R (mg/100 g)	Vitamins	Content (μg/ g)	NRVs-R (mg/100 g)
Carbohydrates	70-75	Ca	15-34	1000	Niacin (B3)	0.86	15
Proteins	10-18	K	141-431	-	Riboflavin (B2)	~1.0	1.2
Lipids	1.5-2.5	Mg	13-42	310	Thiamin (B1)	1.0-4.0	1.2
Fiber	~1.6	Fe	3.6-6.8	22	Pyridoxine (B6)	1.89	1.3
Minerals	~1.6	Se	33.9-70.7	60	Folate (B9)	0.56	400
		Na	2-3.8	-			
		Zn	0.7-4.2	14			

NRVs-R, nutrient reference values-requirements.
Source: FAO & WHO, 2011; Khalid *et al.*, 2023; Marcotuli *et al.*, 2020; Shewry *et al.*, 2013; Wieser *et al.*, 2020.

Proteins are compounds of vital importance for the functioning of all cells (Sallam *et al.*, 2019). Wheat grain proteins are divided into two categories: prolamins and non-prolamins. Prolamins comprise gliadins and glutenins that make up approximately 75% of all grain proteins, while non-prolamins, such as albumin and globulin, represent about 25%. Albumins and globulins are soluble proteins that include various enzymes and inhibitors, playing essential structural and metabolic roles during the grain filling process (B. Zheng *et al.*, 2021). On the other hand, the prolamin content and endosperm composition influence the quality of wheat flour (Khalid *et al.*, 2023), in this context, gliadins contribute to the viscosity of the dough, while glutenins are responsible for providing elasticity and resistance (X. Wang & Liu, 2021), both proteins interact to form a viscoelastic gluten network in the dough, which is essential for determining the baking quality of products made from wheat flour (B. Zheng *et al.*, 2021). Proteins are present throughout the grain, but their concentrations vary considerably between different compartments. The germ has approximately 7.5% of the total proteins, the aleurone layer contains 14.2%, the pericarp and the testa 3.8%, and the starchy endosperm presents 74.5%; considering the distribution of these compartments, the largest amount of proteins is located in the starchy endosperm (Wieser *et al.*, 2020).

Regarding lipid content, wheat germ is one of the main byproducts of wheat milling, with an oil content that varies between 5.2% and 15.5%. This oil is an abundant source of health-beneficial compounds, such as essential fatty acids and unsaponifiable lipids, including tocopherols, phytosterols, and policosanols (Harrabi *et al.*, 2021).

Yellow berry in wheat grain

Yellow berry is a physiological disorder in the wheat grain that is characterized by having a high starch content, significantly affecting the protein content, which results in inferior quality bakery products and pasta production, generating penalties for wheat farmers (Rodríguez *et al.*, 2014). Grains with YB are distinguished by a smooth (Serranti *et al.*, 2013) and mottled appearance due to spots that range from white to yellowish-white (Figure 1), depending on the color of the outer layers of the seed (Solís & Díaz De León, 2001). An insufficient amount of protein in the grain causes areas where the starch granules

Figure 1. Grains of three durum wheat genotypes with YB expression.
Source: Own elaboration.

are not properly cohesive. These areas with low protein are composed of gaps empty of air that appear as clear and mottled patches (Hare, 2017), and in grains normally these spaces are filled with a protein matrix. The gaps in the endosperm reduce translucency, which gives starchy grains an opaque appearance (López-Ahumada *et al.*, 2010). This reduces the vitreous appearance of durum wheat grain, causing it to be more penalized in the market compared to bread wheat (Castro, 2022).

According to the specifications of the Official Mexican Standard NOM-FF-36-1984, YB grains are those grains that have at least a quarter of their surface with a floury appearance (DOF, 1984). In durum wheat, vitreous grains have a higher protein content and therefore higher grain quality than YB grains (Bnejdi & El Gazzah, 2008). In this regard, the minimum content of hard and vitreous grains in the marketing of durum wheat is a key parameter. YB grains are also known as non-vitreous kernels whose protein content is lower than that of vitreous kernels (Dexter & D'Egidio, 2012). Farmers do not typically obtain higher prices for high protein content in grains, but do face lower prices when more than 15-20% of durum wheat grains are affected by YB (Grahmann *et al.*, 2014), because it can reduce the protein content in the grain between 2% and 4% (Ibarra *et al.*, 2023).

Factors that contribute to the development of YB in wheat grain

Among the main biological processes associated with wheat yield is grain development, considered a complex process that is characterized by three fundamental stages: cellularization/differentiation, grain filling, and maturation. The main transformation in grain development occurs when essential storage components such as starch and protein begin to accumulate (Kaushik *et al.*, 2024). During this stage, defects in commercial quality may arise due to environmental conditions, such as relatively low temperatures, low radiation, and high humidity, causing the formation of grains with YB, which are also influenced by genetic factors and low availability of N (Simón, 2022).

It has long been observed that YB grain disorder is mainly related to a limited presence of nitrates in the soil. Furthermore, N stress in the grain in its initial phase of development reduces the concentration of grain protein, and especially the proportion of gliadins (López-Ahumada *et al.*, 2010); likewise, a significant reduction in N leads to a decrease in the number of grains per ear, and consequently affects grain yield in wheat (Zi-meng *et al.*, 2025). For that reason, increasing the availability and improving the efficiency of N uptake is considered crucial to increase both wheat grain yield and protein content. However, one of the challenges in wheat production and breeding is to increase grain yield without compromising its protein content (Derebe *et al.*, 2022).

Impact of N on yellow berry expression and protein content in wheat grain

The photosynthetic capacity of plants is essential during the growth of crops. Concerning N fertilizers, they are a key factor, since N is a critical component of plant amino acids, proteins, and chlorophyll in the photosynthesis process (Xiao *et al.*, 2023). N yield comes from two sources: N is stored in the vegetative parts before flowering and N is absorbed during the grain filling period (X. Zheng *et al.*, 2020). Grain N is produced through two pathways: N remobilized from the canopy (leaves and stems) and up to 50% from the soil after anthesis (Zörb *et al.*, 2018). Applying N during reproductive development increases protein synthesis and storage in the grain, while excessive delay in fertilization can limit the amount of N that is converted into quality protein (Blandino *et al.*, 2015).

Generally, durum wheat is more sensitive to N availability; its protein accumulation exhibits a stronger physiological response to N supply compared with bread wheat (Giunta *et al.*, 2019). On the other hand, there is a negative correlation between grain protein content and grain yield because high transpiration limits the rate of N mineralization (Govta *et al.*, 2022), since a high number of grains contributes to high performance and can establish an imbalance between the N source represented by the amount of N absorbed during anthesis and the N sink represented by the number of fixed grains (Giunta *et al.*, 2019). Additionally, a high yield reflects the starch content and, in the case of wheat, the gluten protein content. In this regard, starch represents approximately 80% of the grain, so protein content is expected to decrease with increasing yield, which is often attributed to yield dilution. Furthermore, mineral micronutrients, such as iron and zinc, may decrease because of yield dilution (Lovegrove *et al.*, 2020). Therefore, as yield increases, there is a higher concentration of starch, consequently, it is possible to consider that YB does not affect crop yield (Ibarra *et al.*, 2023).

The limited availability of N is the main cause that affects the prevalence of grains with YB (Akman, 2013; Sissons *et al.*, 2012); so, by appropriately increasing the N fertilization rate, it can increase wheat production (Ma *et al.*, 2015), improve grain protein content and alter wheat protein composition (Trevisan *et al.*, 2022). Nevertheless, after applying increasing amounts of N fertilizer, the protein content in the grain reaches a maximum peak and then stabilizes, without the crop increasing the absorption or redistribution of N, which reduces the efficiency of fertilizer use (Barneix, 2007), in addition to increasing production costs and causing contamination of groundwater as N leaches into the soil (Ramírez-Wong *et al.*, 2014).

Some studies have proved the effect of N on the expression of YB. Rodríguez *et al.* (2014) investigated three wheat genotypes and found that one of them presented a higher percentage of YB (2.31%); this phenomenon was attributed to the fact that said genotype also showed a higher grain yield compared to the other two; becoming to its tall habit, this genotype had higher N uptake demands, that resulted in a higher YB content and a lower protein content compared to the other genotypes. Ibarra *et al.* (2023) reported that the presence of YB grains in durum wheat was only affected by fertilization doses, with the highest percentage (31%) observed in the lowest N doses of 0 kg N ha^{-1}, while at a high dose of 250 kg N ha^{-1} obtained results of 0%. Mon *et al.* (2016) performed two years of experiments to evaluate the effects of N fertilizers on certain parameters in durum wheat, including YB. The results revealed that, in 2013, YB was expressed in 54 and 7% with N doses of 84 and 168 kg N ha^{-1}, respectively; in 2014, YB occurred in 71 and 37% with N doses of 84 and 168 kg N ha^{-1}, respectively; while at N doses of 252 kg N ha^{-1} or more the YB content was insignificant. Furthermore, it has been shown that applying N at 150 kg N ha^{-1} has reduced the YB content in wheat grain by up to 1% (Ramírez-Wong *et al.*, 2014; Rodríguez-Félix *et al.*, 2014).

Increasing the level of N fertilization from 150 to 200 kg ha^{-1} significantly affects the increase in yield and certain grain quality parameters, such as total protein (8.0% increase), gluten content (9.9%), Zeleny sedimentation indices (15.9%), grain vitreous (7.3%) and falling number by 14.7% (Jańczak-Pieniążek *et al.*, 2020). The Table 2 shows studies in various regions of the world that have focused on the application of different doses of N fertilization (0, 30, 50, 100-300 kg N ha^{-1}), with the aim of increasing the protein content in the grain, which have demonstrated a direct relationship: by increasing the doses of N, both grain yield and protein concentration increase. Hence, the application of N is essential as one of the main management factors that affect wheat production (Zhong *et al.*, 2018), in the yield components (Wang *et al.*, 2022), in the protein storage and the technological quality of the grain (Blandino *et al.*, 2015).

Table 2. Influence of different N levels on the yield and protein content of wheat grain.

N rates (kg ha^{-1})	Grain yield (t ha^{-1})	Grain protein (%)	Reference
0 - 288	1.69 - 9.08	9.35 - 14.08	(Godfrey *et al.*, 2010)
100	-	10.43	(Chope *et al.*, 2014)
350	-	13.34	
0 - 270	0.69 - 3.80	7.50 - 11.50	(Assefa *et al.*, 2023)
30 - 120	3.40 - 4.25	12.40 - 13.09	(Haile *et al.*, 2012)
50 - 150	5.64	11.20 - 14.00	(Rossini *et al.*, 2025)
0 - 270	4.88 - 9.13	9.92 - 15.05	(Meng *et al.*, 2024)
120 (application in four split doses)	5.06	14.90	(Muhammad *et al.*, 2018)
130 (application in two split doses)	6.10 - 6.20	13.30 - 14.40	(Blandino *et al.*, 2016)
0 - 300	7.73 - 8.65	12.00 - 14.40	(Zheng *et al.*, 2020)
170	>7.00	<11.50	(Zheng *et al.*, 2021)
0 - 240	-	14.90 - 16.20	(Gerba *et al.*, 2013)
75 - 250	-	14.28	(Rodríguez *et al.*, 2014)
75 - 250	-	12.02 - 15.22	(Ramírez-Wong *et al.*, 2014)
60 - 110	6.42 - 6.90	12.10 - 12.50	(Tsvey *et al.*, 2021)

Genetics of yellow berry disorder and grain protein content

Although several studies have focused on improving grain quality, particularly protein content, research aimed at identifying genes associated with the expression of the physiological disorder YB remains limited. In this context, Ammiraju *et al.* (2002) reported the association of two microsatellite markers, Xgwm174 and Xgwm190 (located on chromosome 5D). They also identified an inter-simple sequence repeat (ISSR) marker, $UBC842_{600}$, and a randomly amplified polymorphic DNA (RAPD) marker, $OPR8_{1000}$, on chromosome 6B, all linked to YB tolerance. Prashant *et al.* (2011) mapped a major gene associated with YB tolerance to the short arm of chromosome 5D and also identified a minor locus on chromosome 2D that explained 6.9% of the phenotypic variance for this trait.

More recently, Taranto *et al.* (2023) evaluated 123 durum wheat samples by genome-wide association study (GWAS) and revealed 28 reliable quantitative trait nucleotides (QTNs) related to plant morphological characteristics and grain-related traits, highlighting a strong association of YB on chromosome 6A (Q.Yb-6A), in a region containing the NADH-ubiquinone oxidoreductase subunit, a gene involved in starch metabolism.

Grain protein content, in particular, is determined by a complex genetic system and is strongly influenced by environmental factors and agronomic practices (Govta *et al.*, 2022). Accordingly, several studies have focused on identifying molecular markers associated with grain quality traits, especially protein content.

Krystkowiak *et al.* (2017) examined the interaction between alleles at the Glu-1 and Glu-3 loci, identifying several quantitative trait loci (QTL) associated with key quality attributes in bread wheat. Specifically, the Glu-D1 locus was found to influence protein content, thousand-kernel weight, starch content, wet gluten, the Zeleny sedimentation index, the alveograph parameter W, and grain hardness. In contrast, the Glu-B1 locus was associated only with protein content, the Zeleny index, and wet gluten content; while the most important marker-trait associations were found on chromosomes 1D and 5D.

In addition, seven QTLs influencing protein concentration have been reported on the chromosome arms 4BS, 5AL, 6AS (two loci), 6BS, 7AS, and 7BS (Blanco *et al.*, 2002). Complementarily, Suprayogi *et al.* (2009) identified a QTL on chromosome 7A associated with increased protein content, while Gonzalez-Hernandez *et al.* (2004) reported three QTL with similar effects, all in durum wheat.

In a more recent study, Tian *et al.* (2025) conducted a GWAS on 341 bread wheat accessions, identifying 97 significant and stable single-nucleotide polymorphisms (SNPs) distributed across 43 loci associated with protein quality. The most relevant associations were found on chromosomes 1A, 1B, and 1D. The Figure 2 illustrates the most relevant genomic regions, facilitating an integrated representation that synthesizes the findings of some of the cited studies.

The identification of loci and molecular markers associated with these traits enables a more targeted selection approach aimed not only at increasing protein content but also at reducing the incidence of YB, a disorder that adversely affects the industrial quality of the grain.

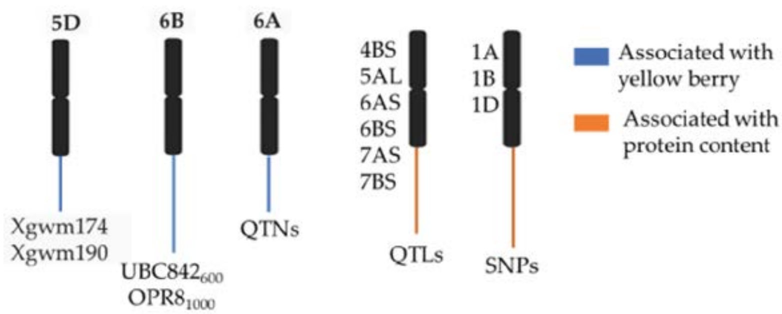

Figure 2. Genomic distribution of QTLs, QTNs, and genes associated with yellow berry and grain protein content in wheat. Source: Ammiraju *et al*., 2002; Taranto *et al*., 2023; Blanco *et al*., 2002; Suprayogi *et al*., 2009; Tian *et al*., 2025.

Impact of wheat quality on the food industry

Over time, rapid population growth and progressive decline in arable land have contributed to pressure on researchers to increase wheat productivity. High concentrations of chemical fertilizer application are generally used to promote wheat yield (Xu *et al*., 2018). However, often, increases in wheat production are related to a decrease in grain quality (Mariem *et al*., 2020).

Wheat grain quality, especially protein content and quality for human nutrition, is considered a fundamental aspect of food security, it has received limited attention, and it is often neglected in the need to improve crop production (Hu *et al*., 2022). Recently the market has paid special attention to the protein content of wheat grain, as farmers receive a higher price when the protein level exceeds 13%, equivalent to the 12% protein in ground semolina. Low protein content can result in significant economic losses for producers, given that protein is a key quality factor in the market (Melash & Ábrahám, 2022).

Wheat quality varies widely due to differences in physiology, growing conditions, crop management practices, and grain storage; for this reason, grain quality control is of utmost importance throughout the world to guarantee a stable quality of wheat for marketing (Jayas *et al*., 2016), in such a way that it is possible to define it through its physical, chemical attributes, and technological. Wheat quality is quite complex, so it can be divided into processing quality including milling, flour yield, grain weight, grain hardness, flour whiteness, flour quality, dough quality, baking quality, baking speed, dough formation time, stability time, settling value, softening degree, etc.; edible quality referring to the flavor of the products during the baking, cooking and frying processes; nutritional quality and phytosanitary quality (Y. Wang *et al*., 2024).

Influence of yellow berry on grain composition and processing quality of wheat

Physical characteristics such as vitreousness, kernel weight, and test weight have a significant impact on the rheological properties and processing of wheat; as for the chemical characteristics, they include the content of proteins, ash, lipids, and gluten, all of which are determinants for the quality of the final product (Manai-Djebali *et al*., 2021). Several factors influence the quality of durum wheat, nonetheless, the three most crucial in determining its commercial value are the proportion of hard vitreous grain, protein content (Xiao Fu *et al.*, 2017), and the concentration of carotenoids, which are responsible for the yellowish color of semolina (Giannetti *et al.*, 2023), and characteristics of the final product, such as color, aroma, and flavor (Menga *et al.*, 2023), and also contribute to good human health on account of its antioxidant properties (Ma *et al.*, 2021; Sai Prasad *et al.*, 2022). Likewise, in the world market, wheat must meet certain quality indicators, such as sedimentation value, percentage of yellow berry (YB), β-carotene content, etc. (Ozberk *et al.*, 2005).

Kernel vitreousness is the primary determinant of milling performance in durum wheat because it reflects protein-rich and compact endosperm structure (Wang *et al.*, 2023). Vitreous kernels generate higher semolina extraction rates and better cooking quality (Molfese *et al.*, 2017), whereas non-vitreous (YB) kernels contain air spaces between starch granules, resulting in softer texture and lower semolina yield (Venora *et al.*, 2009). To ensure adequate protein (12.5%) and acceptable extraction rates, industry standards typically limit YB content to less than 15% (Grahmann *et al.*, 2014). Because YB grains also contain less protein, their presence reduces dough strength and compromises pasta firmness and resistance to breakage (Dexter & D'Egidio, 2012).

The content and composition of proteins in the grain not only defines the nutritional properties, but also the rheological characteristics (Nuttall *et al.*, 2017) and the technological characteristics of the dough, impacting the quality of products such as pasta (De Vita & Taranto, 2019) and baking (Geisslitz *et al.*, 2018). So, they can influence the properties of wheat flour during kneading (such as the water absorption rate), the formation of the gluten network, the characteristics of the dough (hardness, viscosity, elasticity, extensibility, plasticity, water retention, among others) and in cooking qualities (Lin *et al.*, 2019). In this context, a higher protein content is linked to a higher proportion of gliadins and glutenins (Trevisan *et al.*, 2022); when flour is mixed with water, a protein bond is formed because of the precipitation of these two proteins; on the one hand, glutenin polymerizes forming an elastic union, while gliadin is incorporated into an extensible sticky dough, entering the gluten nexus (Varzakas, 2016), so that the properties of these proteins provide viscoelasticity and extensibility to the dough. Furthermore, quantity plays a crucial role in determining its nutritional quality (Yiğit, 2023), given that high protein content, and consequently gluten, are parameters associated with the firmness of the pasta and limited cooking (Menga *et al.*, 2023). Consequently, by decreasing the protein content due to the presence of YB, the cooking quality is also affected (Samson *et al.*, 2005); because the proteins favor the hydration of the semolina particles during the mixing process and provide structure to the fresh or dry pasta. Furthermore, the union and resistance of the protein matrix that is formed during extrusion is essential to determine the texture properties in the cooked pasta, therefore, a high protein content is the essential requirement to obtain a high quality of pasta cooking (Fu *et al.*, 2017).

Impact of yellow berry on wheat processing quality

Milling forms the initial phase of wheat processing. This process constitutes continuous crushing and sieving operations to separate the starchy endosperm from the external layers and the germ (Lullien, 2020). The starchy endosperm of the mature wheat grain is made up of three classes of main cells, that include sub-aleurone cells, prismatic cells, and central cells, which differ in terms of their concentration of functional components: gluten proteins, starch, cell wall polysaccharides, and lipids (Shewry *et al.*, 2020). Semolina consists of a coarse fraction of the endosperm, which results from the first breaking down of the wheat grain before the particle size is reduced to obtain fine flour. It is mainly used for the preparation of various forms of pasta, for which hard semolina is preferred, generally obtained from durum wheat rich in proteins (Miskelly & Suter, 2017), although it can also be produced from bread wheat (Bustos *et al.*, 2015), nevertheless, pasta made from durum wheat exhibits a more intense yellow coloration, the texture of the pasta is denser and firmer and shows more elastic properties than pasta made from bread wheat (Nilusha *et al.*, 2019). In this regard, durum wheat is more resistant to crushing, the endosperm structure is quite compact, the flour is coarse textured with more damaged starchy and with the capacity to absorb more water than soft wheat flour (He *et al.*, 2023). In this sense, during the milling of durum wheat when it has YB there is an increase in the starch content (Prashant *et al.*, 2011), disintegrating into smaller particles, which are incorporated into the finer flour fraction of lower value (Hare, 2017). On the other hand, it is important to mention that in durum wheat, sedimentation values have been positively correlated with the yellow pigment content, percentage of YB, thousand-grain weight, glume color, color, and grain yield (Hailu & Merker, 2008).

Value-added applications of yellow berry affected wheat grain

Given the growing interest in soft wheat in the food industry, a viable alternative for the use of YB grains in this sector is their use as raw materials in the production of cookies and cakes. Specifically, grains with a low protein and gluten content are valued, as these characteristics are essential for obtaining high-quality products, especially in cookies production (Yang *et al.*, 2022). This is because the amount of protein in the grain, especially that stored in the seed, significantly influences the quality of the biscuits. Wheat with low gluten content and a poorly developed gluten network forms doughs that expand more easily, which favors the production of cookies with a wider diameter after baking (Wu *et al.*, 2022).

Furthermore, as previously noted, YB grains have a higher starch content, a compound that plays a key role in the textural properties of numerous foods. Starch is widely used in both the food industry and in industrial applications, where it acts as a thickener, colloidal stabilizer, gelling agent, bulking agent, and water retention agent (Lafiandra *et al.*, 2022). Starch also has significant promise for the development of films aimed at preserving fresh fruits and vegetables. As a biodegradable, non-toxic, and edible material, it represents a sustainable alternative to conventional plastics, reducing both environmental impact and health risks associated with traditional packaging (Karnwal *et al.*, 2025). In addition, starch presents considerable potential in the pharmaceutical industry for the production of nanofibers through the electrospinning process. Starch nanofibers obtained using this technique find applications in areas such as drug delivery, tissue engineering, and the development of wound dressings (Huang *et al.*, 2021).

High protein content is advantageous for farmers and bakers but problematic for the brewery industry, as it causes long filtration periods, fermentation issues, and reduced flavor stability (Faltermaier *et al.*, 2014). The protein content is essential in cereal malting (Padilla *et al.*, 2022); however, durum wheat contains more protein than barley (9.5-10.5% in barley *vs.* 11-13% in durum wheat), which may hinder fermentation and generate undesirable flavors (García *et al.*, 2023). Thus, low protein levels are preferred for malting. The presence of YB in wheat decreases the protein content and increases starch; for this reason, YB grains could have the potential to produce brewing malts (Padilla-Torres *et al.*, 2022).

On the other hand, ethanol production is influenced by the supply of starch-rich crops, among which wheat is one of the main contributors, on account of its price, availability, and conflicts in the use of crops as food or fuel. In the case of wheat, it has a starch content of 62-75% and is mainly used for food, while for the production of ethanol, is produced especially in the United States, China, and Canada (Li *et al.*, 2022). In this sense, it is possible to consider starch-rich YB wheat as raw material to produce ethanol, nonetheless, further studies are still needed in this regard.

CONCLUSION

Nitrogen nutrition plays a central role in wheat quality, as deficiencies promote YB expression by reducing protein and vitreosity while increasing starch, negatively affecting both the nutritional properties and the rheological and technological characteristics of wheat flour. This highlights the need for genetic improvement strategies aimed at enhancing tolerance to YB and stabilizing quality under variable N conditions. At the same time, efficient N management remains essential to balance yield, grain quality, and environmental sustainability. YB-affected grains, with their elevated starch content, offer emerging industrial opportunities in brewing, biofilm, pharmaceuticals, and biofuel production. Future research should prioritize genetic mapping and agronomic optimization to transform YB-affected wheat into a value-added bioresource.

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DATA AVAILABILITY STATEMENT

The data collected in this research are available from the corresponding author upon request.

AUTHOR CONTRIBUTIONS

Espitia-Hernández: Writing – original draft, writing – review & editing manuscript, investigation, conceptualization. Velasco-López: Writing – review & editing manuscript, validation, conceptualization. Ruiz-Torres: Writing – review & editing, validation, conceptualization. Ruelas-Chacón: Writing – review, and editing manuscript, conceptualization. Lozano-del Río: Writing – review & editing, conceptualization. All authors read and approved the final manuscript.

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