

Review

Comprehensive Review of the Quality and Processing Suitability of U.S. Hard Red Spring Wheat: Current Strategies, Challenges, and Future Potential Scope

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Abstract: Hard red spring (HRS) wheat cultivated in the Northern Great Plains of the United States is often considered as premium-quality wheat because of its potential to produce high-quality end-products. The potential of HRS wheat mainly stems from its high protein and strong gluten contents, which make it a valuable ingredient for baking, especially specialized bakery products. It can also be blended with other wheat types for improved flour protein content and is well suited for sourdough, frozen dough, and clean-label baking. However, keeping its quality attributes consistent is often challenging due to the complex interplay of genetic and environmental factors in regulating them. This is further intensified by unpredictable weather events and pest infestations which cause a deterioration of quality. Although HRS wheat is widely used to improve the quality of end-products, comprehensive information about the scientific reasons behind these quality attributes is still lacking. This review summarizes scientific information regarding the unique quality attributes of hard red spring (HRS) wheat and its exclusive applications in the food industry, particularly for high-quality baking. It also identifies the challenges in upholding the standards of HRS wheat and discusses possible strategic approaches to further elevate its quality attributes. The insights gained from this review will be beneficial to a broad spectrum of stakeholders in the food industry, including bakers, millers, breeders, growers, and the scientific community.

Keywords: end-product quality; environmental influence; gluten strength; hard red spring wheat; protein content



Citation: Hoque, M.N.; Islam, S. Comprehensive Review of the Quality and Processing Suitability of U.S. Hard Red Spring Wheat: Current Strategies, Challenges, and Future Potential Scope. *Agriculture* **2024**, *14*, 853. <https://doi.org/10.3390/agriculture14060853>

Received: 29 April 2024

Revised: 24 May 2024

Accepted: 27 May 2024

Published: 29 May 2024



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1. Introduction

Wheat is a fundamental food crop worldwide, comprising approximately 18–21% of global human calorie consumption [1]. In the United States, it ranks as the third most significant field crop. Wheat flour is an essential ingredient in a wide array of products, including bread, cakes, cookies, pizza, pasta, noodles, and more [2]. The quality of these products depends on several physical and chemical properties of wheat, such as its protein content and composition, starch quality, grain hardness, vitreousness, texture, color, and so on. Based on these properties, wheat is categorized into different classes, which are unique to each wheat-growing country [3]. While countries have their own wheat classes, broadly, wheat is divided into soft and hard types based on grain hardness, which is attributed to several of its quality characteristics, including its protein content. Soft wheat varieties are noted for their lower gluten content, whereas hard wheat varieties are recognized for their strong gluten content. In the United States, wheat is categorized into six primary classes: hard red spring, hard red winter, hard white wheat, soft red winter, soft white wheat, and durum [3]. Each of these classes exhibits unique qualities that determine the milling

type and condition, baking purpose, and processing techniques. Particularly, variations in its gluten composition and strength make wheat suitable for a range of uses, resulting in diverse end-use performances [4]. Wheat in Asian countries and Russian wheat are classified as mostly having a 0% moisture level (mb), while North American wheat is classified as having a 12% level (mb). Table 1 represents the common wheat classes found in major wheat-exporting countries.

Table 1. Wheat classification based on the quality parameters in the major wheat-growing countries.

Producing Country	Wheat Type	% Protein Content (12% mb)	Characteristics	Major Food Application	Reference(s)
USA	HWW	10.0–14.0	Medium to high protein	Asian noodles, pan or flat bread.	[5]
	HRS	12.0–15.80	High protein, strong gluten, blendable, clean-label food	Bagels, artisan hearth baked breads, pizza crust, and other strong dough applications.	
	HRW	10.0–13.0	Medium to high protein, medium and mellow gluten, blendable	Pan breads, hard rolls, croissants, and flat bread.	
	SW	8.50–10.50	Low protein	Sponge cakes or Asian noodles.	
	SRW	8.5–10.5	High yield, low protein, weak gluten	Sponge cakes, cookies, crackers.	
	Durum	12.0–15.0	High protein and gluten	Pasta.	
Canada	HRS	13.5–14.0	High protein, superior milling and baking quality	Pan bread, hearth baked bread, steamed bread, noodles, flat bread.	[6]
	HRW	11.0–13.0	Medium to high protein, good milling quality	French breads, flat bread, steamed bread, noodles.	
	SRW	8.50–12.0	Low protein	Cakes, pastry, cereal, crackers, biscuits, and filling.	
	Durum	13.5–14.0	High yield	Pasta.	
UK	HW	10.0–15.0	Medium to high protein	Bread, crackers.	[7]
	SW	11.0–11.50	Low protein	Cakes, pastries.	
Russia	HW	12.5–16.0	High protein	Bread and noodles.	[8]
	SW	12.5–13.5	Low protein	Cakes, pastries.	
	Durum	13.6	Medium to high protein	Pasta.	
Ukraine	HW	13.51	Medium to high protein	Bread and noodles.	[9]
	SW	10.79	Low protein	Cakes and pastries.	
EU	HW	11.0–15.0	Medium to high protein	Bread and noodles.	[10]
	SW	10.5–12.0	Low protein	Cakes and pastries.	
Australia	APH	>13.0	High protein, strong dough with good WAC	Bread, noodles, and wonton skins.	[11]
	AH	>11.5	Strong dough with good WAC	Pan bread, hearth baked bread, and noodles.	
	APW	>10	Low protein	Flat and pocket bread.	
China	HW	9.50–12.50	Medium to high protein	Bread and noodles.	[12]
	SW	8.50–9.60	Low protein	Cakes and pastries.	
India	HW	10.5–12.50	Medium to high protein	Bread and noodles.	[13]
	SW	8.50–12.02	Low protein	Cakes and pastries.	
Japan	HW	10.0–17.20	High protein	Bread and noodles.	[14]
	SW	9.70–11.30	Low protein	Cakes and pastries.	

Note: HRS = hard red spring; HWW = hard white wheat; HRW = hard red winter; SW = soft wheat, SRW = soft red winter; HW = hard wheat; APH= Australian prime hard; AH= Australian hard; APW= Australian premium white.

The hard red spring (HRS) wheat class is renowned for its higher quality and color. HRS wheat comprises up to 25% of the wheat grown in the U.S. and is prized for its

high protein content (12–15%), strong gluten, shiny appearance, and dark color [15]. HRS wheat is further classified into three subclasses based on the proportion of dark, hard, and vitreous (DHV) kernels present [16]. These subclasses determine its pricing, along with its protein premiums. This is because vitreous kernels tend to have a higher protein content with a greater water absorption capacity in flour and a higher loaf volume in baking. These qualities make HRS wheat perfect for many types of special bakery products. Its popularity among millers is strengthened by the practice of blending HRS wheat with other wheat classes to improve dough properties [17]. Concerning its protein composition, HRS wheat stands out well above the other wheat classes and contains higher polymeric protein fractions, making it a key ingredient for high-grade baked items and top-quality end-use products [16]. Additionally, HRS wheat contains a higher number of bioactive compounds, such as dietary fiber, beta-glucan, and arabinoxylan, which are known for their protective effects against chronic diseases, than any other wheat class [18]. HRS wheat also contains a higher amount of high-molecular-weight (HMW) glutenin compared to other wheat classes, leading to the development of a stronger gluten network. This natural enhancement in gluten strength has the potential to reduce the need for the chemical additives (e.g., sodium/calcium stearoyl lactylate) traditionally used as dough conditioners [19]. To get the full benefit from HRS wheat, the baking industry needs more information about its potential use in food industries.

However, consistently maintaining the highest quality of HRS wheat is challenging due to the complex regulatory mechanism of its quality attributes. The quality characteristics of HRS wheat are influenced by a variety of factors, including genetics, growing conditions, milling processes, and post-harvest handling [15]. These factors significantly affect the quality of the flour and dough, which in turn impacts the end-product quality and market value. Gluten properties, especially high-molecular-weight (HMW) gluten composition, are largely determined by genetics [20]. However, environmental factors also play significant roles in shaping these quality attributes. As such, significant variations are observed in HRS wheat quality between different years. Particularly adverse environmental conditions can pose challenges to HRS wheat quality, like starch damage due to pre-harvest sprouting, deoxynivalenol (DON) infection, and reduced protein content due to nitrogen dilution effects [21]. Thus, understanding the interactions between the inherent excellence of HRS wheat and environmental factors is crucial to fully utilizing the potential of HRS wheat in the industry. This information is also valuable for breeders to apply for cultivar enhancement to address challenges in upholding the high quality standards of HRS wheat. An extensive body of information is available regarding the potential of HRS wheat in good-quality end-product development and the influence of environmental factors on its quality attributes. However, this information remains scattered and requires a systematic analysis so that stakeholders can fully utilize the benefits of the unique quality attributes of HRS wheat. Moreover, it is important to investigate the quality characteristics of HRS wheat to be able to improve them.

This article summarizes the potential application of high-quality HRS wheat attributes in the milling and baking industry. It also discusses the challenges in maintaining these quality attributes due to environmental influences and how these can be handled. Additionally, it highlights the characteristics that might further improve HRS wheat quality. The information interpreted in this review is anticipated to be valuable to a wide range of stakeholders in the food industry, including bakers, millers, breeders, growers, and the scientific community.

2. Unique Potential of Hard Red Spring Wheat to Improve Quality

2.1. Blending with Other Classes of Wheat to Improve Flour Protein Content and Quality

The primary determinant of wheat quality is protein content since it is the most important regulator of dough rheological properties and end-product quality. To achieve the desired quality of many bakery products, like loaves of bread, buns, dinner rolls, hearth baked bread, pizza bases, and croissants, flour needs to have a certain protein (e.g., 10–12%)

content [22]. However, several classes of wheat grown all over the world do not meet this protein level (Table 1). A certain protein content, along with a strong gluten composition, is essential to making several bakery products, including good-quality bread loaves. From a commercial milling point of view, using wheat with a relatively low protein content is profitable, as, in most cases, it can be sourced locally and at lower prices. Thus, to raise the protein content, blending low-protein-content wheat with high-protein-content wheat is a common practice in wheat milling industries all over the world. From this perspective, HRS wheat could be a suitable choice, as it has a higher protein content and better gluten strength compared to those of similar kinds of wheat. Several studies have demonstrated that HRS wheat behaves well when blended to improve its protein content and dough rheology. Various methodologies can be used to confirm its performance. Farinographs, extensographs, Mixolab tester/mixographs, and GlutoPeak are some major tools used to analyze dough behavior. The results of blending HRS wheat and a subsequent dough behavioral study using a farinograph and extensograph demonstrated that with an increase in the HRS wheat proportion, the dough's rheological properties increased significantly (Table 2).

Table 2. HRS wheat blended with other wheat classes to improve its protein content.

Sample HRS	Sample HRW	Protein (14%, MB)	Absorption (14%, MB)	Peak Time (Min)	Stability (Min)	Extensibility at 135 min (cm)	Resistance at 135 min (BU)	Area at 135 min (cm ²)
0%	100%	12.7	53.7	1.5	10.6	686.7	96.3	8.1
10%	90%	12.4	55.9	1.6	11.4	639.3	98.7	10.6
20%	80%	12.8	56.4	6.8	11.5	694.7	107.3	13.5
30%	70%	12.1	58.3	6.4	12.1	723.0	116.0	13.7
40%	60%	12.9	58.2	7.8	12.0	779.7	131.7	13.9
100%	0%	13.8	61.7	13.0	12.7	1011.3	170.0	21.3

Source: [22].

Good-quality flour for baking bread is characterized by high water absorption, a medium to medium-long mixing time, satisfactory mixing tolerance, good loaf volume, and excellent internal crumb grain and color. HRS wheat is often used for blending to improve these dough physical properties [17]. For example, there was a study in which three levels of HRS wheat flour (10, 20, and 40%) were selected to cover a broad range of levels without exceeding the majority of the flour blend in commercial applications and blended with HRW wheat [22]. The results of that study indicated that a 40% blend of HRS dough exhibited the highest water absorption (73.10% on a 14% moisture basis) and showed a higher stability (11.05 min) and extensograph resistance. This could be attributed to the high protein content measured in the HRS wheat (15.2%), which contributes to the stronger gluten content in the dough, showing a higher farinographic stability compared to that of HRW wheat, which had a lower protein content (11.3%) [19]. A higher farinograph stability indicates that the dough is less prone to breaking down, which is crucial for the bread-making process. When compared with a commercial dough conditioner, it was found that HRS wheat performed better than most commercial additives as a dough strengthener ($p < 0.05$). A similar observation has been reported in another experiment, in which dough properties were measured by Mixolab (Table 3). Blending 25%, 50%, and 75% HRS wheat with HRW wheat showed significant improvements ($p < 0.05$) in water absorption, protein content, and starch properties [23]. The mechanism behind the HRS blend is the increase in protein content, which also leads to improvements in the protein quality as well as starch granule type and distribution, influencing water absorption (WA) and other dough rheological properties.

Table 3. HRS blending performance study by Mixolab.

Sample		Protein	Absorption	Pasting	Cooking Stability	Protein Weakening
HRS	HRW	(14%, MB)	(14%, MB)	Temperature (°C)	(Nm)	Temperature (°C)
0%	100%	9.4	62.9	19.59	0.1	686.7
25%	75%	10.8	[24] 61.5	18.39	0.1	639.3
50%	50%	11.39	62.8	13.95	0.4	694.7
75%	25%	12.94	65.9	14.21	0.4	723.0
100%	0%	15.88	68.9	12.87	0.5	1011.3

Source: [23].

Another study showed that a 40% blend of HRS wheat to HRW wheat resulted in the highest bread loaf volume, firmness, and dough rheology [24]. This may be attributed to the strong gluten network development facilitated by blending the HRS wheat with HRW wheat. A similar kind of research output was confirmed after the blending of Canadian HRS wheat with soft wheat flour to make crackers. These results revealed a significant improvement in the rheological properties (farinographic stability, gluten development, and so on) of the blended flours (1:3) compared with those of the single soft ones, along with strong gluten aggregation kinetics of up to 25% [17]. These characteristics, especially strong gluten development, are highly desired within the baking industry to make quality bakery products, for example, bread with the desired volume, crumb softness, and an acceptable crust color. The blending of strong-gluten-containing wheat is used in almost every wheat-producing country nowadays to improve the protein contents of other lower-grade wheat products.

2.2. Strong Gluten for Sourdough Fermentation

In recent years, the demand for whole-wheat- and sourdough-based products has increased due to their rich composition of essential nutrients, vitamins, antioxidants, and dietary fiber, surpassing that of refined flour [25]. Whole-wheat, containing brans, has been linked to health benefits, such as reduced cholesterol, cardiovascular disease, obesity, diabetes, and certain cancers [26]. Based on some economic online portals, the whole-wheat flour market is projected to grow significantly, with a forecasted compound annual growth rate (CAGR) of 6.7% during the forecast period. The global market is expected to reach USD 130.34 billion by 2032, up from USD 72.71 billion in 2022 [27]. However, despite its health potential, whole-wheat products face challenges like sensory issues and quality concerns due to insoluble polysaccharides in brans [28]. Sourdough fermentation has the potential to enhance the sensory attributes of whole-wheat products, offering diverse flavor compounds and mitigating the issues associated with dough rheology and texture [29]. The extended shelf life and preservation effects of sourdough, coupled with its ability to mask bitterness and modify texture, contribute to an improved overall consumer experience [25,30]. However, due to the extended fermentation period, sourdough necessitates a relatively higher gluten strength [31]. This strength is essential to undergoing the lengthy fermentation process while maintaining the integrity of the gluten matrix, which is crucial for achieving a desirable end product. A study comparing soft and strong gluten wheat found that the soft wheat had a lower fermentation stability and slower color development reaction than those of the hard wheat [32]. This research suggests that soft wheat, which has a low protein content and slower gluten development during fermentation, is not suitable for products requiring long fermentation times. Wheat classes with a weaker gluten strength may experience a breakdown in the gluten matrix, consequently failing to provide sufficient rising and a proper structure for the final product. To optimize the benefits of whole wheat and sourdough, the choice of wheat class is crucial. In particular, HRS wheat has more potential than many other classes of wheat because of its high gluten strength, which influences the gluten structure, fermentation process, and flavor development.

2.3. HRS in Frozen or Refrigerated Dough and Pre-Baked Product Market

The baking industry commonly uses the terms “refrigerated dough” and “frozen dough”, referring to dough stored at 4–7 °C and –20 °C, respectively, before baking [33]. Products partially or fully baked after proofing are known as par-baked. A very strong and steady growth in the demand for refrigerated and frozen products has been observed in recent decades across the world. More than USD 1.7 billion in frozen dough sales have been recorded in the USA. The global frozen dough market was worth USD 20.99 billion in 2021 and is projected to grow at a rate of 5.1% from 2022 to 2030 [34]. This growth is driven by the rising consumption of bakery products made of convenient and easy-to-use frozen doughs. Additionally, the expansion of the processed food sector is boosting the frozen dough industry. Frozen doughs have a long shelf life and save time, which are advantages that contribute to their popularity [33]. However, one of the major challenges in maintaining frozen products’ quality during storage is the loss of dough strength. Maintaining frozen dough’s strength is crucial for its structural integrity and is influenced by factors like dough syrup formation, starch and non-starch polysaccharide degradation, and starch–protein interactions [34]. Long-term refrigeration induces changes in dough syrup, starch, and arabinoxylan (AX) composition. Under certain conditions, dough can release a liquid, forming a syrup that leaks from the package, a phenomenon known as “dough syringing”, which is unacceptable to consumers.

Research indicates that this issue is associated with the degradation of AX by the xylanase enzyme activity in flour. A study investigated the effect of storage time on frozen dough products. The results showed that after 10 days of storage, there was 2.05% to 14.83% more dough syringing when the arabinoxylan AX content decreased to 0.97–1.54 g/100 g flour [35]. Additionally, the number of freeze–thaw cycles also have a prominent effect on frozen dough products. During multiple freeze–thaw processes, temperature changes cause ice crystals to reform, which weakens the gluten structure in the dough. This results in water being redistributed and speeds up the breakdown of dough molecules, leading to a lower quality and a shorter shelf life [36]. As repeatedly freezing and thawing dough is an ordinary procedure at restaurants, retail stores, and even home kitchens, it is necessary to use strong gluten flour as a baking ingredient. HRS wheat is emerging as a potential solution to minimize issues arising at the time of freezing and after the freeze–thaw cycle, such as syringing, weak gluten formation, or gluten breakdown, and thus may help to improve the dough’s shelf life during storage. Genetically, HRS wheat has a higher percentage of high-molecular-weight glutenin subunits (HMW-GS), which are linked to forming strong gluten [37]. This helps the dough hold more water and lose less water, making it stronger. Additionally, HRS wheat has a higher AX content in bran and endosperm, making it a potential competitor for use in the frozen food industry [35,38]. Understanding the mechanisms of AX and endoxylanase synthesis in developing HRS wheat under various genetic and soil environments could be a game-changer in controlling dough syringing and maintaining product quality under refrigerated conditions.

2.4. Clean-Label Food Production

Clean-label food generally refers to less-processed food without ingredients perceived negatively by consumers, such as allergens, additives, or chemicals. Consumer awareness of clean-label products is growing in the food industry [39]. Consumer food preferences are believed to be significantly formed by how they evaluate and understand the information displayed on food packaging, especially as their concerns about food safety are growing [22]. Bakery products like bread are consumed worldwide and are important for a balanced diet. Chemical dough conditioners are frequently used to improve dough and bread quality, as well as their shelf life. However, these additives are sometimes seen as unhealthy, though often used in whole-wheat bread to reduce the negative effects of bran and germ on dough and bread quality [40]. Some common dough conditioner ingredients, like calcium stearoyl lactylate (CSL), diacetyl tartaric acid esters (DATEM), ethoxylated monodiglycerides (EMG), potassium bromide, and sodium stearoyl lactylate (SSL), are not

considered suitable for clean-label products. However, these are used to improve bread loaf color and firmness. Some approved clean-label alternatives used in the baking industry as dough improvers are ascorbic acid, shortening or oil, enzymes (amylase), vital wheat gluten, and milk [19]. In response to consumer concerns about health, these natural ingredients are being explored as alternatives to synthetic dough improvers, despite their higher cost and variable suitability [39]. In these circumstances, the use of HRS wheat may provide strong-quality gluten, which could be more affordable and available compared to the other ingredients mentioned above. A study on HRS wheat as a dough strengthener when compared with a commercial dough conditioner found the HRS wheat performed better than most of the commercial additives, such as 0.5% EMG, 50 mg/kg CSL, 0.5% DATEM, 2% vegetable shortening, and 2% nonfat dry milk, which all resulted in significantly lower stability times ($p < 0.05$) compared to that of the HRS blend [24,41]. Another study showed that a 40% blend of HRS to HRW wheat resulted in the highest bread loaf volume, good firmness, and good dough rheology. HRS wheat flour naturally contains better protein quantity and quality, leading to the formation of more high-molecular-weight polymeric protein and a stronger gluten network in the dough compared to a base flour dough with artificial additives [24]. Thus, we predict HRS wheat could emerge as an effective natural alternative for bakers seeking to create clean-label wheat products without chemical conditioners or additives. In the future, extensive research should compare HRS wheat's efficacy as a dough enhancer with that of other commercial clean-label dough improvers, focusing on cost efficiency and nutrient availability.

2.5. HRS Wheat for Producing Specialized Products That Require Strong Dough

Previous discussions have highlighted the importance of gluten networks in enhancing the dough strength, elasticity, and texture of baked products. Gluten strength is particularly vital for creating certain baked goods, especially those that require the weakening effects of sugar to be counteracted [42]. This is relevant in many Southeast and South Asian countries where high sugar levels are commonly used in dough preparation. Sugar can tenderize and weaken the gluten network by competing for water, reducing the amount available for gluten formation. As a result, the dough can become weaker and less elastic [43]. To counteract this, using flour with a high gluten strength, such as HRS wheat flour, could be beneficial. HRS wheat's strong gluten network can help to maintain dough stability and elasticity, mitigating the tenderizing effect of sugar [44]. Achieving the right sugar balance is therefore necessary for maintaining both the quality and strength of baked goods.

HRS wheat emerges as the optimal choice for bakery products like pizza due to its higher protein content and strong gluten networks [19]. This makes the dough flexible and soft, which is required for an ideal thin and chewy pizza crust. Moreover, strong gluten allows the dough to expand without tearing, allowing it to be mixed and stretched into the appropriate form. A study on different mixes for hearth baked bread explained that tolerance is associated with a strong gluten composition, which aids in proper gluten development and reduces the negative effects of overmixing. To avoid the overmixing effect, HRS wheat may be used for hearth baked bread, such as country artisan loaves, to make a strong, crusty surface with an open, hole-riddled crumb [45]. Another research study has claimed strong gluten is crucial for bagel dough preparation. Strong gluten helps to properly shape gels as well as improve the dough's ability to withstand boiling before baking [46]. Thus, the strong gluten network from HRS wheat has significant potential for use in high-quality specialized baked items. However, a comprehensive study involving diverse combinations of HRS wheat and baked items is required to identify the most profitable and sustainable combination.

3. Major Challenges to HRS Quality

3.1. Deoxynivalenol Infection

Deoxynivalenol (DON), commonly known as vomitoxin, is a mycotoxin produced by *Fusarium* species, particularly *F. graminearum* and *F. culmorum*, causing *Fusarium* head

blight (FHB) [21]. The occurrence of this disease has been reported in Asia, America, Europe, Australia, and many other countries (Figure 1) [47,48]. Almost all wheat classes are vulnerable to DON contamination, influenced by climatic factors such as temperature and moisture. FHB infections, intensified by warm and humid weather during wheat flowering, are a recurring concern in wheat-growing regions and are impacted by genetic and environmental factors [49]. DON, when present in wheat grain, poses significant health risks for humans and animals, affecting the grain's properties, dough rheology, and end-product quality [50]. DON is known to interfere with protein synthesis, impacting the overall quality of wheat and wheat-derived products. Due to the occurrence of FHB, US production of HRS and durum wheat declined from 12.4 to 4.6 million BU, respectively, between 1998 and 2000. Therefore, the US had to import around 52 million BU of these items from Canada [51]. An article discussed the sequence of severe FHB outbreaks in the United States and Canada, particularly between 1991 and 1996, highlighting the significant economic and sociological impacts of the FHB epidemic on spring grains in the Northern Great Plains region via excessive rainfall [52].

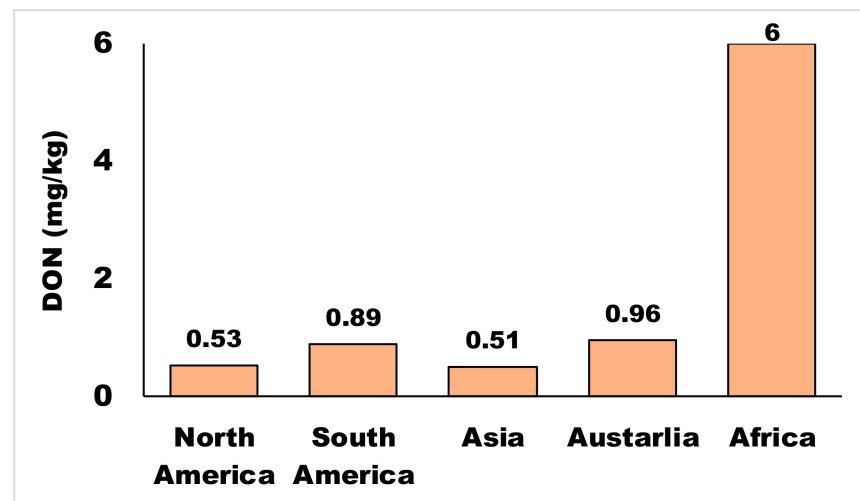


Figure 1. Worldwide DON occurrence report [53].

Within the report, they also mentioned 11 states in the US infected by DON (Figure 2) with a reduction of 25% in total wheat production at that time, which resulted in an estimated USD 56 million loss, in which HRS wheat was one of the major affected wheat classes [53]. FHB can lead to various issues, including reduced grain yield, as well as lower flour, dough, and end-product quality. There was a significant positive correlation ($p < 0.0001$) between DON and D3G in the growing locations that have more intense mycotoxin infections [54,55].

Therefore, effective strategies for managing and preventing Fusarium infection in wheat are essential to ensuring the high quality and safety of HRS wheat for consumption and processing. Various biological and non-biological approaches, such as milling, drying, fungicide application, and non-thermal disinfection techniques, have been explored to mitigate the effects of DON, offering potential solutions for the wheat industry [56]. Non-thermal processes, including high hydrostatic pressure and UV radiation, show promise in reducing contamination without compromising nutritional content [57]. However, genetic and breeding approaches focusing on the DON-resistant cultivar could be the most effective and safe approach for managing FHB. The expression of UDP-glucosyltransferase genes may offer avenues for developing DON-resistant wheat varieties [54]. Despite efforts to enhance HRS wheat resistance against FHB, ongoing research is crucial to identifying cost-effective strategies, with a particular emphasis on the cloning of the resistance gene *Fhb1*, which may provide new genomic tools like genomic selection and gene editing and offer breeders new avenues for developing FHB-resistant cultivars [58].

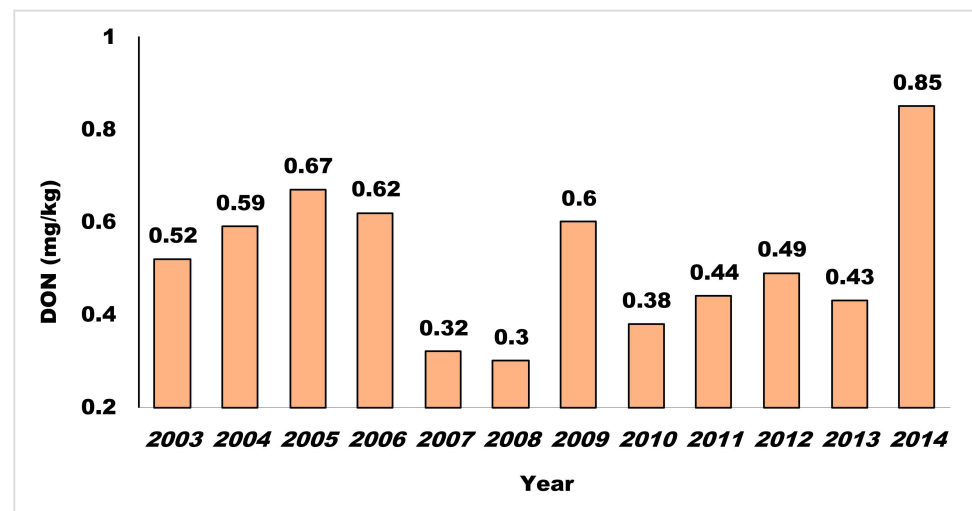


Figure 2. Levels of DON in US wheat harvested from 2003 to 2014 ($n = 42,131$) [53].

3.2. Starch Damage

Starch damage in wheat arises from the breakdown of the glycoside bonds within the starch molecules, accelerated by increased α -amylase concentrations [59]. Factors such as genetic traits, physiological processes like pre-harvest sprouting, and physical damage during milling contribute to the complex interplay influencing the extent of starch damage, resulting in compromised quality and functionality, as well as impacting consumer acceptance [59]. Furthermore, the degree of damage is influenced by the severity of grinding and the hardness of the seed. Starch damage results in the fragmentation of amylopectin molecules, which increases hydrophilic bonds and modifies the surface characteristics of the starch granules [60]. This modification improves the water absorption capacity of wheat flour and promotes starch swelling and gel formation by disrupting the forces that inhibit granule swelling in water. Moreover, heightened starch damage may reduce the crystallinity of starch granules, potentially lowering the falling number and various pasting parameters. Another report showed carcinogenic agent formation due to excessive starch damage, such as acrylamide, during baking when heated under high temperatures [61]. The occurrence of starch damage has been reported in many studies, which explain the consequences of its increase. The environment is a major player in starch damage, which has been found to strongly interact with genetic traits (Figure 3).

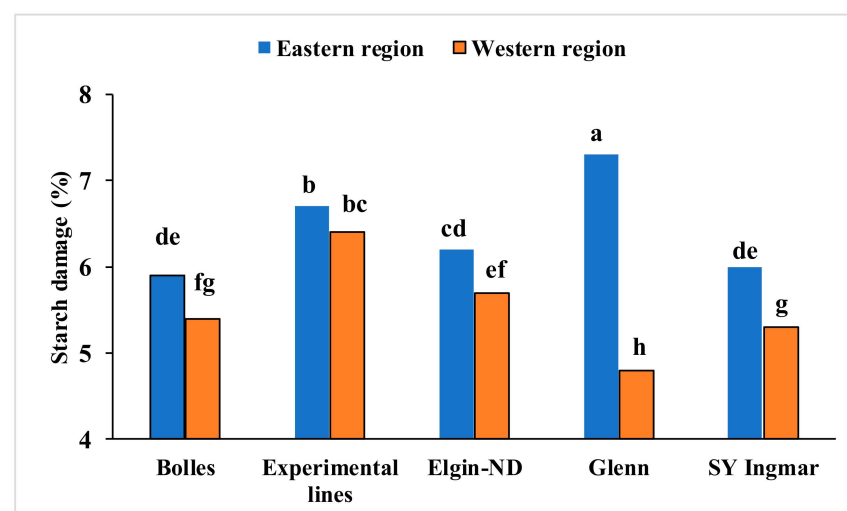


Figure 3. Starch damage content for wheat samples from eastern and western growing regions. Means followed by the same letter are not significantly different ($p > 0.05$) [62].

This study showed that the two significant environmental or physiological factors that degrade Canada western red spring (CWRS) wheat, responsible for about 80% of total Canadian wheat production, are frost and immaturity. Each year, a portion of the HRS crop is frozen before reaching maturity and causes a significant amount of starch damage [63]. Immaturity can also result from secondary growth, which frequently occurs after an early-season drought. While a certain level of starch damage is necessary for optimal water absorption, managing it within limits is crucial for HRS wheat quality [64]. The degree of starch degradation impacts how well the dough mixes and absorbs water. However, high levels of starch damage result in sticky dough, an unfavorable red crusty color, and a poor specific volume. The extent of starch damage depends on a complex interaction of genetic, physiological, and physical factors, which must be understood to maintain the integrity and economic viability of HRS wheat.

3.2.1. Starch Damage Due to Pre-Harvest Sprouting (PHS)

Pre-harvest sprouting (PHS) happens when wheat kernels germinate prematurely on a plant due to high moisture, activating enzymes like α -amylase that break down stored starches, proteins, and fats, diminishing wheat quality, and affecting functionality [65]. This could also be a concern for HRS wheat as PHS negatively impacts physicochemical properties, alters metabolic activities, and influences flavor and water absorption, leading to issues like premature swelling, germ discoloration, seed-coat splitting, and root and shoot emergence [65,66]. A research study on HRS wheat PHS revealed that more than 4% starch damage has a significant economic impact, potentially reducing prices by 20% to 50%. The same study showed higher α -amylase levels in sprouted HRS wheat than those of non-sprouted ones. The average α -amylase value for the sprouted samples was 2.00 CU/g, compared to 0.12 CU/g for the non-sprouted samples [65]. However, HRS wheat had a relatively lower level of PHS damage compared to that of hard white wheat. This could be the reason why HRS wheat has a highly crystalline structure compared to that of other wheat. Furthermore, HRS wheat exhibits a strong potential for starch–protein interaction, which could facilitate the formation of strong interchain disulfide bonds with reduced levels of degradation. Despite its genetically robust or organized structure, similar to that of other wheat classes, HRS wheat is susceptible to environmental stresses, which can activate factors promoting pre-harvest sprouting (PHS) and, in particular, elevated α -amylase levels.

Controlling PHS could involve both management and breeding approaches, addressing factors like spike morphology and seed dormancy [67]. Timely harvesting, having the optimal moisture content during seed storage, and developing a marker-assisted PHS-resistant cultivar using quantitative trait loci (QTLs) may be potential solutions [68]. The impact of PHS on starch–protein interactions and bread making in HRS wheat is underexplored, prompting future research to understand the effects of PHS-based starch damage on flour and dough characteristics and their implications for starch–protein interaction.

3.2.2. Starch Damage by Milling Process

Milling conditions also significantly contribute to starch damage. Several milling factors, including temperature (heating), rotor speed, tempering, and feed rate, influence particle size and are subsequently related to starch damage [69]. A higher rotor speed and lower feed rate result in smaller particle sizes which dislocate the starch crystalline structure and change the molecules that promote higher levels of starch damage [60]. For example, when wheat kernels go through centrifugal milling, regardless of whether the flour is separated or not, bran at a higher rotor speed, a lower tempering level, and a lower feed rate seem to yield flour with a fine particle size and a higher level of starch damage [70]. Research on HRS, durum, and soft wheat under ball milling found higher levels of starch damage (>14.0%) for HRS wheat than soft wheat [71]. This may happen due to the hardness of HRS and durum wheat, which are inherently composed of strong starch–protein interactions. The milling forces to break these interchain disulphide bonds

generate high temperatures that damage the starch and result in fine particle sizes. This is because the high temperature breaks the starch–polymeric bonding which influences the starch–protein interaction during the dough’s formation [59]. The higher the levels of hardness/vitreousness, the higher the levels of starch damage. Thus, HRS wheat is susceptible to mechanical forces due to having a high hardness value and strong bonding. The MIAG-Multomat milling technique significantly influences the physicochemical characteristics of HRS wheat millstreams, but there is limited information available on this topic. A study involving three different break sets (30%, 53%, and 65%) in MIAG-Multomat milling revealed higher levels of damaged starch (ranging from 3.8% to 6.0%) with increasing break set [62]. The study’s findings indicated that genotypic variation can lead to varying levels of starch damage. This may be due to genotypes with stronger starch–protein interactions (a higher protein content) experiencing a greater breakage of bonds under higher mechanical forces, resulting in a higher temperature with finer particle sizes and increased starch damage. The milling conditions mentioned can result in notable starch damage to HRS wheat. Therefore, the selection of the milling type and conditions is crucial for achieving specific research goals.

3.3. Strong Environmental Influence and Complex Genetic Regulation

As per the USW Commercial Sales Report 2023 [5] (Figure 4), HRS wheat emerged as the top-selling wheat class in 2023 and is well known for its exceptional quality. However, a primary challenge in enhancing its quality lies in the intricate regulatory mechanisms, not only for HRS wheat but for wheat in general, that govern most of its quality traits. Broadly speaking, the majority of wheat’s quality traits are heavily influenced by genetic regulations [5]. However, genetic factors (G) account for only around one-third of the overall regulations, with another one-third attributed to environmental factors (E), and the remaining portion arising from the interaction between genetics and the environment ($G \times E$) [72]. The North American HRS-wheat-growing region seems diversified: US HRS wheat is mostly grown in the Great Northern Plains while Canadian HRS wheat is mostly based in the east and west. A significant climatic variation seems have an impact on gluten formation, highlighting the environmental influence on wheat quality. Additionally, atmospheric CO₂ levels exert an influence on grain protein formation and gluten properties [73].

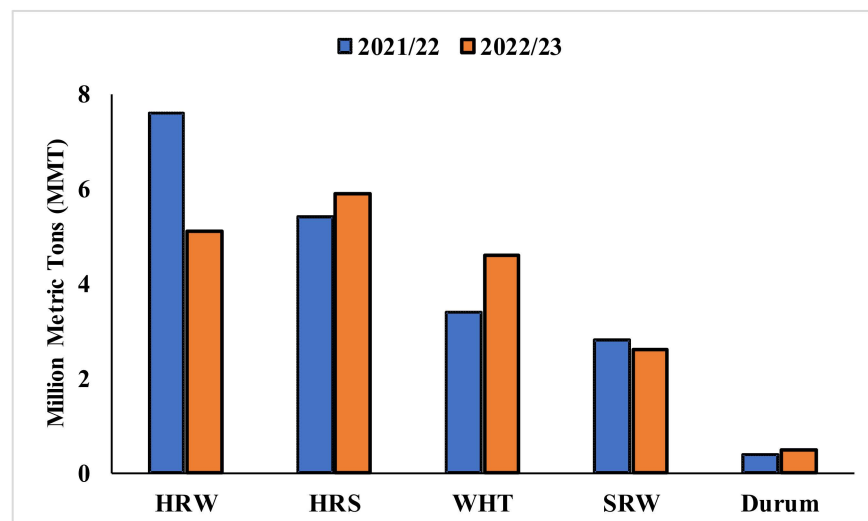


Figure 4. US Wheat classes production report 2022–2023 [60]; (HRW = hard red winter; HRS = hard red spring; WHT = white wheat; SRW = soft red wheat).

Climate change is marked by rising heat and drought conditions. It is expected these will have substantial impacts on the quality of bread wheat. This has raised serious

concerns regarding global food security and economic difficulties. To address this challenge, significant efforts have been directed towards comprehending the genetic factors affecting HRS wheat quality. The performance of genotypes in terms of growth, yield, and quality can vary significantly depending on environmental conditions, which may influence gene expression differently across environments. This variability is observed in all species and can be particularly pronounced within the same species. For HRS wheat, a study conducted in Manitoba, Canada, found approximately a 2.0% variation in yield attributable to the genotype–environment ($G \times E$) interaction [74]. This variation was primarily influenced by the interaction of growing temperature and precipitation, as well as spatial diversity. Cultivars of HRS wheat exhibit genetic variations that influence various traits, such as plant height, tillering, photoperiod sensitivity, and yield. For example, the number of spikes per plant, a crucial quantitative trait in cereal grains, is influenced by environmental conditions, soil fertility, the planting date, and agronomic practices. Research has found several QTL clusters on several chromosomes that affect tillering. The fundamental role of genetics in determining grain quality and baking performance largely depends on kernel physical characteristics and specific QTL clusters on multiple chromosomes [74,75]. These studies focus on the fact that, although particular target genes are incorporated, their expression still varies with environmental conditions. For example, HRS wheat's semi-dwarf growth trait is incorporated by the genes *Rht-B1*, *Rht-D1*, and *Rht-8* on homologous chromosomes 4B, 4D, and 2D, respectively, while their yield improvements still depend on the environment [76]. Notable associations between genetic factors, such as HRS wheat's polymeric proteins, and bread loaf features have also been recorded. For example, starch–protein interactions form a viscoelastic network, and it is often difficult to maintain the wheat's properties due to genotype–environment ($G \times E$) interactions, which are common for all wheat classes, including HRS wheat. Therefore, maintaining the desired starch–protein interaction is a challenging task for bakers due to flour composition and processing diversification. To solve the complexities involved in improving wheat quality, finding a proper balance between genetic and environmental interactions is essential.

3.4. Influence of Processing on the End-Product Quality

The quality of hard red spring (HRS) wheat in the end product significantly depends on the processing procedures. The complex interaction between protein and starch, specifically how the starch interacts within the gluten matrix, strongly determines the final quality. All processing procedures, including grain storage and transportation conditions, milling techniques, flour aging and storage environment, and dough processing protocols and formulation, influence the gluten–starch interaction. The formation of a strong viscoelastic network between starch and gluten proteins largely depends on hydration, starch pasting, and protein denaturation properties [77]. During milling, the degree of starch damage affects water absorption and dough properties, influencing the texture and volume of baked goods [78]. Additionally, the milling environment can significantly alter these interactions by generating a high level of heat, which may denature proteins [59,60]. Thermal processes such as baking and extrusion further modify these interactions by denaturing proteins and gelatinizing starch, impacting the product's texture and structural integrity [79]. Key processing factors include temperature, moisture content, and mechanical shear, which together dictate the extent of starch gelatinization and protein network formation, ultimately determining the quality of the final product [80]. The effective control of these factors ensures optimal starch–protein interactions, leading to a superior end-product quality in terms of texture, volume, and overall consumer acceptability. However, the scientific understanding of starch and gluten interactions is still insufficient to optimize processing based on grain quality attributes, particularly for HRS wheat.

3.5. Human-Health-Related Issues

Although health-related threats in the wheat industry are not prominent, there are some concerns about various levels of sensitivity that have been reported. Over the past two

decades, conditions like celiac disease (CD) and gluten intolerance have attracted significant attention from consumers and the media. The broader spectrum of food intolerance, a common issue linked to cereal grains such as wheat, barley, and rye, may arise from ingesting genetically linked proteins, like prolamin [81]. These genetic factors, specifically prolamin, have been identified as potentially detrimental to the small intestine, particularly in individuals genetically susceptible to CD. Notably, α -gliadin proteins exhibit a high level of antigenicity concerning celiac disease [81,82]. Since HRS wheat contains the highest amount of protein, there is a question of whether it contains the most allergenic proteins. However, from the literature, there is no evidence that HRS wheat results in a higher incidence of gluten sensitivity [81]. These health-related issues are generally triggered by some toxic epitopes, which are a very small proportion of the total protein content. As such, there is no relationship between a higher protein content and a greater level of toxicity. Moreover, there is a common understanding that due to the long breeding and selection process, more toxic epitopes have been incorporated in modern wheat. However, the literature incorporating the historical HRS wheat cultivars from 100 years has shown that there is no evidence of increasing toxic epitopes over this period of time [83]. Thus, consumers should not be worried about modern HRS wheat cultivars with a higher protein content.

However, scientists are working on producing wheat cultivars with lower amounts of toxic epitopes. Particularly with the availability of modern high-tech genetic tools, there is hope to make significant progress in this direction. Researchers have diligently explored remedies to address health-related challenges, utilizing genetic variations among cultivars and advanced genome editing techniques [84]. A combination of breeding techniques, such as mutation breeding and potentially genome editing, will be essential to developing wheat varieties that are safe for individuals with CD [85]. RNA-interference (RNAi) technology has proven effective in down-regulating gluten protein in various studies. The α -gliadin family of grain storage proteins is believed to be the main trigger of the inflammatory response to gluten in individuals with celiac disease. Recent advancements in RNAi have led to the successful reduction in α -gliadin storage proteins in wheat grains. Current RNAi techniques primarily utilize hairpin RNA (hpRNA) vectors to decrease the expression of gliadins in wheat bread [86]. This approach has been widely applied in plants to manipulate metabolic pathways for the enhanced production and yield of substances with health or environmental benefits. An alternative method for reducing CD-eliciting immunogenic gluten epitopes involves the use of microorganisms to hydrolyze gluten, facilitated by enzyme prolyl endopeptidases. Various microorganisms, including *Aspergillus niger*, *Flavobacterium meningosepticum*, *Sphingomonas capsulata*, and *Myxococcus xanthus*, have been employed for this purpose as they have the potentiality to produce prolyl endopeptidases [86]. However, to fully utilize the nutrients and dietary benefits of HRS wheat, healthy and less toxic wheat varieties need to be introduced without compromising baking quality.

4. Scope of Further Quality Improvement of HRS Wheat

As detailed in the first section, HRS wheat possess high quality attributes compared to the other classes of wheat. However, there are some areas in which HRS wheat can be further improved, mostly through genetic approaches. Those potential research areas are highlighted below.

4.1. Improving Water Absorption

The economic aspects of the milling and baking industries are significantly determined by the water absorption capacity of wheat. Wheat varieties with heightened water absorption empower millers, improving the flour yield and overall economic efficiency during tempering. Flour exhibiting strong water absorption facilitates milling by efficiently separating the bran and germ, contributing to increased industrial efficiency [87,88].

HRS wheat is renowned for its strong gluten protein and high arabinoxylan (AX) content [89]. Its flour protein and AX content and structure may impact its water absorption capacity (WAC) and gluten development capability. Research on diverse HRS wheat varieties found that with an increase in their AX content, their WAC increased by 3% [86]. Although HRS wheat contains a higher content of AX compared to other wheat classes, the increase in WAC in a farinograph was not significant [90]. Genetic factors play a crucial role in regulating the WAC of wheat, but the milling process, including the mill settings and particle size, can also have a significant impact. Factors like grain hardness, vitreousness, protein content, gluten strength, and AX contents are recognized as key influencers on the WAC of HRS wheat [91]. HRS wheat was found to be superior in terms of most of its quality traits and baking characteristics when compared with those of other wheat. There are only a few studies that have reported HRS wheat with a high WAC compared to other wheat classes. A study observed that HRS wheat with a protein content of 14% exhibited a 6% ($p < 0.05$) higher farinographic absorption capacity compared to that of HRW wheat, which had a protein content of 11% [92]. Though HRS wheat has a clear superiority in all these traits over the other classes of wheat, the WAC of HRS wheat is not proportionally higher compared to those of these classes of wheat. So, this indicates that we need further research and scientific information to improve the WAC of HRS wheat.

4.2. Increasing Dietary Fiber Content

Dietary fiber (DF) is a mainly plant-based, non-digestible component of the human diet, offering a wide range of physiological benefits, including in diabetes control, the reduction of cholesterol, and improved digestive health. DF not only prevents chronic diseases but also serves as a carrier for many bioactive compounds [93]. Cereals, especially whole-grain cereals and brans, are key sources of DF, particularly in their cell wall. Wheat bran, composed of 15–20% of the total grain, is separated as a by-product from many milling setups. A large portion of this wheat bran goes on to become animal feed, and only 10% is used by the food industry as a supplement. Earlier brans are discouraged from the food industry due to their high transport and processing costs along with their poor texture in functional products [94]. However, recent food markets have realized the importance of DF in food, and consumers' interest in whole-grain food is increasing drastically. HRS wheat is a rich source of DF that may emerge as a potential supplementary food ingredient. HRS wheat contains a significantly higher DF content ($p < 0.05$) compared to that of einkorn and spelt whole-meal flour. Both total DF and insoluble DF are higher in HRS wheat. This could be the reason why HRS wheat inherently contains a higher DF content than that of other wheat classes [91]. HRS wheat not only dominates in terms of its total DF content but also in the presence of high-molecular-weight non-starch polysaccharides (e.g., AX). The content of AX is higher in HRS wheat, and there is significant variation within the species. It is reported that the content and composition of DF varies with genotype, location, and the method of analysis. A significant level of genotypic and environmental variation ($p < 0.05$) was observed when modern and ancient HRS wheats were examined for their DF compositions, particularly AX [95]. However, the functional potential of AX and other similar kinds of dietary fiber depends on several structural, molecular, and chemical properties. For example, the proportion of WEAX and WUAX is crucial. The substitution level of AX and its secondary structure are also important to decide its potentiality. There is still a lack of information on how these properties are genetically regulated in HRS wheat. Generating this information will allow us to improve the dietary fiber properties of HRS wheat. Although limited research has been conducted to enhance the genetic properties of HRS wheat to improve its health potential, there is evidence that mutant HRS lines can lower one's glycemic index (GI) and reduce obesity. A reduction of around 25% in GI and a decrease in body weight of 23–68% in tested mice have been observed when mutant TAC 35 and TAC 28 HRS cultivars were included in their diet [85]. These results reveal that the supramolecular structure of starch influences the change in blood glucose level response to changes in GI. Therefore, there is ample opportunity to harness the genetic potential of

HRS wheat through proper management practices and modern genome editing technology to fully benefit from it.

4.3. Increasing Bioactive Compounds

Consumer interest in bioactive compounds has been increasing in recent years. Such preferences are driven by consumers' consciousness about their health. The demand for bioactive compounds from natural sources has increased significantly. Being a rich source of diverse bioactive compounds, HRS wheat could meet this demand for a healthy diet with potential health benefits. In particular, whole wheat includes a number of these compounds, such as DF, phytochemicals, vitamins, minerals, and so on [96]. Various arguments have been hypothesized regarding the basis of variations, whether they are coming from genetic or environmental factors. However, both G and the E and their interaction may have profound effects on the compositions of bioactive compounds. Substantial variation has been noted among HRS wheat genotypes cultivated in diverse locations. For example, the bound phenolic content from the Auburn location was 130 µg/g higher ($p < 0.05$) than that from St. Marys [97]. This trend was consistent for other bioactive compounds as well. In the cases of different wheat classes, HRS varieties appeared to be richer in bioactive compounds compared to other soft or hard wheats.

Various approaches have been attempted to enhance bioactive compounds without compromising yield potential. However, very few successes have been recorded, and much remains unexplored. Some research has found that sprouted wheat may contain larger amounts of bioactive compounds but at the expense of baking characteristics [98]. However, such outcomes would not be acceptable to bakers. In the same way, several genetic approaches have been tried to improve both products' yield and protein contents, but similar challenges have arisen. Therefore, a comprehensive exploration using diverse genotypes is needed to identify high-yield genotypes rich in bioactive compounds, followed by the use of genetic tools to develop cultivars.

4.4. Improving Protein Quality

HRS wheat is renowned for its strong gluten. The composition of both gliadin and glutenin classes determines how strongly particular wheat varieties will develop a protein network with disulfide bonding. Moreover, the functionality and stability of that protein are mostly determined by these bonds. The composition of the protein is not the same for all HRS genotypes. To make a strong gluten structure during baking, a balance between polymeric protein fractions, especially HMW-GS and LMW-GS, also needs to be considered. Additionally, the unextractable polymeric protein/extractable polymeric protein (UPP/EPP) ratio emerges as a key determinant, as the balance and interaction between the EPP and UPP fractions in HRS wheat significantly determine the strength, structure, and functionality of the gluten network [99,100]. These characteristics of protein polymers are mainly regulated by genetics. Therefore, significant variations are observed within the varieties. These genetic traits can be modified by environmental regulations, which may reduce varietal differences within the species.

Some commonly practiced protein modification methods include breeding strategy and soil N management. With the modification of nitrogen levels, protein properties and yield can be improved up to a certain limit before reaching their phytotoxicity levels. Studies conducted in the USA, Canada, and Spain have reported that HRS wheat shows the highest yield (3–5 tons/ha) and protein composition at a nitrogen level of 100 kg/ha [101]. The difference in wheat lies not only in its inherently high protein levels but also in the quality of these proteins, especially the relative abundance of glutenin and gliadin fractions [102]. Several studies have focused on HRS yield and the total protein content, shaping their breeding or environmental strategies based on the total protein. However, the factors like the polymeric/monomeric, HMW-GS/LMWS, and UPP/EPP ratios have been overlooked for decades. Thus, there is an opportunity to develop strategies that specifically target these parameters, either through molecular techniques or nitrogen management.

4.5. Improving Starch Properties

The composition of starch has a significant influence on end-use quality. The contents and ratio of amylose and amylopectin and the size distribution of starch granules are two influential factors in determining starch functionality. Changes in the amylose/amylopectin ratio significantly affect various parameters relevant to the baking industry, such as starch crystalline structure, gelatinization properties, and digestibility [103]. The amylose/amylopectin ratio and granule size are largely genetically regulated but strongly influenced by environmental conditions and their interaction, leading to diverse effects on starch physicochemical, structural, and functional properties. The genetic modification of the amylose/amylopectin ratio has been demonstrated by developing high-amylose-content wheat, which is known as waxy wheat. Notably, a significant level of diversity in the amylose/amylopectin ratio across the genotypes has been widely documented, which indicates that breeder have further opportunities to optimize the amylose/amylopectin ratio as required by the industry.

However, the mechanism of the genetic regulation of starch granule size is largely unknown, which makes it challenging for breeders to optimize this trait to improve starch functional properties [104]. It is worth mentioning that starch damage represents a significant industrial concern, closely related to the size of starch granules. HRS wheat offers the potential for reducing this damage, as it possesses a more organized structure with a higher crystallinity compared to HRW wheat [6]. Thus, the HRS breeding program has the opportunity to maintain this well-organized structure by considering this trait in the selection process. These approaches will have the potential to contribute to the most desirable formation and distribution of starch granules in HRS wheat, minimizing the risk of damage. However, it will be crucial to explore how changes in granule size distribution affect starch functional properties at different growth stages and locations to reveal the genotype–environment impacts on starch properties.

4.6. Optimizing End-Product Processing

To maximize the quality of the end products, HRS wheat is often blended with other wheat classes. However, the processing needs can vary greatly depending on the properties of the blend and the type of final product, such as bread or pasta. Also, due to the unique characteristics of HRS wheat, the processing requirements and quality standards particular to each product need to be optimized. For example, HRS wheat's strong viscoelasticity and gas retention are essential for achieving a good bread loaf volume and texture [23]. Numerous studies have explored specific processing methods for various bakery items, revealing that dough characteristics may need adjustment for different types of bread, such as artisan breads or sandwich loaves, which may require different blends compared to loaves of bread to achieve the desired quality. Research has shown that among three bread-making methods (sponge-and-dough, straight-dough, and no-time dough), the sponge-and-dough method is the best for describing whole-wheat bread quality [105]. There is diversification within this methodology; although each of these methods can be used to make loaves of bread, quality whole-wheat bread can only be expected when using the sponge-and-dough method which follows different processing techniques. Additionally, HRS wheat blending for pasta processing can significantly enhance pasta's qualities, such as its elasticity and cooking properties, through its protein interaction and hydration properties [106]. This also is processed differently compared to pasta from durum. Despite these insights, the field still lacks comprehensive knowledge to fully optimize processing methods for blending HRS wheat with other wheat classes in various products. More research is needed to understand its unique processing-related interactions, including hydration dynamics, starch gelatinization, and protein denaturation.

5. Conclusions

HRS wheat is distinguished by its higher protein content, stronger gluten, and better protein quality, making it a preferred choice for producing a variety of specialized bakery

items and for blending with other wheat classes to improve flour quality. These unique characteristics also make it suitable for frozen products, whole-wheat baking, and clean-label product development. However, these inherent quality attributes of HRS wheat are often challenged by extreme weather events and other environmental influences. In particular, DON contamination and starch damage from pre-harvest sprouting are major environmental issues. Although research has been conducted and breeding progress have been implemented to improve genetic resistance against these challenges, extensive research is still required to unravel the complex genetic–environment interactions that regulate them. The translation of the HRS wheat’s quality attributes to the final product is further challenged by variabilities in processing procedures. Considering the grain quality and the type of end product, the processing of HRS wheat needs to be optimized, which requires a deep scientific understanding. Advancements in research are needed to characterize the changes in protein and starch properties and their interactions in response to processing variables such as the milling environment, hydration, temperature, and pasting conditions. This optimization is essential for achieving the finest end-product quality when using HRS wheat. Additionally, the contribution of protein and starch quality in determining dough physical properties and end-product quality is less explored, despite their significant roles. The lack of adequate information in this area is a key reason why wheat breeding programs struggle to set precise targets for improvement, which warrants more research attention. Furthermore, HRS quality can also be enhanced by increasing water absorption capacity, improving dietary fiber properties, and enhancing bioactive components through breeding approaches. However, extensive research is needed to explore the variability and genetic potential of these important quality traits in HRS wheat (Figure 5).

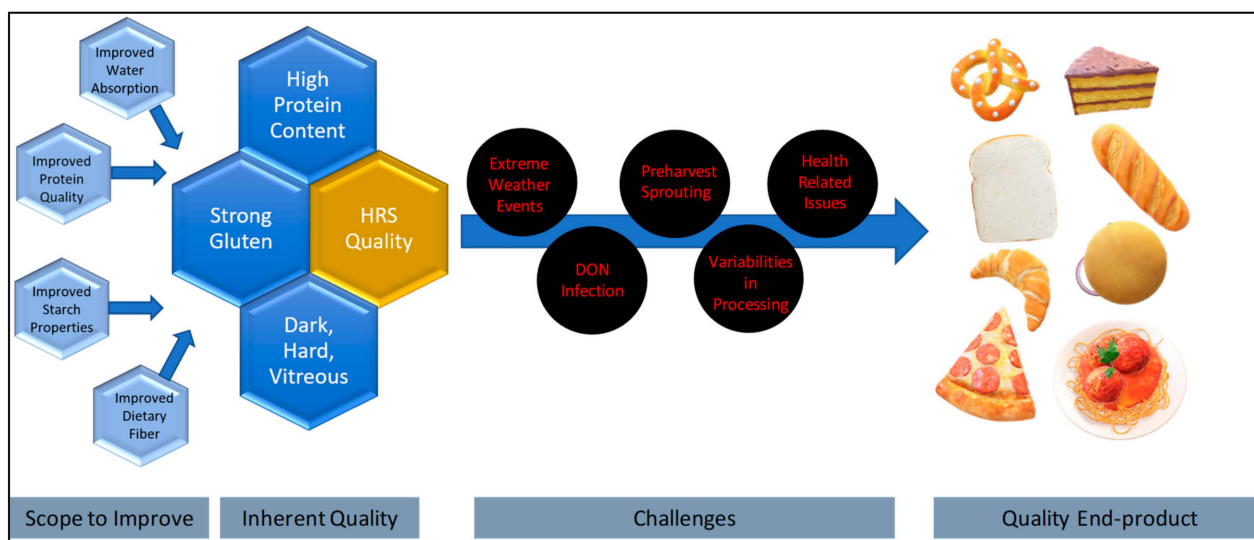


Figure 5. Schematic representation of HRS potentiality in baking along with challenges and development scope.

Author Contributions: M.N.H., writing—original draft preparation; S.I., Conceptualization, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the USDA National Institute of Food and Agriculture, Hatch project accession number 7005543, and North Dakota Wheat Commission, Award Number FAR0036898.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We would like to thank the USDA National Institute of Food and Agriculture and the North Dakota Wheat Commission for providing funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Erenstein, O.; Jaleta, M.; Mottaleb, K.A.; Sonder, K.; Donovan, J.; Braun, H.-J. Global Trends in Wheat Production, Consumption and Trade. In *Wheat Improvement: Food Security in a Changing Climate*; Springer International Publishing: Cham, Switzerland, 2022; pp. 47–66. [CrossRef]
2. Liu, Y.; Jochum, J.O.; Daniel, W.; Ars, U. Associations of Sulfur Content and Protein Molecular Weight Distribution with Bread-Making Quality for Patent and Mill Stream Flours in Hard Red Spring Wheat Grown under Sulfur Fertilization at Two Locations. *J. Agric. Crop Res.* **2021**, *9*, 60–71. [CrossRef]
3. Kusunose, Y.; Rossi, J.J.; Van Sanford, D.A.; Alderman, P.D.; Anderson, J.A.; Chai, Y.; Gerullis, M.K.; Jagadish, S.V.K.; Paul, P.A.; Tack, J.B.; et al. Sustaining Productivity Gains in the Face of Climate Change: A Research Agenda for US Wheat. *Glob. Chang. Biol.* **2023**, *29*, 926–934. [CrossRef] [PubMed]
4. Sun, J.; Chen, M.; Hou, X.; Li, T.; Qian, H.; Zhang, H.; Li, Y.; Qi, X.; Wang, L. Effect of Phosphate Salts on the Gluten Network Structure and Quality of Wheat Noodles. *Food Chem.* **2021**, *358*, 129895. [CrossRef] [PubMed]
5. USW Commercial Sales Report 2023. 2023. Available online: <https://www.msici.com/www/quick-take/us-commercial-property-distress/04355163707> (accessed on 24 March 2023).
6. Canadian Grain Commission Exports of Canadian Grain and Wheat Flour, 2014 to Date. 2023. Available online: <https://www.grainscanada.gc.ca/en/grain-research/statistics/exports-grain-wheat-flour/index.html>: (accessed on 25 March 2024).
7. Fradgley, N.S.; Gardner, K.A.; Kerton, M.; Swarbreck, S.M.; Bentley, A.R. Balancing Quality with Quantity: A Case Study of UK Bread Wheat. *Plants People Planet* **2023**, *5*, 1–14. [CrossRef]
8. USDA Russian Wheat: The New Reference for Cash Wheat Worldwide. From Net Importer to No. 1 Exporter. 2017. Available online: https://www.usda.gov/sites/default/files/documents/Swithun_Still.pdf: (accessed on 25 March 2024).
9. Kingwell, R. Ukraine: An Emerging Challenge for Australian Wheat Exports. 2016. Available online: https://www.researchgate.net/publication/301558932_Ukraine_An_emerging_challenge_for_Australian_wheat_exports (accessed on 24 March 2024).
10. Cseh, A.; Poczai, P.; Kiss, T.; Balla, K.; Berki, Z.; Horváth, Á.; Kuti, C.; Karsai, I. Exploring the Legacy of Central European Historical Winter Wheat Landraces. *Sci. Rep.* **2021**, *11*, 23915. [CrossRef]
11. AEGIC Australian Wheat Australian Wheat for Premium Products. 2024. Available online: <https://www.aegic.org.au/2024/> (accessed on 25 March 2024).
12. Sun, X.; Marza, F.; Ma, H.; Carver, B.F.; Bai, G. Mapping Quantitative Trait Loci for Quality Factors in an Inter-Class Cross of US and Chinese Wheat. *Theor. Appl. Genet.* **2010**, *120*, 1041–1051. [CrossRef]
13. Ronge, R.V.; Sardeshmukh, M.M. Comparative Analysis of Indian Wheat Seed Classification. In Proceedings of the 2014 International Conference on Advances in Computing, Communications and Informatics (ICACCI), Delhi, India, 24–27 September 2014; pp. 937–942. [CrossRef]
14. Caplan, L.A.; Webb, A.J. *Japan: Determinants of Wheat Import Demand*; Staff Report no. AGES 9404; U.S. Department of Agriculture, Economic Research Service, Agriculture and Trade Analysis Division: Washington, DC, USA, 1994.
15. Dorrian, K.; Mkhabela, M.; Sapirstein, H.; Bullock, P. Effects of Delayed Harvest on Wheat Quality, Gluten Strength, and Protein Composition of Hard Red Spring Wheat. *Cereal Chem.* **2023**, *100*, 196–212. [CrossRef]
16. Baasandorj, T.; Ohm, J.B.; Simsek, S. Effects of Kernel Vitreousness and Protein Level on Protein Molecular Weight Distribution, Milling Quality, and Breadmaking Quality in Hard Red Spring Wheat. *Cereal Chem.* **2016**, *93*, 426–434. [CrossRef]
17. Issarny, C.; Cao, W.; Falk, D.; Seetharaman, K.; Bock, J.E. Exploring Functionality of Hard and Soft Wheat Flour Blends for Improved End-Use Quality Prediction. *Cereal Chem.* **2017**, *94*, 723–732. [CrossRef]
18. Mendis, M.; Leclerc, E.; Simsek, S. Arabinoxylans, Gut Microbiota and Immunity. *Carbohydr. Polym.* **2016**, *139*, 159–166. [CrossRef]
19. Simsek, S. Clean-Label Bread: Using Hard Red Spring Wheat to Replace Dough Improvers in Whole Wheat Bread. *J. Food Process. Preserv.* **2020**, *44*, 1–9. [CrossRef]
20. Mkhabela, M.; Bullock, P.; Sapirstein, H.; Courcelles, J.; Abbasi, S.; Koxsel, F. Exploring the Influence of Weather on Gluten Strength of Hard Red Spring Wheat (*Triticum aestivum* L.) on the Canadian Prairies. *J. Cereal Sci.* **2022**, *104*, 103410. [CrossRef]
21. Miguel-Rojas, C.; Cavinder, B.; Townsend, J.P.; Trail, F. Comparative Transcriptomics of *Fusarium Graminearum* and *Magnaporthe Oryzae* Spore Germination Leading up to Infection. *MBio* **2023**, *14*, e02442-22. [CrossRef]
22. Rahman, M.M.; Simsek, S. Go Clean Label: Replacement of Commercial Dough Strengtheners with Hard Red Spring Wheat Flour in Bread Formulations. *J. Food Sci. Technol.* **2020**, *57*, 3581–3590. [CrossRef]
23. Suprabha Raj, A.; Boyacioglu, M.H.; Dogan, H.; Siliveru, K. Investigating the Contribution of Blending on the Dough Rheology of Roller-Milled Hard Red Wheat. *Foods* **2023**, *12*, 2078. [CrossRef]
24. Rahman, M.M.; Ohm, J.B.; Simsek, S. Clean-Label Breadmaking: Size Exclusion HPLC Analysis of Proteins in Dough Supplemented with Additives vs Hard Red Spring Wheat Flour. *J. Cereal Sci.* **2022**, *104*, 103426. [CrossRef]
25. Seis Subaşı, A.; Ercan, R. The Effects of Wheat Variety, Sourdough Treatment and Sourdough Level on Nutritional Characteristics of Whole Wheat Bread. *J. Cereal Sci.* **2023**, *110*, 103637. [CrossRef]

26. Mellen, P.B.; Walsh, T.F.; Herrington, D.M. Whole Grain Intake and Cardiovascular Disease: A Meta-Analysis. *Nutr. Metab. Cardiovasc. Dis.* **2008**, *18*, 283–290. [CrossRef]
27. Future Market Insight Inc. Whole Wheat Flour Market Outlook (2022 to 2032). 2022. Available online: <https://www.futuremarketinsights.com/reports/whole-wheat-flour-market> (accessed on 24 March 2024).
28. Bressiani, J.; Oro, T.; Santetti, G.S.; Almeida, J.L.; Bertolin, T.E.; Gómez, M.; Gutkoski, L.C. Properties of Whole Grain Wheat Flour and Performance in Bakery Products as a Function of Particle Size. *J. Cereal Sci.* **2017**, *75*, 269–277. [CrossRef]
29. Xu, X.; Yang, Q.; Luo, Z.; Xiao, Z. Effects of Sourdough Fermentation and an Innovative Compound Improver on the Baking Performance, Nutritional Quality, and Antistaling Property of Whole Wheat Bread. *ACS Food Sci. Technol.* **2021**, *2*, 825–835. [CrossRef]
30. Chochkov, R.; Savov, M.; Gotcheva, V.; Papageorgiou, M.; Rocha, J.M.; Baev, V.; Angelov, A. Effects of Sourdough on Rheological Properties of Dough, Quality Characteristics and Staling Time of Wholemeal Wheat Croissants. *Ital. J. Food Sci.* **2023**, *35*, 115–129. [CrossRef]
31. Balestra, F.; Pinnavaia, G.G.; Romani, S. Evaluation of the Effects of Different Fermentation Methods on Dough Characteristics. *J. Texture Stud.* **2015**, *46*, 262–271. [CrossRef]
32. Rinaldi, M.; Paciulli, M.; Caligiani, A.; Sgarbi, E.; Cirlini, M.; Dall'Asta, C.; Chiavaro, E. Durum and Soft Wheat Flours in Sourdough and Straight-Dough Bread-Making. *J. Food Sci. Technol.* **2015**, *52*, 6254–6265. [CrossRef] [PubMed]
33. Omedi, J.O.; Huang, W.; Zhang, B.; Li, Z.; Zheng, J. Advances in Present-Day Frozen Dough Technology and Its Improver and Novel Biotech Ingredients Development Trends—A Review. *Cereal Chem.* **2019**, *96*, 34–56. [CrossRef]
34. Simsek, S. Application of Xanthan Gum for Reducing Syruping in Refrigerated Doughs. *Food Hydrocoll.* **2009**, *23*, 2354–2358. [CrossRef]
35. Simsek, S.; Whitney, K.L.; Ohm, J.B.; Anderson, J.; Mergoum, M. Refrigerated Dough Quality: Effect of Environment and Genotypes of Hard Red Spring Wheat. *J. Food Sci.* **2011**, *76*, S101–S107. [CrossRef] [PubMed]
36. Zhang, Y.; Li, Y.; Liu, Y.; Zhang, H. Effects of Multiple Freeze–Thaw Cycles on the Quality of Frozen Dough. *Cereal Chem.* **2018**, *95*, 499–507. [CrossRef]
37. Malalgoda, M.; Ohm, J.B.; Meinhardt, S.; Simsek, S. Association between Gluten Protein Composition and Breadmaking Quality Characteristics in Historical and Modern Spring Wheat. *Cereal Chem.* **2018**, *95*, 226–238. [CrossRef]
38. Zhang, Y.; Simsek, S. Physicochemical Changes of Starch in Refrigerated Dough during Storage. *Carbohydr. Polym.* **2009**, *78*, 268–274. [CrossRef]
39. Aschemann-Witzel, J.; Varela, P.; Peschel, A.O. Consumers' Categorization of Food Ingredients: Do Consumers Perceive Them as 'Clean Label' Producers Expect? An Exploration with Projective Mapping. *Food Qual. Prefer.* **2019**, *71*, 117–128. [CrossRef]
40. Vargas, M.C.A.; Simsek, S. Clean Label in Bread. *Foods* **2021**, *10*, 2054. [CrossRef] [PubMed]
41. Padalino, L.; Conte, A.; Del Nobile, M.A. Overview on the General Approaches to Improve Gluten-Free Pasta and Bread. *Foods* **2016**, *5*, 87. [CrossRef]
42. Pareyt, B.; Delcour, J.A. The Role of Wheat Flour Constituents, Sugar, and Fat in Low Moisture Cereal Based Products: A Review on Sugar-Snap Cookies. *Crit. Rev. Food Sci. Nutr.* **2008**, *48*, 824–839. [CrossRef]
43. Hu, X.; Cheng, L.; Hong, Y.; Li, Z.; Li, C.; Gu, Z. Impact of Celluloses and Pectins Restrictions on Gluten Development and Water Distribution in Potato-Wheat Flour Dough. *Int. J. Biol. Macromol.* **2022**, *206*, 534–542. [CrossRef] [PubMed]
44. Baasandorj, T.; Ohm, J.B.; Dykes, L.; Simsek, S. Evaluation of the Quality Scoring System of Hard Red Spring Wheat Using Four Different Roller Mills. *Int. J. Food Prop.* **2018**, *21*, 1017–1030. [CrossRef]
45. Færgestad, E.M.; Magnus, E.M.; Sahlström, S.; Næs, T. Influence of Flour Quality and Baking Process on Hearth Bread Characteristics Made Using Gentle Mixing. *J. Cereal Sci.* **1999**, *30*, 61–70. [CrossRef]
46. Girard, A.L.; Awika, J.M. Effects of Edible Plant Polyphenols on Gluten Protein Functionality and Potential Applications of Polyphenol–Gluten Interactions. *Compr. Rev. Food Sci. Food Saf.* **2020**, *19*, 2164–2199. [CrossRef] [PubMed]
47. Xian, L.; Zhang, Y.; Hu, Y.; Zhu, S.; Wen, Z.; Hua, C.; Li, L.; Sun, Z.; Li, T. Mycotoxin DON Accumulation in Wheat Grains Caused by Fusarium Head Blight Are Significantly Subjected to Inoculation Methods. *Toxins* **2022**, *14*, 409. [CrossRef] [PubMed]
48. McMullen, M.; Bergstrom, G.; De Wolf, E.; Dill-Macky, R.; Hershman, D.; Shaner, G.; Van Sanford, D. Fusarium Head Blight Disease Cycle, Symptoms, and Impact on Grain Yield and Quality Frequency and Magnitude of Epidemics Since 1997. *Plant Dis.* **2012**, *96*, 1712–1728. [CrossRef] [PubMed]
49. Rasmussen, P.H.; Nielsen, K.F.; Ghorbani, F.; Spliid, N.H.; Nielsen, G.C.; Jørgensen, L.N. Occurrence of Different Trichothecenes and Deoxynivalenol-3- β -D-Glucoside in Naturally and Artificially Contaminated Danish Cereal Grains and Whole Maize Plants. *Mycotoxin Res.* **2012**, *28*, 181–190. [CrossRef]
50. Ovando-Martínez, M.; Ozsisli, B.; Anderson, J.; Whitney, K.; Ohm, J.B.; Simsek, S. Analysis of Deoxynivalenol and Deoxynivalenol-3-Glucoside in Hard Red Spring Wheat Inoculated with Fusarium Graminearum. *Toxins* **2013**, *5*, 2522–2532. [CrossRef]
51. Nganje, W.E.; Bangsund, D.A.; Larry Leistritz, F.; Wilson, W.W.; Tiapo, N.M. Regional Economic Impacts of Fusarium Head Blight in Wheat and Barley. *Rev. Agric. Econ.* **2004**, *26*, 332–347. [CrossRef]
52. McMullen, M.; Jones, R.; Gallenberg, D.; America, S. Scab of Wheat and Barley: A Re-Emerging Disease of Devastating Impact. *Plant Dis.* **1997**, *81*, 1339–1472. [CrossRef] [PubMed]

53. Bianchini, A.; Horsley, R.; Jack, M.M.; Kobielski, B.; Ryu, D.; Tittlemier, S.; Wilson, W.W.; Abbas, H.K.; Abel, S.; Harrison, G.; et al. DON Occurrence in Grains: A North American Perspective. *Cereal Foods World* **2015**, *60*, 32–56. [\[CrossRef\]](#)
54. Simsek, S.; Ovando-Martínez, M.; Ozsisli, B.; Whitney, K.; Ohm, J.B. Occurrence of Deoxynivalenol and Deoxynivalenol-3-Glucoside in Hard Red Spring Wheat Grown in the USA. *Toxins* **2013**, *5*, 2656–2670. [\[CrossRef\]](#)
55. Horvat, D.; Spanic, V.; Dvojtkovic, K.; Simic, G.; Magdic, D.; Nevistic, A. The Influence of Fusarium Infection on Wheat (*Triticum aestivum* L.) Proteins Distribution and Baking Quality. *Cereal Res. Commun.* **2015**, *43*, 61–71. [\[CrossRef\]](#)
56. Amit, S.K.; Uddin, M.M.; Rahman, R.; Islam, S.M.R.; Khan, M.S. A Review on Mechanisms and Commercial Aspects of Food Preservation and Processing. *Agric. Food Secur.* **2017**, *6*, 51. [\[CrossRef\]](#)
57. Sánchez-Rubio, M.; Taboada-Rodríguez, A.; Cava-Roda, R.; López-Gómez, A.; Marín-Iniesta, F. Combined Use of Thermo-Ultrasound and Cinnamon Leaf Essential Oil to Inactivate *Saccharomyces Cerevisiae* in Natural Orange and Pomegranate Juices. *LWT* **2016**, *73*, 140–146. [\[CrossRef\]](#)
58. Zhu, Z.; Hao, Y.; Mergoum, M.; Bai, G.; Humphreys, G.; Cloutier, S.; Xia, X.; He, Z. Breeding Wheat for Resistance to Fusarium Head Blight in the Global North: China, USA, and Canada. *Crop J.* **2019**, *7*, 730–738. [\[CrossRef\]](#)
59. Wang, S.; Yu, J.; Xin, Q.; Wang, S.; Copeland, L. Effects of Starch Damage and Yeast Fermentation on Acrylamide Formation in Bread. *Food Control* **2017**, *73*, 230–236. [\[CrossRef\]](#)
60. Liu, C.; Li, L.; Hong, J.; Zheng, X.; Bian, K.; Sun, Y.; Zhang, J. Effect of Mechanically Damaged Starch on Wheat Flour, Noodle and Steamed Bread Making Quality. *Int. J. Food Sci. Technol.* **2014**, *49*, 253–260. [\[CrossRef\]](#)
61. Ortolan, F.; Brites, L.T.G.; Montenegro, F.M.; Schmiele, M.; Steel, C.J.; Clerici, M.T.P.S.; Almeida, E.L.; Chang, Y.K. Effect of Extruded Wheat Flour and Pre-Gelatinized Cassava Starch on Process and Quality Parameters of French-Type Bread Elaborated from Frozen Dough. *Food Res. Int.* **2015**, *76*, 402–409. [\[CrossRef\]](#) [\[PubMed\]](#)
62. Baasandorj, T.; Ohm, J.B.; Simsek, S. Physicochemical and Bread-Making Characteristics of Millstreams Obtained from an Experimental Long-Flow Mill in Hard Red Spring Wheat. *Cereal Chem.* **2021**, *98*, 517–531. [\[CrossRef\]](#)
63. Preston, K.R.; Kilborn, R.H.; Morgan, B.C.; Babb, J.C. Effects of Frost and Immaturity on the Quality of a Canadian Hard Red Spring Wheat. *Cereal Chem.* **1991**, *68*, 133–138.
64. Khalid, K.H.; Manthey, F.; Simsek, S. Whole Grain Wheat Flour Production Using an Ultracentrifugal Mill. *Cereal Chem.* **2017**, *94*, 1001–1007. [\[CrossRef\]](#)
65. Simsek, S.; Ohm, J.B.; Lu, H.; Rugg, M.; Berzonsky, W.; Alamri, M.S.; Mergoum, M. Effect of Pre-Harvest Sprouting on Physicochemical Changes of Proteins in Wheat. *J. Sci. Food Agric.* **2014**, *94*, 205–212. [\[CrossRef\]](#) [\[PubMed\]](#)
66. Patwa, N.; Penning, B.W. Environmental Impact on Cereal Crop Grain Damage from Pre-harvest Sprouting and Late Maturity Alpha-Amylase. In *Sustainable Agriculture in the Era of Climate Change*; Roychowdhury, R., Choudhury, S., Hasanuzzaman, M., Srivastava, S., Eds.; Springer: Cham, Switzerland, 2020; Volume 4, pp. 23–41. [\[CrossRef\]](#)
67. Nakamura, S. Grain Dormancy Genes Responsible for Preventing Pre-Harvest Sprouting in Barley and Wheat. *Breed. Sci.* **2018**, *68*, 295–304. [\[CrossRef\]](#) [\[PubMed\]](#)
68. Ali, A.; Cao, J.; Jiang, H.; Chang, C.; Zhang, H.P.; Sheikh, S.W.; Shah, L.; Ma, C. Unraveling Molecular and Genetic Studies of Wheat (*Triticum aestivum* L.) Resistance against Factors Causing Pre-Harvest Sprouting. *Agronomy* **2019**, *9*, 117. [\[CrossRef\]](#)
69. Chen, Y.X.; Guo, X.N.; Xing, J.J.; Zhu, K.X. Effects of Tempering with Steam on the Water Distribution of Wheat Grains and Quality Properties of Wheat Flour. *Food Chem.* **2020**, *323*, 126842. [\[CrossRef\]](#)
70. Khalid, K.H.; Manthey, F.; Simsek, S. Centrifugal Milling of Wheat Bran. *Cereal Chem.* **2018**, *95*, 330–341. [\[CrossRef\]](#)
71. Mok, C.; Dick, J.W. Response of Starch of Different Wheat Classes to Ball Milling. *Cereal Chem.* **1991**, *68*, 409–412.
72. Kumar, A.; Mantovani, E.E.; Seetan, R.; Soltani, A.; Echeverry-Solarte, M.; Jain, S.; Simsek, S.; Doehlert, D.; Alamri, M.S.; Elias, E.M.; et al. Dissection of Genetic Factors Underlying Wheat Kernel Shape and Size in an Elite × Nonadapted Cross Using a High Density SNP Linkage Map. *Plant Genome* **2016**, *9*, 1–22. [\[CrossRef\]](#) [\[PubMed\]](#)
73. Xiao, D.; Bai, H.; Liu, D.L. Impact of Future Climate Change on Wheat Production: A Simulated Case for China's Wheat System. *Sustainability* **2018**, *10*, 1277. [\[CrossRef\]](#)
74. Richard, C.; Elwin, G.S.; Cynthia, G. Factors Influencing Wheat Yield and Variability: Evidence from Manitoba, Canada. *J. Agric. Appl. Econ.* **2015**, *41*, 625–639.
75. Tsilo, T.J.; Hareland, G.A.; Simsek, S.; Chao, S.; Anderson, J.A. Genome Mapping of Kernel Characteristics in Hard Red Spring Wheat Breeding Lines. *Theor. Appl. Genet.* **2010**, *121*, 717–730. [\[CrossRef\]](#) [\[PubMed\]](#)
76. Kumar, A.; Mantovani, E.E.; Simsek, S.; Jain, S.; Elias, E.M.; Mergoum, M. Genome Wide Genetic Dissection of Wheat Quality and Yield Related Traits and Their Relationship with Grain Shape and Size Traits in an Elite × Non-Adapted Bread Wheat Cross. *PLoS ONE* **2019**, *14*, e0221826. [\[CrossRef\]](#)
77. Gao, X.; Tong, J.; Guo, L.; Yu, L.; Li, S.; Yang, B.; Wang, L.; Liu, Y.; Li, F.; Guo, J.; et al. Influence of Gluten and Starch Granules Interactions on Dough Mixing Properties in Wheat (*Triticum aestivum* L.). *Food Hydrocoll.* **2020**, *106*, 105885. [\[CrossRef\]](#)
78. Deng, L. Whole-Wheat Flour Milling and the Effect of Durum Genotypes and Traits on Whole-Wheat Pasta Quality. Ph.D. Thesis, North Dakota State University, Fargo, ND, USA, 2017. Available online: <https://ezproxy.lib.ndsu.nodak.edu/login?url=https://www.proquest.com/dissertations-theses/whole-wheat-flour-milling-effect-durum-genotypes/docview/2009010780/se-2> (accessed on 24 March 2024).

79. Narpinder, S.; Jaspreet, S.; Lovedeep, K.; Navdeep, S.S.; Balmeet, S.G. Morphological, Thermal and Rheological Properties of Starches from Different Botanical Sources. *Food Chem.* **2003**, *81*, 219–231. [\[CrossRef\]](#)
80. Zhang, P.; Hu, X.; Zhao, H.; Xia, X. Effects of High Hydrostatic Pressure and Thermal Processing on the Structure and Properties of Wheat Starch. *Food Hydrocoll.* **2019**, *87*, 72–82.
81. Mehring, G.H.; Wiersma, J.J.; Stanley, J.D.; Ransom, J.K. Genetic and Environmental Predictors for Determining Optimal Seeding Rates of Diverse Wheat Cultivars. *Agronomy* **2020**, *10*, 332. [\[CrossRef\]](#)
82. Malalgoda, M.; Meinhardt, S.W.; Simsek, S. Detection and Quantitation of Immunogenic Epitopes Related to Celiac Disease in Historical and Modern Hard Red Spring Wheat Cultivars. *Food Chem.* **2018**, *264*, 101–107. [\[CrossRef\]](#)
83. Scherf, K.A.; Koehler, P.; Wieser, H. Gluten and Wheat Sensitivities—An Overview. *J. Cereal Sci.* **2016**, *67*, 2–11. [\[CrossRef\]](#)
84. Schalk, K.; Lang, C.; Wieser, H.; Koehler, P.; Scherf, K.A. Quantitation of the Immunodominant 33-Mer Peptide from α -Gliadin in Wheat Flours by Liquid Chromatography Tandem Mass Spectrometry. *Sci. Rep.* **2017**, *7*, 45092. [\[CrossRef\]](#)
85. Rahim, M.S.; Kumar, V.; Mishra, A.; Fandade, V.; Kumar, V.; Kiran Kondepudi, K.; Bishnoi, M.; Roy, J. High Resistant Starch Mutant Wheat ‘TAC 35’ Reduced Glycemia and Ameliorated High Fat Diet Induced Metabolic Dysregulation in Mice. *J. Cereal Sci.* **2022**, *105*, 103459. [\[CrossRef\]](#)
86. Jouanin, A.; Gilissen, L.J.W.J.; Boyd, L.A.; Cockram, J.; Leigh, F.J.; Wallington, E.J.; van den Broeck, H.C.; van der Meer, I.M.; Schaart, J.G.; Visser, R.G.F.; et al. Food Processing and Breeding Strategies for Coeliac-Safe and Healthy Wheat Products. *Food Res. Int.* **2018**, *110*, 11–21. [\[CrossRef\]](#) [\[PubMed\]](#)
87. Sharma, N.; Bhatia, S.; Chunduri, V.; Kaur, S.; Sharma, S.; Kapoor, P.; Kumari, A.; Garg, M. Pathogenesis of Celiac Disease and Other Gluten Related Disorders in Wheat and Strategies for Mitigating Them. *Front. Nutr.* **2020**, *7*, 1–26. [\[CrossRef\]](#)
88. Mustafa, K.; Dizlek, H. The Effects of Two-Step Tempering Treatment on the Rheological Characteristics of Flour in Bread Wheat (*Triticum aestivum* L.). *Kahramanmaraş Sütçü İmam Üniversitesi Tarım Doğa Derg.* **2022**, *25*, 565–573.
89. Duyvejonck, A.E.; Lagrain, B.; Pareyt, B.; Courtin, C.M.; Delcour, J.A. Relative Contribution of Wheat Flour Constituents to Solvent Retention Capacity Profiles of European Wheats. *J. Cereal Sci.* **2011**, *53*, 312–318. [\[CrossRef\]](#)
90. Kulathunga, J.; Simsek, S. Dietary Fiber Variation in Ancient and Modern Wheat Species: Einkorn, Emmer, Spelt and Hard Red Spring Wheat. *J. Cereal Sci.* **2022**, *104*, 103420. [\[CrossRef\]](#)
91. Sapirstein, H.; Wu, Y.; Koksels, F.; Graf, R. A Study of Factors Influencing the Water Absorption Capacity of Canadian Hard Red Winter Wheat Flour. *J. Cereal Sci.* **2018**, *81*, 52–59. [\[CrossRef\]](#)
92. Maghirang, E.B.; Lookhart, G.L.; Bean, S.R.; Pierce, R.O.; Xie, F.; Caley, M.S.; Wilson, J.D.; Seabourn, B.W.; Ram, M.S.; Park, S.H.; et al. Comparison of Quality Characteristics and Breadmaking Functionality of Hard Red Winter and Hard Red Spring Wheat. *Cereal Chem.* **2006**, *83*, 520–528. [\[CrossRef\]](#)
93. Waddell, I.S.; Orfila, C. Dietary Fiber in the Prevention of Obesity and Obesity-Related Chronic Diseases: From Epidemiological Evidence to Potential Molecular Mechanisms. *Crit. Rev. Food Sci. Nutr.* **2023**, *63*, 8752–8767. [\[CrossRef\]](#) [\[PubMed\]](#)
94. Simsek, S.; Budak, B.; Schwebach, C.S.; Ovando-Martínez, M. Historical vs. Modern Hard Red Spring Wheat: Analysis of the Chemical Composition. *Cereal Chem.* **2019**, *96*, 937–949. [\[CrossRef\]](#)
95. Kulathunga, J.; Reuhs, B.L.; Zwinger, S.; Simsek, S. Comparative Study on Kernel Quality and Chemical Composition of Ancient and Modern Wheat Species: Einkorn, Emmer, Spelt and Hard Red Spring Wheat. *Foods* **2021**, *10*, 761. [\[CrossRef\]](#) [\[PubMed\]](#)
96. Ragae, S.; Guzar, I.; Abdel-Aal, E.S.M.; Seetharaman, K. Bioactive Components and Antioxidant Capacity of Ontario Hard and Soft Wheat Varieties. *Can. J. Plant Sci.* **2012**, *92*, 19–30. [\[CrossRef\]](#)
97. Žilić, S.; Basić, Z.; Hadži-Tašković Šukalović, V.; Maksimović, V.; Janković, M.; Filipović, M. Can the Sprouting Process Applied to Wheat Improve the Contents of Vitamins and Phenolic Compounds and Antioxidant Capacity of the Flour? *Int. J. Food Sci. Technol.* **2014**, *49*, 1040–1047. [\[CrossRef\]](#)
98. Lin, L.; Yu, X.; Gao, Y.; Mei, L.; Zhu, Z.; Du, X. Physicochemical Properties and in Vitro Starch Digestibility of Wheat Starch/Rice Protein Hydrolysate Complexes. *Food Hydrocoll.* **2022**, *125*, 107348. [\[CrossRef\]](#)
99. Hammed, A.M.; Ozsisli, B.; Ohm, J.B.; Simsek, S. Relationship between Solvent Retention Capacity and Protein Molecular Weight Distribution, Quality Characteristics, and Breadmaking Functionality of Hard Red Spring Wheat Flour. *Cereal Chem.* **2015**, *92*, 466–474. [\[CrossRef\]](#)
100. Corassa, G.M.; Hansel, F.D.; Lollato, R.; Pires, J.L.F.; Schwalbert, R.; Amado, T.J.C.; Guarienti, E.M.; Gaviraghi, R.; Bisognin, M.B.; Reimche, G.B.; et al. Nitrogen Management Strategies to Improve Yield and Dough Properties in Hard Red Spring Wheat. *Agron. J.* **2018**, *110*, 2417–2429. [\[CrossRef\]](#)
101. Hu, X.; Cheng, L.; Hong, Y.; Li, Z.; Li, C.; Gu, Z. Combined Effects of Wheat Gluten and Carboxymethylcellulose on Dough Rheological Behaviours and Gluten Network of Potato–Wheat Flour-Based Bread. *Int. J. Food Sci. Technol.* **2021**, *56*, 4149–4158. [\[CrossRef\]](#)
102. Hu, X.; Cheng, L.; Hong, Y.; Li, Z.; Li, C.; Gu, Z. An Extensive Review: How Starch and Gluten Impact Dough Machinability and Resultant Bread Qualities. *Crit. Rev. Food Sci. Nutr.* **2023**, *63*, 1930–1941. [\[CrossRef\]](#) [\[PubMed\]](#)
103. Simsek, S.; Budak, B.; Schwebach, C.S.; Ovando-Martínez, M. Starch Digestibility Properties of Bread from Hard Red Spring Wheat Cultivars Released in the Last 100 Years. *Cereal Chem.* **2020**, *97*, 138–148. [\[CrossRef\]](#)
104. Park, S.H.; Wilson, J.D.; Seabourn, B.W. Starch Granule Size Distribution of Hard Red Winter and Hard Red Spring Wheat: Its Effects on Mixing and Breadmaking Quality. *J. Cereal Sci.* **2009**, *49*, 98–105. [\[CrossRef\]](#)

105. Khalid, K.H.; Ohm, J.B.; Simsek, S. Influence of Bread-Making Method, Genotype, and Growing Location on Whole-Wheat Bread Quality in Hard Red Spring Wheat. *Cereal Chem.* **2022**, *99*, 467–481. [[CrossRef](#)]
106. Lafiandra, D.; Sestili, F.; Sissons, M.; Kiszonas, A.; Morris, C.F. Increasing the Versatility of Durum Wheat through Modifications of Protein and Starch Composition and Grain Hardness. *Foods* **2022**, *11*, 1532. [[CrossRef](#)] [[PubMed](#)]

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