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Advances in Wheat Flour Processing: Strategies for Enhancing Nutritional Quality, Functional Properties, and Industrial Application

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Abstract Wheat flour is a fundamental ingredient in global food production, forming the basis of numerous staple foods. However, traditional wheat flour processing presents several challenges, including nutrient degradation, limited functional properties, and inefficiencies in industrial production. Recent advancements have focused on improving the nutritional quality of wheat flour through biofortification, whole grain fortification, and the incorporation of functional ingredients, enhancing fibre content, vitamins, and essential minerals. Functional optimization has been achieved via enzymatic modifications, hydrothermal treatments, and biochemical processing, which enhance dough rheology, hydration capacity, and structural stability. Moreover, industrial innovations such as high-pressure processing (HPP), extrusion, ultrasound, and pulsed electric field (PEF) technology have significantly improved flour texture, shelf life, and safety. Additionally, sustainable milling techniques and by-product valorization strategies are being widely adopted to minimize environmental impact and optimize resource utilization. Looking ahead, bioengineered wheat varieties, AI-driven quality assessment, and precision fermentation are poised to revolutionize the wheat flour processing industry, aligning with consumer demands for healthier and more sustainable food products.

Keywords Wheat flour processing; Nutritional enhancement; Functional properties; Advanced processing technologies; Sustainable food production

1 Introduction

Wheat is not only one of the most important staple crops but also the primary raw material for global flour production. As a cornerstone of global agriculture and nutrition systems, wheat plays a crucial role in providing essential nutrients such as proteins, vitamins, and dietary fibre, all of which are vital for human health (Shewry and Hey, 2015). Due to its adaptability to various growing conditions and its versatility in food processing, wheat is widely used in the production of diverse food products, including bread, noodles and pasta, instant noodles, biscuits and baked goods, and flatbreads such as roti. This versatility makes wheat an indispensable component of diets in both developed and developing countries (Kumar et al., 2019). The accelerating pace of urbanization and industrialization has further increased the demand for wheat and its derivatives, reinforcing its position as a key global staple crop.

The global demand for wheat is primarily driven by its functional properties and nutritional value. Wheat contributes to over 50% of daily caloric intake for a significant portion of the global population, making it a crucial component of food security. The continued rise in wheat consumption, especially in urban areas where processed wheat-based products are more accessible, reflects broader dietary shifts influenced by population growth and urbanization (Grote et al., 2021). This trend is evident not only in developed economies but also in emerging markets, where wheat-based foods have become integral to daily diets (Shewry and Hey, 2015). However, the increasing demand for wheat products presents significant challenges, necessitating the adoption of sustainable production practices to ensure long-term stability in the global food supply.

Despite its importance, conventional wheat flour processing faces several challenges that impact its nutritional quality, functional properties, and industrial applications. Traditional milling techniques often result in the removal of nutrient-rich components, such as bran and germ, leading to significant losses of essential micronutrients such as iron and zinc, which are critical for human health (Shewry and Hey, 2015). Additionally, wheat flour exhibits limitations in dough rheology and reduced antioxidant properties, which negatively affect the texture and shelf life of end products (Cappelli and Cini, 2021; Zarzycki et al., 2024). From an industrial perspective, increasing production efficiency and reducing costs often come at the expense of flour quality, resulting in inconsistencies in product performance. Furthermore, the environmental footprint of wheat cultivation and processing, including water consumption and carbon emissions, poses a major challenge for sustainability (Cappelli and Cini, 2021; Grote et al., 2021). Consequently, innovative processing strategies are essential to enhance the nutritional and functional attributes of wheat flour while mitigating its environmental impact.

This study aims to systematically explore the latest advancements in wheat flour processing, focusing on innovative strategies to enhance its nutritional quality, functional properties, and industrial applications. The research will critically examine the limitations of conventional processing methods and highlight emerging technologies that address these challenges. Specifically, this study will analyze the role of genome editing and marker-assisted selection in improving the nutritional profile and processing traits of wheat, as well as investigate the integration of sustainability principles in the wheat value chain to balance environmental and economic feasibility. Key research areas include the genetic and biochemical factors influencing wheat quality, the impact of processing technologies on the nutritional and functional properties of wheat flour, and the potential for utilizing food industry by-products in wheat flour processing. By providing a comprehensive assessment of these topics, this research aims to contribute to the development of more nutritious, functional, and sustainable wheat-based products, ultimately supporting global food security and public health.

2 Enhancing Nutritional Quality in Wheat Flour Processing

2.1 Impact of traditional processing on nutrient composition

Traditional wheat flour processing methods, including milling, refining, and heat treatments, often remove nutrient-rich components from the grain, resulting in significant losses of dietary fibre, vitamins, and minerals.

2.1.1 Effects of milling, refining, and heat treatments on nutrient retention

Traditional wheat flour processing methods, such as milling and refining, have a considerable impact on the nutritional composition of wheat flour. High-extraction milling processes, in particular, can lead to substantial nutrient losses. Liang et al. (2020) reported that a milling process with a 70% extraction rate could cause up to 71% loss of folate content. Similarly, Garg et al. (2021) found that the refining process frequently reduces essential vitamins and minerals because the outer layers of the grain (bran and germ), which are rich in nutrients, are removed during processing.

Heat treatments, such as extrusion, also affect nutrient retention. While extrusion has been shown to increase the levels of certain nutrients, such as iron and copper in whole black-grained wheat flour, it may also lead to a reduction in total starch content (Liu et al., 2021). Furthermore, Garg et al. (2021) suggested that different heat treatment methods have varying effects on vitamin loss, with pressure cooking causing significant vitamin degradation, whereas boiling results in minimal vitamin loss.

2.1.2 Loss of dietary fibre, vitamins, and minerals

Traditional wheat flour processing often leads to a reduction in dietary fibre, vitamins, and minerals. Milling and refining, in particular, significantly decrease the fibre content in wheat flour, as these processes remove the bran and germ, which are the primary sources of dietary fibre in wheat (Jiang et al., 2023). Jiang et al. (2023) further demonstrated that the total dietary fibre content in coarse bran declines substantially during milling.

Vitamins are also highly susceptible to losses during processing. For instance, vitamin B2 content decreases significantly due to processing modifications such as microwave and extrusion treatments (Ye et al., 2021). Additionally, storage conditions can exacerbate vitamin losses- under severe storage conditions, the degradation rate of vitamin A can exceed 85% within three months (Hemery et al., 2018).

The processing of wheat flour can also affect the levels of essential minerals such as zinc and iron. Although biofortification strategies have been proven effective in enhancing mineral content in wheat flour (Jiang et al., 2023), the molar ratio of phytic acid to zinc may decrease, which does not necessarily improve zinc bioaccessibility (Jiang et al., 2023).

2.2 Strategies for enhancing nutritional quality

Enhancing the nutritional quality of wheat flour requires a combination of whole grain and bran fortification, biofortification techniques, functional ingredient enrichment, and fermentation-based bioprocessing. These approaches work synergistically to increase dietary fibre content, micronutrient levels, and bioavailability of essential nutrients, ultimately promoting the production of healthier wheat-based foods.

2.2.1 Whole grain and bran fortification: impact on fibre and bioactive compounds

Fortifying wheat flour with whole grains and bran can significantly improve its nutritional profile by increasing fibre content and bioactive compounds. A study by Li et al. (2024) found that incorporating wheat bran aqueous extract (WBE) into wheat flour enhanced the dietary fibre and protein content of bread, while also improving dough characteristics and loaf volume. Similarly, Han et al. (2024) reported that adding whole soybean pulp (WSP) to wheat flour increased the total dietary fibre, total phenolic compounds, and protein content in bread, thereby improving its nutritional quality without significantly affecting its physical properties.

2.2.2 Biofortification: enhancing micronutrient content through genetic and agronomic strategies

Biofortification is a method of increasing micronutrient content (iron, zinc, and selenium) in wheat flour through genetic and agronomic strategies. This approach includes breeding wheat varieties with higher micronutrient levels and employing agronomic measures to improve nutrient uptake from the soil.

Garg et al. (2018) extensively explored biofortification technologies in crop research, particularly for wheat. They highlighted that biofortification can be achieved through genetic modification (conventional breeding and transgenic techniques) and agronomic strategies (fertilization and soil management) to increase micronutrient content in crops and address global nutritional deficiencies. Figure 1 illustrates the different approaches used in biofortified crops, including transgenic, bio-breeding, and agronomic interventions applied to staple cereals, vegetables, legumes, and fruits (Garg et al., 2018).

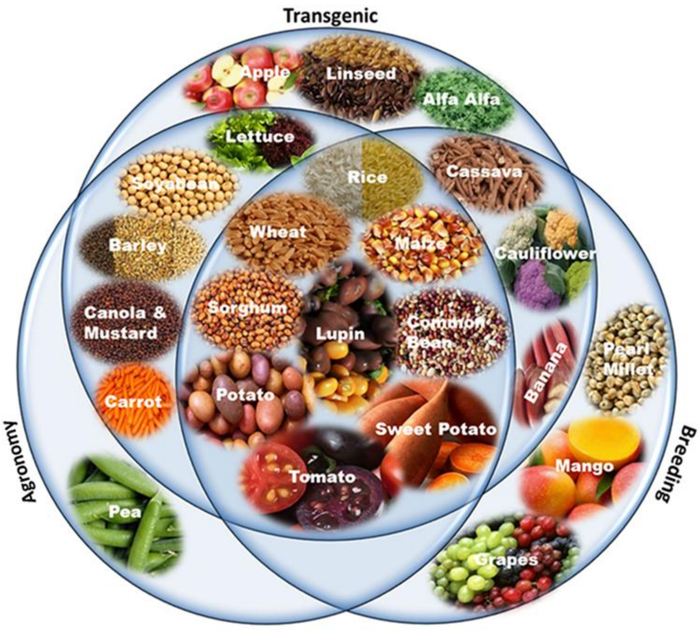

Figure 1 Biofortified crops generated by different approaches: transgenic, agronomic, and breeding. Staple cereals, most common vegetables, beans, and fruits have been targeted by all three approaches. Some crops have been targeted by only one or two approaches depending on its significance and prevalence in the daily human diet (Adopted from Garg et al., 2018)

In genetic modification, Garg et al. (2018) summarized the role of selective breeding and transgenic approaches in enhancing wheat micronutrient content. Traditional breeding methods have successfully developed wheat varieties with higher iron and zinc concentrations, further optimized using marker-assisted selection (MAS). Meanwhile, transgenic techniques offer an alternative where genetic diversity is limited. For instance, introducing ferritin genes into wheat has been shown to increase grain iron content while reducing the impact of anti-nutritional factors such as phytic acid.

In terms of agronomic strategies, Garg et al. (2018) reported that applying iron-enriched foliar urea fertilizer to wheat can effectively increase iron accumulation in grains. Similarly, zinc fertilization improves wheat zinc content and enhances its bioavailability by reducing phytic acid levels. Additionally, in regions with low soil selenium levels, the application of selenium-enriched fertilizers has been proven to significantly enhance wheat grain selenium content and subsequently increase human blood selenium levels. This technique has been successfully implemented in Finland and other countries.

2.2.3 Enrichment with functional ingredients: addition of proteins, fibres, and phytochemicals

The enrichment of wheat flour with functional ingredients can significantly enhance its nutritional quality. For example, incorporating quinoa flour into wheat bread has been shown to increase protein, ash, fat, essential minerals, and amino acid content, thus improving its nutritional profile (Coțovanu et al., 2023). Similarly, adding amaranth flour to wheat flour enhances protein and mineral content, offering a nutritionally superior alternative. Moreover, the addition of walnut flour can boost protein and fat content, though it may impact the bread's physical properties (Almoraie, 2019).

2.2.4 Fermentation and bioprocessing: improving nutrient bioavailability through sourdough and microbial fermentation

Fermentation and bioprocessing, particularly sourdough fermentation, play a crucial role in improving the bioavailability of wheat flour nutrients. Çetin-Babaoğlu et al. (2020) demonstrated that the use of immature wheat flour in sourdough fermentation promotes the growth of lactic acid bacteria, enhances fermentation activity, and increases the dietary fibre content of bread. This process not only improves nutritional quality but also has a positive effect on the texture and flavour of the final product.

3 Optimization of Functional Properties in Wheat Flour

3.1 Key functional properties of wheat flour

The optimization of wheat flour's functional properties primarily involves enhancing the gluten network, increasing water absorption capacity, and improving dough rheology. These factors collectively contribute to the texture and sensory attributes of wheat-based products. By employing various processing techniques and functional ingredients, wheat flour's industrial applications can be further optimized to improve consumer satisfaction.

3.1.1 Gluten network formation and dough rheology

The formation of the gluten network is crucial for the rheological properties of wheat flour dough, directly influencing its elasticity and extensibility. The addition of various components can significantly alter the structure of the gluten network and its rheological properties. Studies have shown that incorporating defatted maize germ flour (DMGF) into wheat flour can significantly increase the apparent viscosity and dough hardness, indicating a stronger gluten network and improved dough rheology (Siddiq et al., 2009). Similarly, the inclusion of bean flour in wheat flour has been found to enhance farinograph absorption and mixing tolerance, further strengthening gluten formation (Deshpande et al., 1983). Moreover, optimizing the content of iron and oligofructose in wheat flour has been shown to affect dough rheological properties, with oligofructose significantly improving dough tenacity and extensibility (Codină et al., 2019).

3.1.2 Water absorption capacity, viscosity, and elasticity

Water absorption capacity is a key functional property affecting the viscosity and elasticity of wheat flour dough. Research suggests that wheat germination can enhance wheat flour's water absorption capacity, positively impacting dough elasticity and overall texture (Hussain and Uddin, 2012). Additionally, the incorporation of DMGF has been shown to improve wheat flour's water absorption and emulsifying capacities, further enhancing dough viscosity and elasticity (Siddiq et al., 2009). Furthermore, annealing treatment has been found to optimize the water-bound capacity of wheat flour, a critical factor in maintaining dough elasticity and achieving the desired texture (Youssouf et al., 2019).

3.1.3 Impact on end-product texture and sensory attributes

The functional properties of wheat flour significantly impact the texture and sensory attributes of final products. Studies have reported that adding DMGF to wheat flour increases dough hardness, resulting in a firmer texture in baked goods (Siddiq et al., 2009). The use of composite flours, such as those incorporating amaranth seed, brewers' spent grain, and apple pomace, has been shown to enhance the nutritional and rheological properties of wheat flour, improving both the texture and sensory appeal of final products (Awolu et al., 2016). Additionally, optimizing germination conditions for wheat flour can enhance its functional properties, making it suitable for producing weaning foods with desirable textures (Hussain and Uddin, 2012).

3.2 Innovative processing technologies for functional enhancement

Hydrothermal treatments, enzymatic modifications, biochemical processing, and nanotechnology offer diverse strategies for enhancing the functional properties of wheat flour. These methods can be tailored to meet the increasing market demand for high-quality wheat flour products.

3.2.1 Hydrothermal treatments: impact of heat-moisture and extrusion processing

Hydrothermal treatments, including heat-moisture treatment (HMT) and extrusion processing, significantly influence the functional properties of wheat flour. Extrusion processing, in particular, enhances hydration properties, emulsifying capacity, thermal stability, and pasting properties. It increases water binding capacity and swelling while modifying emulsification properties and free sugar content. The severity of extrusion conditions may reduce resistant starch levels while increasing enzymatic hydrolysis susceptibility, thereby altering wheat flour functionality (Martinez et al., 2024). Hydrothermal enzyme-assisted treatments can improve flour viscosity and dough stability, although they may negatively impact protein structure and reduce dough elasticity (Lewko et al., 2024).

3.2.2 Enzymatic modifications: application of amylases, proteases, and transglutaminase

Enzymatic modifications, particularly the use of amylases, proteases, and transglutaminase, can significantly alter the functional properties of wheat flour. These enzymes enhance the quality of gluten proteins, thereby improving the flour's rheological properties and baking strength. Enzyme-assisted treatments, especially when combined with extrusion, have been found to increase hydration properties, modify starch structure, improve dough stability, and reduce the initial gelatinization temperature (Lewko et al., 2024). Such enzymatic modifications are crucial for developing wheat flour with specific functional attributes for various industrial applications.

3.2.3 Biochemical treatments: role of fermentation and sprouting techniques

Biochemical treatments such as fermentation and sprouting are effective in enhancing the functional properties of wheat flour. Germination increases the digestibility of starch and proteins due to the action of hydrolytic enzymes, while also enhancing the bioactive potential of the flour by increasing phenolic and flavonoid content (Singh et al., 2021). The combination of germination and fermentation further improves protein and starch digestibility, antioxidant activities, and mineral content while reducing anti-nutritional factors. These techniques modify the thermal, functional, and pasting properties of wheat flour, making them valuable for producing naturally modified flour with enhanced functionality (Chinma et al., 2024).

3.2.4 Nanotechnology applications: improvement of flour structure and stability

Nanotechnology holds promising applications for improving the structure and stability of wheat flour. Although research on nanotechnology in wheat flour is still limited, its potential for functional modification is significant. Atmospheric cold plasma treatment has been shown to alter the physicochemical and functional properties of wheat flour, including increased hydration properties and altered starch crystallinity (Chaple et al., 2020). These advancements indicate that nanotechnology could play a crucial role in the future development of high-functionality wheat flour products.

4 Industrial Applications and Technological Innovations

4.1 Applications of wheat flour in traditional and modern food products

4.1.1 Bakery applications: bread, pastries, and noodles

Wheat flour plays a crucial role in traditional bakery products such as bread, pastries, and noodles due to its unique gluten protein composition, primarily glutenins and gliadins. These proteins provide elasticity and extensibility, enabling dough to expand and retain gases, thereby giving bread a soft, airy texture and ensuring the firmness and cohesiveness of pasta and lasagna (Brites et al., 2018). The rheological properties of wheat gluten can be optimized through various processing techniques, making it a widely used ingredient in the food industry (Zhang et al., 2022).

4.1.2 Gluten-free alternatives and modified wheat-based formulations

The increasing prevalence of gluten-related disorders, such as celiac disease, coupled with growing consumer demand for healthier diets, has led to a significant rise in the market for gluten-free products. However, producing gluten-free bakery goods such as bread and pasta remains challenging, as the absence of gluten affects texture and processing performance. Researchers have explored the use of gluten-free alternatives such as rice flour, corn flour, and legume-based flours to mimic gluten's functional properties (Ronnie et al., 2021). These substitutes not only cater to dietary restrictions but also enhance the nutritional profile of products, as they are rich in proteins, dietary fibre, vitamins, and minerals (Foschia et al., 2017; Cairano et al., 2020).

4.1.3 Application of wheat-derived bioactive compounds in functional foods

Bioactive compounds derived from wheat are increasingly being utilized in the development of functional foods. These compounds, including various proteins and peptides, contribute to nutritional enhancement. The gelation and foamability properties of wheat gluten make it an effective food additive and an encapsulation material for functional ingredients (Zhang et al., 2022). Additionally, studies suggest that wheat gluten can serve as a raw material for developing functional foods and biodegradable materials, offering further innovation opportunities for the food industry (Kalin, 1979; Day et al., 2006).

4.2 Advanced industrial processing technologies

4.2.1 Extrusion technology: enhancing texture and nutritional properties

Extrusion technology represents a significant advancement in wheat flour processing, primarily aimed at improving its texture and nutritional properties. This high-temperature, high-pressure process enhances the digestibility and bioavailability of nutrients in wheat flour while increasing the economic efficiency of production. The incorporation of extrusion technology in cereal processing has been shown to significantly boost product yield and profitability. Studies indicate that the application of extrusion technology can increase wheat flour production profitability by 15%, primarily due to reduced raw material costs and minimized processing losses (Yanova et al., 2019).

4.2.2 High-pressure processing (HPP): improving microbial safety and flour performance

High-Pressure Processing (HPP) is an innovative technology designed to enhance the microbial safety and processing performance of wheat flour. HPP utilizes high-pressure treatment to inactivate microorganisms without the need for high temperatures, thereby preserving the nutritional and functional properties of wheat flour. This method is particularly beneficial for whole grain flour, which has a higher oil content and is more susceptible to microbial contamination. HPP not only extends product shelf life but also maintains key nutrients and functional characteristics, improving its suitability for baking applications (Zhygunov et al., 2020; Lesnikova et al., 2023).

4.2.3 Ultrasound and pulsed electric field (PEF) processing: modulating flour characteristics

Ultrasound and Pulsed Electric Field (PEF) processing are emerging technologies that optimize the physical and chemical properties of wheat flour. Ultrasound treatment enhances water absorption capacity and dough rheology, making the flour more suitable for various baking applications. Conversely, PEF processing facilitates the extraction of bioactive compounds, improving the nutritional profile of wheat flour. These non-thermal processing methods contribute to the development of healthier, more functional wheat flour products (Tursynbaeva et al., 2020; Dziki, 2023).

4.3 Sustainability and future trends in wheat flour processing

4.3.1 Valorization of by-products

By-product valorization, particularly the utilization of bran and germ, is a key aspect of sustainable wheat flour processing. These by-products are rich in proteins and soluble dietary fibres, which can be extracted using enzyme-assisted extraction and membrane filtration techniques (Galanakis, 2022). Such methods not only enhance the nutritional value of by-products but also support the circular economy by converting waste into value-added products, thereby promoting more environmentally friendly production models (Danciu et al., 2023).

4.3.2 Sustainable milling practices and energy-efficient processing

The adoption of sustainable milling practices can significantly reduce the environmental footprint of wheat flour production. Studies indicate that combining dry and wet fractionation processes enhances component separation efficiency while minimizing waste (Abdel-Aal, 2024). Moreover, life-cycle assessment (LCA) is instrumental in developing eco-friendly strategies across the wheat production chain, from cultivation to milling and final product manufacturing, thereby improving resource utilization efficiency (Cappelli and Cini, 2021).

4.3.3 Application of artificial intelligence and smart technologies in flour quality assessment

Artificial intelligence (AI) and smart technologies are gradually being integrated into the wheat flour processing industry to optimize quality assessment and production efficiency. Machine learning techniques enable the analysis of multiple wheat quality parameters, providing decision support tools for process optimization (Parrenin et al., 2022). Additionally, the combination of near-infrared (NIR) spectroscopy with AI-driven methods, such as fuzzy cognitive maps (FCMs), facilitates non-destructive and cost-effective detection of key parameters such as protein, moisture, and ash content in wheat flour. This improves production precision while reducing material waste (Boglou et al., 2023).

5 Future Perspectives and Research Directions

The future of wheat flour processing will rely on the integration of bioengineering, precision fermentation, and alternative proteins to produce more nutritious and sustainable food products. These innovations, combined with evolving consumer trends and regulatory frameworks, will collectively shape the future of the wheat flour industry, significantly impacting public health and food security.

5.1 Emerging trends in bioengineered wheat varieties

The development of bioengineered wheat varieties is becoming an essential strategy for enhancing the nutritional quality and functional properties of wheat flour. Studies have shown that ancient wheat varieties, such as emmer and spelt, exhibit significantly improved bioaccessibility of phenolic compounds and antioxidant capacity when combined with sourdough fermentation, suggesting that bioengineering could further optimize these nutritional advantages (Dapčević-Hadnađev et al., 2022). Additionally, fermentation processing of wheat germ has been proven to enhance its nutritional composition and antioxidant properties, indicating that bioengineering could play a crucial role in developing wheat varieties with superior health benefits in the future (Bayat et al., 2022).

5.2 Potential of precision fermentation and alternative protein integration

Precision fermentation is emerging as a transformative technology in the production of food ingredients, including alternative proteins. Advances in genome-based technologies and synthetic biology enable the production of fermentation-derived proteins, which can be integrated into wheat flour products to enhance their nutritional profile (Augustin et al., 2023). Optimized fermentation processes for legume- and seed-based proteins have demonstrated significant potential in improving protein digestibility and nutritional value, providing a promising direction for the development of healthier and more digestible wheat flour products (De Pasquale et al., 2019; Garrido-Galand et al., 2021).

5.3 Consumer trends and regulatory considerations for novel flour products

The growing consumer demand for high-nutritional-value and functional foods is driving innovation in wheat flour processing. For example, the substitution of wheat with legumes, which are rich in protein and dietary fibre, has become a popular choice in the food industry (De Pasquale et al., 2019). However, the commercialization of novel flour products must comply with food safety and labelling regulations. In particular, the introduction of fermentation-derived ingredients requires a transdisciplinary policy approach to ensure consumer safety and market acceptance (Augustin et al., 2023).

5.4 Long-term impact of wheat flour innovations on public health and food security

Innovations in wheat flour processing hold significant potential to improve public health and global food security. Enhancing the nutritional quality of wheat flour through bioengineering and fermentation could promote healthier diets worldwide. For instance, the integration of alternative proteins and the reduction of anti-nutritional factors can contribute to more sustainable and nutritionally enriched food systems, addressing global food security challenges (Montemurro et al., 2021). Furthermore, the adoption of life-cycle assessment (LCA)-based sustainable production strategies can reduce the environmental footprint of food production while ensuring long-term food security (Cappelli and Cini, 2021).

6 Conclusion

The continuous advancement of wheat flour processing technologies has made significant progress in improving nutritional quality, functional properties, and industrial applications. However, conventional processing methods still face challenges related to nutrient loss, functional limitations, and sustainability. In response, recent developments in biofortification, functional ingredient enrichment, and advanced processing technologies offer new opportunities for optimizing wheat flour's nutritional value and processing performance. Additionally, the adoption of emerging technologies such as artificial intelligence, precision fermentation, and energy-efficient milling has enhanced wheat flour quality control and production efficiency while promoting a shift toward smarter and more sustainable processing methods.

The complexity of wheat flour processing necessitates interdisciplinary collaboration to ensure that technological innovations effectively meet industrial and consumer demands. The integration of food science, agricultural technology, bioengineering, environmental science, and artificial intelligence has provided systematic solutions for wheat variety improvement, milling process optimization, by-product utilization, and food safety control. Such collaborative efforts not only enhance the nutritional value and processing adaptability of wheat flour but also contribute to the development of a green food system and the efficient utilization of global food resources.

Moving forward, continued research and industry collaboration will be essential to addressing global food security, consumer health demands, and sustainability objectives. Strengthening technological innovation, regulatory optimization, and international industry cooperation will contribute to the high-quality development of the wheat flour processing sector, creating a lasting impact on the global food industry while supporting public health and economic growth worldwide.

Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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