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Unlocking wheat bran's potential: a comprehensive review of its chemistry, nutritional composition, and promising technological pathways

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Abstract

Wheat bran, the principal by-product obtained during the grain milling process, accounts for approximately 14–19% of the total grain weight and is distinguished by its high content of dietary fiber, proteins, minerals, B-complex vitamins, and bioactive compounds such as arabinoxylans and lignans. In the context of human nutrition, it functions as a valuable functional ingredient, associated with promoting intestinal health, reducing serum cholesterol levels, and modulating glycemic response, and is widely incorporated into formulations of breads, biscuits, pasta, and extruded products. In animal nutrition, wheat bran serves as an energy and fiber source in diets formulated for ruminants, swine, and poultry; however, its high lignin content and low digestibility pose challenges, particularly for monogastric animals. Among the critical concerns, the presence of mycotoxins, especially deoxynivalenol, produced by *Fusarium* species stands out, as it compromises food quality and safety, with significant repercussions for both animal and human health. Recent technological advances have explored novel applications, including the extraction of arabinoxylans for prebiotic use, the recovery of natural antioxidants, and the utilization of wheat bran as a substrate in fermentation processes to produce bioethanol and other high-value compounds. Despite these promising prospects, notable challenges remain, such as the complex structural nature of the cell wall, the compositional variability depending on origin and processing, and the need to overcome sensory and technological barriers to fully realize its potential in food systems. Thus, this review aims to provide a comprehensive overview of wheat bran's nutritional and functional properties, its current applications in human and animal nutrition, associated safety concerns, and emerging biotechnological uses, while also discussing the main challenges that limit its broader utilization.

Keywords: fiber; deoxynivalenol; human nutrition; animal nutrition.

Practical Application: This review paper examines the significant potential of wheat bran (WB), a prominent by-product of the cereal-processing industry, which contains substantial amounts of biologically beneficial material suitable for various applications. It offers a thorough overview of the nutritional and functional properties of WB, its existing uses in both human and animal nutrition, potential safety concerns, and emerging biotechnological applications. Additionally, this review addresses the primary challenges that hinder its wider utilization, thereby highlighting the need for further exploration and innovation in this field.

1 INTRODUCTION

Wheat (*Triticum* spp.), belonging to the Poaceae family, is one of the most significant agricultural crops worldwide, playing a crucial role in global food security. Cultivated over an estimated area of 220 million hectares, it has an annual production exceeding 700 million metric tons, contributing approximately 20% of the global daily caloric intake (Amer et al., 2023; Ma et al., 2022; Saini et al., 2023). According to the Food and Agriculture Organization of the United Nations (FAO, n.d.), the leading global producers include the European Union, China, India, and North America, while Brazil ranks fifteenth, with an estimated annual production of 9.5 million metric tons.

Wheat grains, extensively cultivated for human consumption, undergo milling, a fundamental stage in the industrial processing of this cereal. This process involves the mechanical reduction of the endosperm into fine particles, yielding refined white flour, a key ingredient in staple food products such as bread, cakes, cookies, and pasta. Additionally, milling also generates wheat bran, the main by-product of this process. Global WB production is estimated at approximately 150 million metric tons annually, with its predominant application in the animal feed industry (Amer et al., 2023; Parenti et al., 2020; Prückler et al., 2014; Yan et al., 2022).

Despite the abundance and relevant nutritional composition, only about 10% of WB is allocated for human consumption, while the majority is used in animal feed at low market prices (Hadidi et al., 2024). Although technological advancements have expanded the potential applications of WB, its utilization

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rate remains below its full potential, highlighting the need for more efficient strategies to enhance the value of this by-product.

In response to the growing demand for sustainable food alternatives and functional ingredients, WB has been investigated as a promising raw material for the food and nutraceutical industries. Its fractionation and modification through physical, chemical, and biotechnological processes enable the extraction of bioactive compounds and proteins with potential industrial applications. Due to its low commercial value and wide availability, WB derivatives can be utilized in the development of innovative and technologically advanced products (Amer et al., 2023; Gong et al., 2023; Ma et al., 2022; Saini et al., 2023). In this context, the present review aims to discuss the nutritional aspects of WB, examine the challenges associated with its utilization, and explore opportunities for its application in high-value industrial processes and products.

1.1 Relevance of the work

This review focuses on wheat bran, which accounts for approximately 14–19% of the total grain weight upon milling and has a high content of dietary fiber, proteins, minerals, B-complex vitamins, and bioactive compounds such as arabinoxylans (AXs) and lignans. WB is associated with promoting intestinal health, reducing serum cholesterol levels, and modulating glycemic response, and is widely incorporated into formulations of breads, biscuits, pasta, and extruded products. WB also serves as an energy and fiber source in diets formulated for ruminants, swine, and poultry. Some critical concerns involve the presence of mycotoxins, especially deoxynivalenol (DON), from *Fusarium* species. Novel applications, including the extraction of AXs for prebiotic use, the recovery of natural antioxidants, and the utilization of WB as a substrate in fermentation processes to produce bioethanol and other high-value compounds, are also included. Thus, this review aims to provide a comprehensive overview of WB's nutritional and functional properties, its current applications in human and animal nutrition, associated safety concerns, and emerging biotechnological uses, while also discussing the main challenges that limit its broader utilization.

2 CHEMICAL AND NUTRITIONAL COMPOSITION OF WHEAT BRAN

WB exhibits a chemical composition that varies depending on the cultivar, cultivation conditions, and processing methods employed. Its structure consists of several layers, including the pericarp, *testa*, hyaline layer, and aleurone, each of which contributes distinctly to the nutritional profile of the bran (Chen et al., 2022; Katileviciute et al., 2019).

WB is distinguished by its composition, which is rich in dietary fibers, accounting for approximately 50% of its total weight. About 90% of this fiber fraction consists of insoluble fibers, such as cellulose, hemicelluloses, lignin, and resistant starch. Soluble fibers, including β-glucans and xylans, represent approximately 5% of the total fiber content. This diverse composition of dietary fibers provides WB with a broad range of biological activities, including benefits for gut health, reduction of blood cholesterol levels, and a decreased risk of cardiovascular diseases, type 2 diabetes, colon cancer, and obesity (Chen et al., 2022; Katileviciute et al., 2019; Li, Stump, et al., 2023; Sui et al., 2018; Zhuang et al., 2024).

The pericarp, accounting for approximately 5% of the grain, is rich in insoluble fibers such as cellulose (32.1%), hemicellulose (29.2%), and lignin (16.4%), in addition to containing proteins (6%), ash (2%), and lipids (0.5%). This layer is characterized by high levels of branched heteroxylans and lignified tissues. The *testa* concentrates almost all the alkylresorcinols in the grain, a class of phenolic lipids with antioxidant properties. The intermediate hyaline layer consists of arabinoxylans (AXs) and ferulic acid (FA) monomers (Chen et al., 2022; Katileviciute et al., 2019; Li, Sun, et al., 2023; Sui et al., 2018; Zhuang et al., 2024).

The aleurone layer, located internally within the WB and partially shared with the endosperm, plays a central role in the nutritional composition of the whole grain. This layer is responsible for providing approximately 80% of the niacin, 60% of vitamin B6, and 32% of thiamine present in the grain. Furthermore, aleurone is rich in lignans, proteins with a balanced amino acid profile, particularly high levels of lysine, bioactive compounds, phytic acid, antioxidants, vitamins, and minerals. Due to this composition, aleurone has attracted scientific interest for its potential use as a functional ingredient in various cereal-based products (Sui et al., 2018; Zhuang et al., 2024).

In comparison, while WB contains approximately 428 g/kg of total dietary fiber, wheat flour has a significantly lower content, around 30 g/kg. Specifically, WB is an abundant source of AXs (22–30%), cellulose (6.5–9.9%), and β-D-glucans (2.2–2.6%), reinforcing its role as a valuable dietary component in promoting gastrointestinal health (Chen et al., 2022; Sui et al., 2018; Zhuang et al., 2024).

WB is notable for its diverse nutritional composition, including proteins (13–19%), lipids, B-vitamins, and essential minerals such as iron, zinc, manganese, magnesium, and phosphorus, with higher concentrations found in the outer layers of the grains. Approximately 80% of the phosphorus present in wheat is in the form of phytic acid, a compound that can bind to minerals such as calcium, zinc, and magnesium, thus reducing the bioavailability of those elements. Phytic acid, previously considered an antinutrient primarily, has been reevaluated in recent studies, which suggest its role as an antioxidant, with potential benefits in cancer prevention. Additionally, solid-state fermentation of WB has shown a positive effect on the activation of the enzyme phytase, leading to the degradation of phytic acid and the increase in bioactive compounds (Alkandari et al., 2021; Gupta et al., 2015; Katileviciute et al., 2019; Shang et al., 2021; Zhuang et al., 2024).

Arte et al. (2019), Coda et al. (2014), and Dimoso et al. (2025) reported on the impact of bioprocessing on the protein composition and peptide concentration in WB. The application of enzymes such as xylanase, β-glucanase, phytase, cellulase, protease, and endoglucanase, combined with lactic acid fermentation, promoted protein hydrolysis, resulting in improved protein digestibility and solubility due to the degradation of cell walls. Co-fermentation enhanced the rheological properties of the dough, associated with the release of FA. This phenolic acid, predominantly found in WB, is primarily in its bound form. Its release during bioprocessing improves dough quality by promoting gluten protein aggregation and preventing the degradation of the protein network by the bran.

Chamlagain et al. (2024) demonstrated that the proteins and nutrients in WB can be effectively solubilized into liquid extracts. The use of hydrolytic enzymes, alone or combined with microorganisms, enhances this solubilization, yielding protein extracts suitable for producing WB protein isolates with improved techno-functional properties compared to untreated bran.

The extraction of bioactive and nutritional compounds from complex matrices such as WB poses a considerable challenge within food science. Process efficiency and environmental sustainability are critical to the viability of the extraction methods applied. Among emerging technologies, steam explosion (SE) has gained attention as a sustainable and efficient pretreatment for various biomass sources, including wheat straw, sugarcane bagasse, rice husk, and corn stover (Li, Huang, & Xi, 2024). This method enhances the accessibility of valuable compounds in WB by subjecting the material to high temperature and pressure in the presence of steam, followed by an abrupt pressure release in less than 0.1 s, causing hydrolysis and structural disruption (Zheng et al., 2015). Despite its promising potential, large-scale application of SE for extracting bioactive compounds from agro-industrial by-products still demands further optimization (Li, Huang, & Xi, 2024).

3 APPLICATIONS OF WHEAT BRAN

3.1 Human nutrition

Dietary fiber intake remains below recommended levels in most countries, particularly in Europe (Stevenson et al., 2012). In response to the growing demand for healthier eating habits, WB has been extensively studied due to its high fiber content, demonstrating significant potential to address deficiencies in fiber consumption. Its application spans various sectors of the food industry, including bakery products and breakfast cereals (Chen et al., 2023; Sui et al., 2018).

White wheat flour, obtained through the milling process, exhibits an increased surface area compared to coarser flour particles, facilitating starch hydrolysis by amylase. This phenomenon accelerates sugar release, thereby elevating the glycemic response and contributing to higher caloric intake, which is associated with an increased risk of obesity and type II diabetes. The presence of residual bran particles in flour can modulate the glycemic response and satiety perception, significantly mitigating these adverse metabolic effects (Amer et al., 2023). Additionally, dietary fiber, along with phenolic compounds and other bioactive constituents of WB, can regulate starch hydrolysis, promoting its delay (Wu et al., 2022).

The predominant fraction of phenolic compounds present in WB is bound to structural carbohydrates, such as pentoses and hexoses, through phenolic hydroxyl groups or covalent linkages with aromatic carbons, thereby limiting their bioavailability and functionality in the human body. However, due to their high antioxidant potential and associated health benefits, WB has been studied as a sustainable source and a promising functional ingredient for whole food formulations. To enhance the release of these compounds in their free form, improve their functionality, optimize the nutritional profile, and ensure greater quality and stability of food products during storage, various chemical, physical, and biological modification strategies have been employed. Among these approaches, enzymatic hydrolysis, fermentation, and thermal treatment stand out, as they have demonstrated high efficiency in disrupting interactions that restrict phenolic compound availability, thereby enhancing their absorption and maximizing their biological activity (Germec et al., 2019; Li, Sun, et al., 2023; Zhang, Jia, et al., 2022).

Several studies have investigated changes in texture, nutritional composition of food products, and strategies to mitigate or prevent adverse effects associated with WB supplementation, as summarized in Table 1. Zhang, Liu, et al. (2022) reported that the addition of 15% fermented WB led to sensory improvements, including enhanced flavor and greater consumer acceptance of bread, while also contributing to freshness preservation and extending the product's shelf life.

Among the physical modification approaches for WB, SE stands out, as described by Sui et al. (2018). In their study, rehydrated WB was prepared using a bran-to-water ratio of 1:1 and subjected to a reactor, where the temperature was increased and maintained under pressures of 0.5 MPa (151.9°C), 0.8 MPa (170.4°C), and 1.0 MPa (180.0°C) for 3 and 5 min, respectively. Subsequently, the treated bran was rapidly released into the receiving chamber by opening the ball valve.

SE treatments led to an increase of up to 2.08 times in the soluble fiber fraction compared to untreated bran, resulting in a significant improvement in hydration capacity. This phenomenon influenced the interaction between bran and gluten, impacting the rheological properties of the dough. The analysis of viscoelastic profiles demonstrated that the application of SE to WB enhanced dough elasticity, as evidenced by the increase in the elastic (G') and viscous (G'') moduli, along with a reduction in the loss factor ($\tan \delta$), indicating a more cohesive and elastic structure.

WB is incorporated into food products to enhance specific functional properties, such as water retention capacity, textural attributes, and syneresis prevention. Furthermore, its application aids in the stabilization of emulsions in high-fat foods, contributes to increased antioxidant capacity, and consequently extends the shelf life of products. Another advantage associated with its use is the reduction of *in vitro* starch digestibility, providing potential metabolic and nutritional benefits (Zhang, Jia, et al., 2019, 2022).

The continuous growth of the global population, combined with growing concerns about climate change, healthy diets, animal welfare, and the sustainability of food systems, has intensified discussions about reducing or replacing animal-based products with plant-based protein alternatives. In this context, the purification and isolation of WB proteins have emerged as

Table 1. Wheat bran and its applications.

WB uses	Main facts reported	References
Food	Particle size reduction through air milling; high digestibility, presence of antioxidants, and a versatile nutrient profile.	(Li, Wang, et al., 2023a, 2023b)
	Extraction of nutrients and bioactive compounds; value-added by-products.	(Nayak & Bhushan, 2019)
	Food fortification achieved through the modification of wheat bran blended with vitamin A, enhancing its nutritional value.	(Van Wayenbergh et al., 2023)
	Extrusion of WB combined with semi-solid enzymatic hydrolysis – potential functional ingredient – reduced in vitro digestibility.	(Zhang, Zhou, et al., 2022)
	Hydrothermal treatment of wheat bran, improving the rheological and nutritional properties of bread.	(Cingöz et al., 2023)
	Solid-state fermentation by *Rhizopus oryzae*, improving the sensory properties of cake containing WB.	(Wu et al., 2022; Yan et al., 2023)
	Ingredients for enriched products; versatility of dietary fibers in the formulation of health-oriented products.	(Alkandari et al, 2021; Ciudad-Mulero, 2019; Menis-Henrique et al., 2020; Parenti et al., 2020; Prückler et al., 2014; Saini et al., 2023; Seal et al., 2021; Yan et al., 2022, 2023; Zerlasht et al., 2023; Zhang, Li, et al., 2023)
	Different milling techniques impact the bio accessibility of sugars in WB, affecting the nutritional characteristics of the final products.	(Amer et al., 2023)
	Climate change and genetic adaptations may affect the protein concentration in wheat, resulting in WB enriched with this macronutrient.	(Asseng et al., 2019)
	WB used as a raw material for fermentative xylitol production, following pretreatment with wet oxidation.	(Bhavana et al., 2023)
	WB from different varieties affects the rheological properties of bread; bran with lower insoluble fiber and phytic acid content improves the sensory characteristics of whole wheat bread.	(Cai et al., 2014)
	Production of vitamin B12 from bioprocessed WB for the fortification of plant-based foods.	(Chamlagain et al., 2024)
	Extrusion was used to enhance the bioactive properties of phenolic compounds in black WB.	(Chen et al., 2023)
	Chitosan-based edible films enriched with WB arabinoxylans, improving the material's properties.	(Costa et al., 2015)
	Impact of WB dietary fiber on gluten behavior during the dough-making process.	(Fan et al., 2024; Li, Li, et al., 2024; Ma et al., 2022)
	Processing technology of WB using *Lactobacillus apis*, isolated from the bee gut, to enhance antioxidant bioactivity.	(Ghamry et al., 2023)
	Studies employing methods such as fermentation, germination, enzymatic treatment with phytase, and genetic biofortification have been developed to reduce phytic acid content and enhance the nutritional value of foods.	(Gupta et al., 2015)
	Study of WB properties desirable for the food and pharmaceutical industries, such as solubility, emulsification, and gel formation.	(Chamlagain et al., 2024; Dimoso et al., 2025; Hadidi et al.,2024; Wang et al., 2023; Xiao et al., 2020)
	Extraction methods of polyphenols from WB, with analysis of antioxidant activity and bioactive compounds for application in functional products.	(Huang et al., 2023)
	Extraction through steam explosion pretreatment to improve the efficiency of bioactive compound recovery from plant materials; enhancement of dough properties.	(Li, Huang, & Xi, 2024; Sui et al., 2018; Zheng et a., 2015)
	Use of modified WB to improve and delay staling in Chinese steamed bread.	(Li, Li, et al., 2024; Li, Wu, et al., 2024; Zhang, Jia, et al., 2022)
	Fermentation of WB improves its nutritional properties, adding value to this by-product.	(Li & Liu, 2022; Li et al., 2022; Sahin et al., 2021; Verni et al., 2019; Zhang, Zhou, et al., 2022)
	Co-fermentation of WB with *Lactobacillus plantarum* and yeasts is an efficient approach to enhance whole wheat products.	(Li, Sun, et al., 2023)
	Antioxidant properties of polysaccharides extracted from WB, suggesting their strategic use in the formulation of health-oriented products.	(Shang et al., 2021; Zhang et al., 2019)
	Superfine milling enhances the extraction, digestibility, and functional activity of WB proteins, expanding their potential as a nutritional and multifunctional ingredient.	(Li et al., 2017; Li, et al., 2024)
	Alkaline extraction may be an effective strategy to increase β-glucan content, release arabinoxylans, and enhance the prebiotic potential of WB.	(Paesani et al., 2024)
	Investigation of the co-generation of hydrolytic enzymes in a biorefinery plant for citric acid fermentation, using white grape pomace and WB bleaching residues as raw material sources.	(Papadaki et al., 2020)

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Table 1. Wheat bran and its applications.

WB uses	Main facts reported	References
Food	Investigation of the use of a mixture of Caatinga passion fruit waste and WB as substrate for pectinase enzyme production by *Aspergillus niger*, with application in grape juice clarification.	(Patrício et al., 2024)
	WB albumin isolate obtained by extraction and ultrasonication was used to fortify bread, enhancing its protein content, volume, and overall quality.	(Uttam et al., 2023)
	Dual enzymatic treatment of WB enhances protein and polysaccharide recovery, improving antioxidant activity and gut fermentation.	(Zhuang et al., 2024)
Animal nutrition	Reduced-size WB combined with endoxylanases improves arabinoxylan fermentation in the chicken gut, promoting metabolic benefits.	(Bautil et al., 2023)
	Use of polysaccharides from fermented WB as a dietary supplement for fish.	(Chen et al., 2022)
	Evaluation of fermented WB inclusion in pig diets aimed at improving growth performance.	(He et al., 2023; Xu et al., 2023; Zhang, Liu, et al., 2023)
	Impact of XGP enzyme on improving the digestibility of WB-based diets and enhancing broiler performance.	(Idan et al., 2023)
	Implementation of WB in cow diets to improve productive performance.	(Jiang et al, 2021; Mpairwe et al., 2003)
	Investigation of the effects of wheat bran fiber on growth performance and intestinal epithelial functions in Xiangcun pigs.	(Liu et al., 2023)
	Effects of WB fermentation by *Saccharomyces cerevisiae* on tilapia performance, focusing on growth, feed utilization, and blood parameters.	(Mohammady et al., 2023)
Other applications	Acid pretreatment of WB for the production of ethanol, lactic acid, and inulinase via microbial processes.	(Germec et al., 2019)
	Mycelium-based biocomposite as a potential innovative application of WB.	(Sisti et al., 2021)
	Use of hydrothermally carbonized WB as a tanning agent in leather processing.	(Gong et al., 2023)
	Trends in the use of WB in industrial compounds, highlighting biotechnological applications, enzyme production, and organic acid synthesis.	(Katileviciute et al, 2019)
	Production of acetic acid from WB through the action of a recombinant enzyme, acetylxylan esterase, using p-nitrophenyl butyrate and p-nitrophenyl acetate as substrates.	(Aluthge et al., 2025; Li, Tang, et al., 2024)
	Use of WB as a natural fiber for bio-based composites after chemical modification with sodium hydroxide, aiming to improve its functional properties in polymer matrices such as polypropylene and polylactic acid.	(Rahman et al., 2021)
	The study provides a strategic foundation for optimizing the industrial bioengineering of essential amino acids, expanding commercial and industrial applications.	(Li et al., 2017)
	WB-based insulation boards with water or banana pulp binders show competitive thermomechanical performance and low emissions.	(Sisti, et al., 2021)
	WB enables low-emission thermal boards with natural binders and biomass-comparable performance.	(Di Canto et al., 2023)
	WB-derived CNCs offer biocompatible reinforcement for nanocomposites, with strong adsorption and retention properties.	(Xiao et al., 2019)
	WB and other residues can partially replace wood in biofuel pellets, enhancing sustainability and reducing emissions.	(Kamperidou et al., 2017)

WB: wheat bran; CPFW: Caatinga passion fruit waste; XGP: multi-enzyme premix, xylanase, glucanase, and phytase; CNC: cellulose nanocrystals.

an innovative research avenue, offering potential for the development of economically viable and environmentally sustainable production methods (Hadidi et al., 2024).

According to Uttam et al. (2023), WB has a substantial protein content of approximately 160 g/kg, and these proteins can be isolated to enhance their applicability as a sustainable and nutritionally improved ingredient in human nutrition. The extraction and fractionation of these proteins not only add value to WB but also enable the production of an ingredient with superior functional and technological properties compared to the use of whole bran. Moreover, the presence of bioactive peptides in the protein fraction of WB has garnered increasing interest due to their potential in promoting health. These compounds exhibit bioactive properties such as antioxidant, antimicrobial, and antihypertensive activities, making them highly relevant for the development of novel food and nutraceutical products with additional functional benefits.

From a technological perspective, the inclusion of WB negatively affects the final quality of breadcrumbs. This detrimental effect is associated with the interaction of bran with the gluten network, leading to a reduction in its strength and a decrease in the dough's gas retention capacity. In addition to diluting the gluten content in the dough, the addition of WB introduces an irregular granular structure that disrupts the formation of the gluten network, rendering it weaker and consequently affecting the texture and flavor of the final product (Cai et al., 2014; Sui et al., 2018; Yan et al., 2022). To improve the quality of whole wheat bread, an in-depth understanding of the physicochemical properties of WB and its role in the development of desirable dough characteristics is essential.

Recent studies indicate that WB derived from different genetic origins can influence the baking properties of food products. In a study comparing 12 U.S. wheat varieties and six Korean wheat varieties, it was observed that soft and club WB from the U.S., with lower insoluble dietary fiber and phytate contents, resulted in superior mixing properties for whole wheat dough and produced higher bread volume compared to U.S. hard WB (Cai et al., 2014). These findings highlight the importance of selecting specific types of WB based on their unique characteristics, such as fiber and phytate composition, to enhance the quality of whole wheat bread.

3.2 Animal nutrition

WB is widely recognized as an alternative and underutilized feed resource with significant potential, particularly in animal supplementation. Its application can lead to substantial cost reductions, while also providing relevant nutritional benefits, thereby contributing to the diversification of feed sources in animal production (Aluthge et al., 2025; Desai et al., 2016).

Furthermore, WB plays a significant role in modulating the intestinal environment. It promotes the regulation of microbiota, favoring the balance between beneficial and pathogenic microorganisms, and stimulates the production of intestinal mucosa, thereby strengthening the gastrointestinal tract's defense barrier and reducing sensitivity to pathogenic agents (Xu et al., 2023).

Moreover, WB can positively influence metabolic and digestive parameters. Among its effects, its role in appetite regulation and the improvement of glycemic and lipid responses stands out, both of which are essential for maintaining metabolic homeostasis. Its action in limiting the reabsorption of bile salts contributes to the regulation of plasma cholesterol levels, while the optimization of nutrient digestion and absorption enhances the utilization of other dietary components, resulting in improved productive performance in animals (Han et al., 2023).

Mohammady et al. (2023) investigated the fermentation of WB using the yeast *Saccharomyces cerevisiae* and observed a significant reduction in fiber content because of this process. This modification in the composition of WB renders it suitable for inclusion at levels of up to 20% in the diet of tilapia, enhancing nutrient digestibility and bioavailability. Consequently, fish receiving the supplemented diet exhibited improved growth performance, as evidenced by optimized blood indices and enhanced intestinal and hepatic architecture. These findings suggest that fermentation can mitigate the negative effects of excess fiber on nutrient absorption.

In complementary studies, Chen et al. (2022) demonstrated that supplementation with fermented WB has a positive effect on the intestinal health of zebrafish. The results indicated favorable regulation of the transcription of genes related to antioxidant defense in the intestine, which may contribute to increased resistance to oxidative stress. Furthermore, this approach has the potential to enhance the diversity and abundance of beneficial microorganisms in the intestinal microbiota, promoting a more balanced and healthier gastrointestinal environment. These findings reinforce the applicability of fermented WB as a functional ingredient in fish diets, with significant implications for performance and health in aquaculture systems.

Zhang, Liu, et al. (2023) demonstrated that the inclusion of finely ground WB in sow diets reduced the passage rate of food, potentially improving nutrient digestion and absorption. Supplementation with WB was linked to increased abundance of beneficial microorganisms in the gastrointestinal tract, as well as elevated concentrations of peptide YY and short-chain fatty acids, which are essential for metabolic regulation and intestinal mucosal integrity. Additionally, the results indicated positive effects on satiety and gut microbial composition, suggesting a potential impact on digestive efficiency and overall animal health.

Xu et al. (2023) observed that the inclusion of 35.3% WB in the diet of pregnant sows resulted in satisfactory performance, likely due to improved digestibility and a balanced supply of essential nutrients. Similarly, the addition of fermented WB in pig diets enhanced the anti-inflammatory state and antioxidant activity and promoted increased production of beneficial microbial metabolites, while improving feed digestibility (Feng et al., 2023; He et al., 2023; Liu et al., 2023). These findings underscore the potential of both raw and fermented WB as a strategic functional component in animal diets, contributing to the optimization of intestinal health and productive performance.

According to experiments conducted by Idan et al. (2023), the progressive inclusion of WB in broiler diets showed a linear positive effect on high-density lipoprotein (HDL) cholesterol levels. This finding suggests a favorable modulation of the lipid profile in the birds, indicating a potential improvement in metabolic parameters and, consequently, cardiovascular health. The significance of this effect can be attributed to WB's ability to interact with enzymatic and metabolic mechanisms in supplemented diets, resulting in a positive response in lipid transport and homeostasis.

Studies have indicated that the optimal inclusion of WB in poultry diets is approximately 4%, when combined with multienzyme supplementation, thereby achieving maximum broiler performance. This finding underscores the importance of establishing optimized supplementation levels to balance nutritional benefits with metabolic and physiological aspects. Concurrently, ongoing efforts to supplement feed with WB, as highlighted by Bautil et al., 2023, emphasize the growing interest in exploring this alternative feed resource to enhance efficiency and sustainability in poultry production.

The substitution of soybean meal with WB in the diet of Dutch cows led to significant changes in the ruminal bacterial community composition, as demonstrated by Jiang et al., 2021. Those changes resulted in improved nutrient digestibility, likely due to enhanced fermentative processes that optimize the conversion of feed substrates into energy. Consequently, the animals exhibited better lactation performance, reflecting more efficient utilization of available dietary nutrients.

Positive responses to WB supplementation have also been observed in dairy cows in Africa, with evidence indicating an increase in milk production (Mpairwe et al., 2003). This productive response can be attributed to both the nutritional benefits of WB and its ability to modulate the ruminal microbiota, promoting metabolic conditions that enhance energy efficiency and, consequently, lactational productivity. These findings highlight the potential of WB as a strategic component in cattle diet formulations, contributing to overall improvements in productive performance and animal health.

3.3 Bioproducts

WB stands out as a promising substrate to produce various industrially relevant bioproducts, including biofuels, organic acids, enzymes, antibiotics, and other value-added secondary metabolites. Its composition, rich in fibers, proteins, and complex carbohydrates, supports the growth of various microorganisms, which utilize it as a carbon and nitrogen source for the biosynthesis of bioactive compounds. Additionally, its large-scale availability as a by-product of the milling industry makes it an economically viable and environmentally sustainable alternative for biotechnological processes (Katileviciute et al., 2019).

WB is an abundant source of structural polymers, such as lignin, cellulose, and hemicellulose, making it a complex carbon substrate highly suitable for the proliferation of microorganisms capable of producing a wide range of hydrolytic enzymes. Notably, these include hemicellulases, cellulases, proteases, pectinases, amylases, and xylanases, which are essential for the degradation of plant components and the conversion of biomass into high-value biotechnological compounds. Recent studies suggest that combining WB with agro-industrial residues, such as those from passion fruit, contributes to a favorable nutritional balance for the development of fungi like *Aspergillus niger*, promoting greater efficiency in the production of pectinase, an enzyme of significant interest for the food and pharmaceutical sectors (Patrício et al., 2024).

In the study conducted by Katileviciute et al. (2019), *Bacillus megatherium* demonstrated the ability to synthesize xylanases, pectinases, and amylases, as well as to promote the release of total soluble carbohydrates and reducing sugars during the fermentation process. For the investigation, samples consisting of WB, grasses, and palm leaves were subjected to solid-state fermentation, allowing the evaluation of each substrate's efficiency in inducing enzymatic production. Among the agricultural residues tested, WB exhibited the most significant performance, resulting in the highest enzymatic synthesis. This effect was attributed to its balanced chemical composition, rich in structural carbohydrates and essential nutrients, eliminating the need for supplementation with additional carbon and nitrogen sources, thus reinforcing its potential as a preferred substrate for biotechnological processes.

In the study conducted by Li, Tang, et al. (2024), the conversion of WB into acetic acid was demonstrated through the action of the esterase enzyme produced by *Sphingobacterium solosilvae* Em02. This enzyme exhibits a remarkable capacity for lignocellulosic biomass degradation, acting on natural substrates rich in lignin and cellulose and promoting the synthesis of high-value chemical compounds. The methodology employed involved an enzymatic pretreatment of WB biomass, followed by catalysis mediated by acetyl xylanol esterase, offering a novel approach for the decomposition of lignocellulosic biomass.

Various modification techniques have been extensively explored to enhance the release of soluble dietary fiber from WB, as well as to improve its nutritional functionality and adaptability to industrial processes. Among these strategies, solid-state fermentation has gained increasing attention from the scientific community due to its potential to optimize the nutritional and technological properties of this agro-industrial by-product (Katileviciute et al., 2019; Li & Liu, 2022; Li, Wang, et al., 2022; Patrício et al., 2024).

Solid-state fermentation is an alternative established biotechnological technology that allows the conversion of agricultural residues and lignocellulosic substrates into a wide range of bioproducts of industrial interest, including biosurfactants, pigments, biofertilizers, and organic acids. In this context, microorganisms such as yeasts and lactic acid bacteria play a crucial role in the degradation of the cellular structures of WB, resulting in increased bioavailability of soluble fibers, phenolic compounds, vitamins, and minerals. Moreover, the fermentation process induces significant sensory modifications, generating characteristic aromas derived from the partial degradation of the aleurone cell walls and the proteins present in WB (Li & Liu, 2022; Li, Wang, et al., 2022; Verni et al., 2019).

Fermentation of WB with *Rhizopus oryzae* at 50% moisture resulted in a significant increase in fiber content, from 1.89 to 8.5%. This process induces structural modifications in the lignocellulosic matrix, making bioactive compounds more accessible. Similarly, fermentation with *A. niger* led to the release of phenolic acids previously bound to the WB matrix, enhancing their anti-inflammatory properties and antioxidant capacity compared to freely available FA. These findings emphasize the role of filamentous fungi in the biotransformation of WB, aiming to develop functional ingredients and enhance health benefits (Li & Liu, 2022; Li, Li, et al., 2024; Li, Wang, et al., 2022).

Zhang, Zhou, et al. (2022) demonstrated that solid-state fermentation using *Aspergillus oryzae*, *R. oryzae*, and *A. niger* effectively increased the yield of bioactive components such as FA and pentosans. These metabolites play a crucial role in enhancing the antioxidant and prebiotic properties of WB. Thus, the application of filamentous fungi not only enhances the bioactivity of WB but also promotes a more efficient utilization of agro-industrial waste, adding value to agricultural by-products and supporting their incorporation into food and nutraceutical formulations.

Verni et al. (2019) also reported that traditional fermentation processes, conducted by a stable microbiota composed of lactic acid bacteria and yeasts, resulted in a significant increase of up to 30% in the soluble dietary fiber fraction, along with the synthesis of bioactive compounds. These structural and chemical modifications not only enhance the nutritional value of WB but also facilitate its incorporation into food formulations, particularly in bakery products, improving both the nutritional profile and functionality of the foods.

In the study conducted by Li and Liu (2022) and Li, Wang, et al. (2022), co-fermentation technology using *Lactobacillus* *plantarum* LB-1 and yeasts was employed to optimize the release of FA in whole wheat flour, aiming to enhance the rheological properties of the dough. The results indicated that the amount of FA released through co-fermentation was significantly higher than that obtained with conventional yeast fermentation. This effect was attributed to the increased production of hydrolytic enzymes responsible for degrading the cell wall, as well as the generation of organic acids that positively influence the dough characteristics. Thus, co-fermentation emerges as a promising approach for valorizing wheat by-products, contributing to the development of functional ingredients and the improvement of the technological quality of baked goods.

Sahin et al. (2021) investigated the enhancement of WB and oat bran properties through controlled fermentation with *Leuconostoc citreum* TR116. The study examined changes in sugar and acid profiles, pH, and total titratable acidity during fermentation, as well as the impact of fermented bran on dough and biscuit properties. The results showed significant improvements in biscuit quality, including increased crispness and reduced glycemic index and maintained sensory quality compared to the control formulation.

The research also assessed the impact of fermented bran on *in vitro* starch digestibility, highlighting the potential of this approach to modulate the glycemic response of the final products. Fermentation further enhanced the sensory attributes of the brans, making them more suitable for food applications. These findings underscore the importance of microbial fermentation as a strategy to improve the nutritional and functional properties of WB and oat bran, enabling their incorporation into healthier and more technically viable formulations.

3.4 Other applications

In addition to improving nutritional and sensory attributes, the application of WB and fermented WB aligns with broader sustainability goals. These advancements can be contextualized within the framework of the circular economy, which offers a systemic alternative to the traditional linear model by promoting resource optimization through reuse, recovery, and recycling. By valorizing wheat-derived by-products, such as WB, through strategies like fermentation, it is possible to reduce waste, enhance product functionality, and contribute to more sustainable food systems, thereby addressing key social, economic, and environmental challenges (Aluthge et al., 2025; Sisti et al., 2021).

In this context, WB attracts attention as a promising source to produce biofuels and as a raw material in the manufacturing of biodegradable packaging, contributing to environmentally sustainable solutions (Gong et al., 2023).

Gong et al. (2023) demonstrated that WB can also serve as an efficient precursor to produce carbon-based materials, expanding its potential applications in industry. The study highlighted its potential as a source of leather tanning agents, providing a sustainable alternative to conventional methods. The results indicated that the carbon materials derived from WB are both effective and environmentally viable, reinforcing its role in promoting more sustainable industrial processes aligned with the principles of the circular economy.

The construction sector plays a central role in global climate change, as it consumes large amounts of energy and significantly contributes to greenhouse gas emissions. In this context, the search for sustainable solutions and the reduction of the carbon footprint in the sector has never been more urgent. Among the promising alternatives, the development of technologies based on sustainable thermal insulation materials, such as those derived from WB, stands out (Di Canto et al., 2023).

WB has emerged as a promising alternative in the production of mycelium-based materials, combining sustainability with performance. In the study by Sisti et al. (2021), WB was investigated as a raw material for biological and biodegradable composites, highlighting benefits such as reduced production time and improved mechanical properties. The research, grounded in the concepts of biorefinery and circular economy, identified three key strategies for utilizing WB: extraction of valuable components (hemicellulose, proteins, and polyphenols, among others), use as a filler or reinforcement in bio composites, and, innovatively, the development of materials composed of mycelium and WB. This approach demonstrated that WB serves as an efficient nutrient source, accelerating mycelium growth and resulting in homogeneous, hydrophobic materials with favorable mechanical properties and biodegradability.

Papadaki et al. (2020) explored the potential of enzyme cogeneration in biorefineries during citric acid fermentation, using second-generation feedstocks derived from agro-industrial lignocellulosic wastes, specifically red grape pomace and WB. Their findings revealed the production of multiple enzymes with notable activity levels, suggesting that enzyme production could play a key role in ensuring the economic viability of biorefinery operations.

The increasing demand for renewable and environmentally sustainable materials has stimulated the search for alternatives to synthetic polymers used in food packaging, given their significant environmental impact. In this regard, WB presents itself as a viable option for incorporation into chitosan-based edible films, offering additional functional properties. Studies have demonstrated that AXs extracted from WB through various methods can be integrated into chitosan biofilms. The extraction method directly influences the presence of polyphenols bound to the AXs and the degradation of these polysaccharides into arabino-xylan-oligosaccharides (AXOs), compounds with recognized prebiotic activity. The resulting biofilms exhibited favorable mechanical properties and functional enhancements, such as increased dietary fiber content and prebiotic activity, complementing the inherent characteristics of chitosan. These findings underscore the potential of WB as a raw material for the development of advanced biomaterials with improved technological and functional properties, promoting sustainable alternatives in the food packaging industry (Costa et al., 2015).

WB, in its commercial form, has a bulk density ranging from 0.35 t/m^3 to 0.40 t/m^3, consisting of milling fractions that may contain fines and impurities (Lopes et al., 2022). This low density poses challenges for bulk storage and transportation in the milling industry, requiring solutions to optimize logistics. Among the strategies employed, pelleting stands out as a widely used practice in various countries, offering advantages such as volume reduction, increased storage capacity, improved flowability, and reduced logistical costs. Furthermore, this process allows the incorporation of solid or liquid ingredients for the nutritional enrichment of animal feed. Pelleting can be performed both hot and cold, and regardless of the method used, the main advantage is the increased material density, which reaches approximately 0.67 t/m^3 after processing (Pfost, 1962).

Pedrazzi et al. (2018) investigated the use of WB pellets as fuel for boilers and furnaces, comparing their performance to wood pellets. The results showed a slight reduction in thermal efficiency for WB pellets (33.5%) compared to wood pellets (39.4%), though the performance remained comparable. In addition to their energy potential, the combustion of WB pellets produced ash with high levels of phosphorus (P) and potassium (K), highlighting their potential as a source for fertilizer production. Economically, WB pellets proved to be more profitable and less susceptible to price fluctuations than their bulk form, making them a viable alternative from both an energy and commercial perspective.

Kamperidou et al. (2017) conducted a study in Greece to evaluate the calorific value of wood pellets in comparison to agricultural residues, aiming to explore viable alternatives for partially replacing wood as fuel. The results showed that wood pellets have a calorific value of 4,589.9 kcal/kg, while WB and wheat straw pellets have values of 3,632.9 kcal/kg and 4,373.8 kcal/kg, respectively. Although agricultural residues exhibit slightly lower calorific values than wood, their use is promising due to lower commercial costs and the potential for reducing pollutant emissions, highlighting their viability as a sustainable energy alternative.

The increasing demand for sustainable technologies and the adoption of the circular economy concept have driven the utilization of agro-industrial by-products in new applications. WB, a low-value by-product, stands out as a promising source for nanocellulose production (Xiao et al., 2019). In that study, cellulose nanocrystals (CNCs) were extracted from WB through sulfuric acid hydrolysis. Characterization of WB revealed 31.1% cellulose, 34.3% hemicellulose, and 16.3% lignin, indicating its potential as a raw material for nanocellulose production. The authors concluded that CNCs derived from WB exhibited suitable structural and functional properties for use as reinforcing agents in renewable nanocomposites.

Cellulose, the most abundant structural biopolymer in the biosphere, consists of anhydro glucose units (AGUs) linked by β-1,4 glycosidic bonds (Xiao et al., 2019). It is a renewable, non-toxic, biocompatible, and sustainable polymer with applications across various industrial sectors, including biodegradable packaging and coatings (Xiao et al., 2020). Additionally, as a non-digestible polysaccharide in the human body, cellulose passes through the digestive system without adverse effects, making it widely used in food products and functional biomaterials.

CNCs are rod-shaped nanoparticles with lengths ranging from hundreds of nanometers and diameters between 10 and 30 nm. Acid hydrolysis is commonly used in their production, as it selectively removes the amorphous regions of cellulose while preserving the highly organized crystalline domains. CNCs exhibit exceptional properties, such as high crystallinity, large specific surface area, and a chemical structure rich in active hydroxyl groups. These characteristics result in low density and high mechanical strength, making CNCs innovative materials with significant potential for industrial applications (Rahman et al., 2021; Xiao et al., 2019).

The composition of WB, predominantly lignocellulosic, provides structural advantages to the biomaterial due to its microfibrous organization and lower cost compared to traditional cellulose sources like wood. Recent studies explore the use of WB fibers in applications such as starch-based edible films and foams, as well as bio composites reinforced with natural rubber. Pretreatment of lignocellulosic residues to remove impurities and increase the available cellulose fraction has shown significant improvements in the mechanical properties of bio composites. Alkaline treatments using NaOH have been investigated to optimize the compatibility of WB cellulose in bio composite formulations, resulting in enhanced mechanical strength of the produced materials (Huda et al., 2008; Rahman et al., 2021).

4 SAFETY FOR HUMAN AND ANIMAL CONSUMPTION: DEOXYNIVALENOL ANDZEARALENONE IN WHEAT BRAN

El-Sayed et al. (2022) emphasize the risks associated with mycotoxins, toxic substances produced during fungal metabolism by genera such as *Aspergillus*, *Fusarium*, and *Penicillium*. The severity of those mycotoxins depends on factors such as the amount ingested, exposure duration, and the affected animal's age, sex, and health. In the wheat milling industry, deoxynivalenol and zearalenone (ZEN) are the most prevalent and concerning mycotoxins. While wheat processing can reduce contamination, it is important to note that during grain cleaning, mycotoxin concentrations decrease in the cleaned grain but accumulate significantly in the cleaning by-products (Edwards et al., 2018; Hemery et al., 2010; Liu et al., 2020; Mishra et al., 2020).

Alexandre et al. (2018) describe DON, also known as vomitoxin, as primarily causing weight loss, digestive disturbances, feed refusal, and vomiting, with swine being particularly sensitive to its toxicity compared to birds and ruminants. Gott et al. (2019) investigated the presence of various toxins, including DON and ZEN, in wheat milling by-products used in feed production. Their study found that 91.8% of the samples were contaminated, with 89.7% containing DON (average level of 1,875 ppb) and ZEN exceeding regulatory limits in several countries (average level of 106.7 ppb).

Irakli et al. (2017) reported that while the outer layers of wheat kernels provide nutritional benefits, they are highly susceptible to mycotoxin contamination. The researchers analyzed 34 wheat samples from various warehouses in Greece, including 16 samples of *Triticum aestivum* and 18 of *Triticum durum*. Using the Mini Testing Husker (Taka Yama, MTH 35 A, Taiwan), they removed the outer bran layers through pearling to produce 1.5% bran from each sample. Their results showed that 25% of the bran samples were contaminated with DON levels exceeding the European Union's safety threshold of 750 µg/kg.

In a study conducted in Paraguay, including wheat kernels and foods containing WB, the highest DON level (11.8 ppm) was found in cream cracker cookies (Arrúa Alvarenga et al., 2018). The average DON level across 27 samples was 1.25 ppm, which is relatively high when compared to international legislation.

Tibola et al. (2019) showed that surface treatment of wheat kernels before milling effectively reduced mycotoxin contamination in whole flours. Their study analyzed 30 wheat samples from South Brazil, where grains underwent pearling with rice polishing equipment (Zaccaria, PAZ-1-DTA). Bran removal ranged from 4% to 15%, and the grains were then milled using a laboratory mill (Perten 3100). The highest contamination levels were found in untreated wheat, while pearled samples showed significant reductions in contamination by 25, 31, and 31% after 15, 30, and 60 s of grinding process, respectively.

According to Brazilian regulation issued by National Health Surveillance Agency (Brasil, 2017), the maximum allowable DON contamination in wheat is 1,250 µg/kg. Surface treatment effectively reduced DON levels to within permissible limits. The legislation also sets maximum allowable limits for other mycotoxins, such as ZEN (200 µg/kg). Globally, cereals contaminated by *Fusarium* species are associated with various toxic effects, including esophagitis, esophageal cancer, early puberty, cervical cancer, endometrial hyperplasia, and toxic leukemia.

Surface treatment (de-branning) of wheat kernels reduced DON contamination by 62% compared with the control sample. This method, which removes the outer layers of wheat kernels, appears promising for reducing mycotoxin contamination in both WB and whole wheat products, benefiting human and animal nutrition (Edwards et al., 2018; Gott et al., 2019; Mishra et al., 2020; Gozzi et al., 2024; Mankevičienė et al., 2014; Qi et al., 2022). This method, which removes the outer layers of wheat kernels, appears promising for reducing mycotoxin contamination in both WB and whole wheat products, benefiting human and animal nutrition (Edwards et al., 2018; Gott et al., 2019; Gozzi et al., 2024; Mankevičienė et al., 2014; Mishra et al., 2020; Qi et al., 2022).

Another study, which utilized wheat pearling in conjunction with a vertical rice whitener (SATAKE – VTA 10AB-L) within an industrial wheat mill (with a capacity of 10 t/h), showcased a reduction in DON levels that correlated with the increased removal of external layers (Lopes et al., 2022). The produced flour had reduced DON levels as well as improved color and enzymatic activity.

An additional risk to the quality of bran produced by commercial mills is that impurities removed during wheat cleaning are sometimes added to the bran. The analysis of 32 samples of wheat harvested in the years 2020 and 2021 showed intriguing results, with superior DON and ZEN contents in the impurities of the samples (mainly stem and straw) (Gozzi et al., 2024). In the case of DON, the levels found were superior to the established limits for several countries.

Alexandre et al. (2018) assessed the effectiveness of ozonation in reducing mycotoxins in WB, finding a greater reduction in ZEN (61%) compared to DON (32%) after 240 min of ozone exposure (62 mg/L). The study also evaluated the impact on WB's nutritional profile, including total phenolic content and antioxidant activity, and found no significant changes, highlighting ozonation as an effective and safe method for reducing mycotoxin contamination in WB.

Liu et al. (2020) demonstrated the benefits of ozonation for reducing microorganisms in WB under optimized conditions. WB was treated with ozone gas at 10 g/h for varying durations, with the best results achieved at 15% moisture content, 15 mesh particle size, and 50 min of treatment. Significant reductions in microbial counts, including molds, yeast, total plate count, and *Escherichia coli*, were observed compared to untreated samples, leading to improved shelf life of noodles produced with the treated bran over a 30-day period.

5 CLIMATE CHANGES AND OTHER FACTORS AFFECTING WHEAT CROP

Plant breeding has been underway for several decades, and wheat, alongside other cereals, stands as one of the primary crops to reap the rewards of such human endeavors. Within this cereal, aside from enhancing production yields, one notable outcome has been the significant increase in kernel size, estimated to have grown by approximately 40% between 1940 and 2000 (Mahato et al., 2014; Metcalfe et al., 2022), *viz.* the thousand kernel weight (TKW) jumping from 31.5 to 44.64 g (Wang et al., 2012). Kernel size impacts the overall quality of flour, and millers benefit from larger and more uniform kernels, which are highly desirable (Baasandorj et al., 2015; Ye et al., 2021).

Wheat breeding also considers protein concentration, which plays a significant role in the technological quality of wheat flour, in addition to its nutritional aspect (Asseng et al., 2019). While climate changes involving increased carbon dioxide levels may offer benefits to cereal crops, the simultaneous occurrence of other changes, such as higher temperatures and altered rainfall patterns, is likely to counteract these advantages. Lower protein levels may also emerge as a serious concern in the face of impending climate change.

Developing drought- and heat-resistant wheat varieties poses a significant challenge to wheat breeding researchers as they strive to adapt to climate change. As global food demand is anticipated to significantly increase over the coming decades (projected to rise by an estimated 70% between 2020 and 2050), enhancing productivity within the context of climate change presents a formidable challenge (Vitale et al., 2020).

It appears the decrease in wheat crop yield due to climate change, with warming temperatures and weather extremes, may be foreseeable (Tack et al., 2015). In addition to yield concerns, the quality of wheat may also be impacted by rising temperatures and shifts in rainfall patterns, exacerbating the significant threat of mycotoxin contamination (Ozturk & Aydin, 2004).

Environmental conditions and crop management significantly affect wheat cultivation, with diseases and contamination primarily occurring in the outer layers. Modern milling processes cannot effectively reduce contaminants, as they are more concentrated in the outer layers, bran, and impurities added by commercial mills. Despite advancements in genetics and management, wheat remains vulnerable to unfavorable climatic conditions, with seasonal variations and climate change impacting yield and quality. Studies highlight the role of irrigation and rainfall in plant development, affecting nutrient absorption, fertilization, and quality, particularly protein content and kernel weight (Lopes et al., 2022; Mahato et al., 2014; Ozturk & Aydin, 2004).

Rainfall during the pre-harvest period impacts the distribution of mycotoxins (DON and ZEA) in wheat milling fractions. Field experiments showed that repeated wetting and drying processes caused DON to move through the fractions, with high rainfall reducing DON levels in the grain, particularly in the bran, while increasing it in the endosperm. ZEA was less mobile and detected in fewer samples. The study emphasized the importance for the industry to monitor mycotoxin distribution to prevent contamination levels exceeding legal limits in final products (Baasandorj et al., 2015; Tack et al., 2015).

Ye et al. (2021) studied the impact of global warming on wheat crops over 17 years, finding that while warming is generally harmful, temperature increases in colder regions and high latitudes can benefit crop productivity. This warming positively impacted spring wheat yield in regions where temperatures were previously too low. The study suggested that increased temperatures, if not accompanied by water stress, could enhance productivity in specific areas. Additionally, Hemery et al. (2010) found that higher humidity increases the moisture content and plasticity of WB, while temperature rises strengthen the bran but reduce its elasticity. These findings highlight how climate factors affect both wheat crop productivity and bran properties.

6 FINAL CONSIDERATIONS AND PERSPECTIVES

Bran is the primary by-product of wheat milling, produced in significant quantities by the large-scale wheat flour industry. With its valuable nutritional profile––rich in fiber, starch, protein, minerals, and vitamins––WB holds potential for both animal and human nutrition. However, despite its abundance, it is commercially considered a low-value by-product, with its utilization rate remaining relatively low. Thus, ongoing research is essential to identify new and innovative processes and applications for this underutilized resource.

Key challenges include the storage and transportation of this low-density by-product, along with contamination from mycotoxins, glyphosate, and other pesticides. To address these issues, superficial abrasion treatments are applied to the grains, reducing external contamination. Bran produced from the initial pearling of wheat kernels demonstrates lower concentrations of these toxic and hazardous compounds, making it safer for consumption by both humans and animals.

Exploring new applications in bioprocess technology, materials science, and construction, among others, is vital for enhancing the value of this agro-industrial by-product and finding alternatives for non-feed uses. This is particularly important considering the increasing challenges posed by climate change, which is expected to exacerbate phytopathological issues and degrade the post-harvest quality of wheat. As a result, the food processing sector will likely face growing concerns over mycotoxin contamination and pesticide residues soon.

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