Refined Thinking: Wheat Processing for Food Safety and Nutritional Enhancement

A PLAN B RESEARCH PROJECT
SUBMITTED TO THE FACULTY OF THE UNIVERSITY OF MINNESOTA
BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

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August 2025

Acknowledgments

In light of finishing this paper, I would like to express my sincerest gratitude to my advisor, Dr. Joanne Slavin, who acted as an extremely knowledgeable guide and advocate during the completion of my Master's degree. Without Joanne's guidance, I may not have pursued a degree in Food Science, nor would I have had the same opportunities to foster my affinity for food, both academically and through practical experience. I am incredibly grateful for Joanne's flexibility and dedication to her students, as well as her commitment to the food science and nutrition fields. Her unwavering passion continues to inspire me while I begin my career in the food science field, where I feel that I have finally found my purpose. Thank you for being my mentor throughout this process and for your inspiring mindset and refreshing perspectives related to the food science field.

I would also like to acknowledge my committee members, Dr. Bill Atwell and Dr. Mitch Kanter, and communicate my sincerest appreciation for their willingness to support my academic growth through my research process. I am extremely grateful that Dr. Atwell and Dr. Kanter both agreed to help guide my research efforts; their diverse backgrounds helped to motivate my writing and evaluation of scientific resources. Thank you both for your support while finalizing my research and completing my degree.

A special thank you to my supervisors and mentors at General Mills, Angie Horstman and Sarah Meacham, as well as the other team members on the Betty Crocker team. Being able to work under Angie and Sarah was an extremely rewarding experience. They shared invaluable knowledge about working in the food industry and helped me understand the technical side of food product development and maintenance, along with the daily ins and outs of being a working professional. Their welcoming presence made me feel extremely comfortable at work and helped give me more confidence in projects and in applying the knowledge I learned throughout my studies. Their willingness to share their expertise and provide opportunities for hands-on experience made my experience at General Mills truly unforgettable and reinforced my love and joy in cooking, baking, and all things food.

Lastly, I would like to thank my parents, who offered so much encouragement and support throughout the completion of my degree. I could not have reached this milestone without their unwavering belief during some of the more challenging moments during the past few years. Their advice and guidance during moments of doubt and fatigue helped me maintain a healthy balance inside and outside of academia. I am so thankful to have two people who are constantly looking out for my best interests and motivate me to reach my full potential, purely to see me accomplish my goals and find fulfillment and true happiness in my career and personal life. They continually inspire me to be the best student, friend, colleague, and overall person that I can be. Thank you for always believing in me, Mom and Dad, I love you!

I cannot express enough my gratitude to everyone who has helped me throughout this process. I feel incredibly fortunate to have been given this opportunity and to have received all the support that I have received. Thank you!

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Abstract

Wheat processing is an essential practice that ensures that wheat, one of the most widely used ingredients in our food system, is safe to consume and remains a dependable energy source for our growing population. Processing procedures are critical, not only for ensuring the safety and reliability of wheat as an energy source, but also for enhancing its nutritional benefits via increased digestibility and the removal of harmful contaminants and pathogens. Whole grains, and in the case of this review, whole wheat, are often considered superior food ingredients when compared to refined grains due in part to their implicitly acknowledged "unprocessed" nature. However, the contrary is true: these substances can often exhibit a lower nutritive value and reduced digestibility, requiring a higher degree of processing to meet standards for human consumption. Given the growing spread of information promoting the perceived superiority of 'unprocessed' and natural foods, there is a corresponding need to provide the public with accurate, evidence-based information—particularly regarding the processing involved in all wheat products, whether whole or refined. This review examines the physical and nutritional composition of the wheat kernel, the NOVA classification of refined flour and its derivative food products, and the implications of wheat processing. Special attention is given to how processing addresses naturally occurring antinutritional factors and fungal pathogens in unprocessed wheat, while also enhancing the bioavailability of essential micronutrients to help reduce micronutrient deficiencies.

Introduction

Since the beginning of the twentieth century, there have been significant advances in the development and security of our food processing techniques, many of which have greatly contributed to the safety and reliability of the most widely used ingredients across the food industry today, particularly so in the case of wheat ingredients. For thousands of years, wheat derivatives have played a crucial role in the evolution of our food system, with the agricultural cultivation and processing methods of wheat crops deeply ingrained in various cultural traditions, cuisines, and socioeconomic systems (de Sousa et al., 2021). Common, or bread, wheat and Durum wheat, *Triticum aestivum* and *Triticum durum,* respectively, are both descendants of the ancient cultivated hulled Emmer wheat (*T. turgidum* spp*. dicoccum*), and are the two most widely used species of wheat, with 95% of wheat grown today being Bread wheat and the following 5% being Durum wheat (Vergauwen & Smet, 2017). While cultivated Emmer wheat, which is tetraploid, was crossed with *Aegilops tauschii* to produce hexaploid Common wheat, Durum wheat still maintains the same ploidy as Emmer wheat since they share a more direct lineage (Vergauwen & Smet, 2017). This system of plant breeding via allopolyploidization and subsequent cultivar development helped to greatly increase the desirable economically driven traits of this plant type, such as yield and increased milling capacity, while simultaneously leaving the crop susceptible to both abiotic and biotic stressors and partially deflating its nutritional quality (de Sousa et al., 2021). In light of these subtle changes to ancient wheat's nutrient profile and physiological resilience, an increased need for processing procedures came about, shaping the trajectory of wheat's cultivation further and thus creating an interdependence between the processing requirements of wheat and its agricultural growing methods. For this reason, processing is a crucial requirement for ensuring that wheat, whether whole or refined, is adequately integrated into the human diet. Therefore, understanding the evolution of wheat processing is essential not only for optimizing its use in the human diet but also for ensuring its safety, enhancing its nutritional value, and mitigating potential risks associated with modern cultivation practices.

Section 1. Wheat Kernel Physical and Nutritional Composition

To comprehend why wheat must undergo a certain degree of processing to be deemed suitable for human consumption, it is important to first examine the physical structure of the wheat plant, with particular attention to the wheat kernel. Common wheat (*Triticum aestivum*) is a member of the Poaceae family, commonly known as the grass family. It produces a type of fruit called a caryopsis (Iqbal et al., 2022; Shewry et al., 2009). This fruit is typical of cereals and features a pericarp, which is the ripened ovary, that is fused with the seed coat (Shewry et al., 2009). As a result, the separation of these parts is not possible without specialized extraction techniques. In the case of wheat, this process is known as milling (Dziki & Laskowski, 2005). The caryopsis, or wheat kernel, is encased in an inedible hull or husk, which forms a spikelet; these spikelets are then attached to a rachis, collectively creating the wheat spike. During the harvest, the majority of the collected material comprises the wheat spikes, while the stalks are typically left behind. The kernels within the spikes are then gathered for subsequent processing (Shewry et al., 2009).

A common wheat kernel contains three main components: the endosperm, bran, and germ. The endosperm totals about 83% of the kernel's weight and contains the majority of the carbohydrate and protein, since this is the area of the seed where all the nutrients are stored for if the seed is dispersed and grown as a new plant (Dziki & Laskowski, 2005; Iqbal et al., 2022). The endosperm is also the part of the wheat kernel that is processed to make refined flour, a constituent ingredient in many popular baked goods and snack foods today, in addition to determining the majority of the physical properties associated with flour (Dziki & Laskowski, 2005). The bran is the outer component of the wheat kernel and contains the majority of soluble and insoluble dietary fiber within the seed; it is composed of two main series of layers, the three outermost layers being the outer pericarp, and the three innermost layers of the bran being the inner pericarp (Šramková et al., 2009). These two components, plus the Aleurone layer, a thin layer of living protoplast cells surrounding the endosperm, are all removed as part of the milling process to expose the starchy endosperm for the production of refined flour (Balandrán-Quintana et al., 2015). This part of the kernel also holds a plethora of vitamins and minerals, possessing high levels of phosphorus, iron, zinc, and many B vitamins (niacin, Vitamin B6, with lower levels of thiamine and riboflavin), while simultaneously containing phytates and other antinutritional factors alongside high levels of fiber, which can cause digestive issues for some (Balandrán-Quintana et al., 2015).

The bran layer makes up 14.5% of the wheat kernel, leaving only 2.5% of the wheat kernel mass dedicated to the wheat germ (Iqbal et al., 2022). The wheat germ is the seed's embryo, meaning it contains a variety of nutrients, including lots of dietary fiber, vitamin E, and minerals (comparatively speaking), as well as proteins (25% of proteins in the kernel) and lipids (11% of lipids in the kernel) (Šramková et al., 2009). This portion of the wheat kernel is removed from the starchy endosperm after the bran layer is removed from the kernel during milling (Iqbal et al., 2022). While there are benefits to consuming all three main components within the wheat kernel compared to that of refined wheat, processing is still a crucial step to remove the inedible husk and any accessory parts that are still intact from the harvesting process.

In terms of a wheat kernel's overall nutritional composition, wheat contains approximately 1-2% lipids, 4% ash, 8-15% protein, 10-15% moisture, and 60-70% starch. Both wheat starch and wheat protein can be broken up into different components. Wheat starch is composed of 20-30% amylose and 70-80% amylopectin (Iqbal et al., 2022). Wheat protein contains three components; gluten, albumin, and globulin. Gluten, the primary storage protein in wheat, composes of 85% to 90%, and albumin and globulin compose the other 10-15% (Biesiekierski, 2017). Albumin proteins contribute partially to the antinutritional factors found within the wheat kernel, since they are the basis for Amylase-trypsin inhibitors (ATIs), which will be discussed in a later section (Biesiekierski, 2017). The protein content in wheat changes based on the cultivar being grown, with soft wheat containing 7-10.5% protein/ kernel and hard wheat containing closer to 10-13% protein/ kernel (Shevkani et al., 2024).

Wheat is not considered a complete protein due to its low lysine content, which limits its overall protein quality. According to the Digestible Indispensable Amino Acid Score (DIAAS), a system used to evaluate protein quality based on the digestibility of essential amino acids, wheat generally scores below 75, with some studies even reporting an average DIAAS of 56 (Herreman et al., 2020; Oh et al., 2025). This places wheat below the threshold set by FAO guidelines for a food to be considered a well-rounded, complete protein source. In contrast, other plant-based proteins, such as soy protein isolate, achieve higher scores, averaging around 74, while most animal-based proteins score well above 100, indicating higher digestibility and a more complete amino acid profile (Herreman et al., 2020; Oh et al., 2025). These comparisons highlight the limitations of wheat as a standalone protein source, particularly in diets lacking complementary proteins. So, considering wheat's importance as a food source in both developed and developing countries, it's essential to adopt a comprehensive perspective on wheat processing, particularly in relation to its naturally occurring antinutrients and its dual role as a key source of carbohydrates and protein.

Section 2. NOVA Ranking of Wheat Derivatives

Food processing encompasses a wide spectrum, with processing techniques that range from simpler modes of action, such as heating or soaking, to more intensive modes of action, such as extrusion or hydrogenation, which have grown in popularity within the modern diet. Most average consumers do not realize that the products they believe to be whole foods, including many wheat products, have some level of processing to make them digestible for the human body. In order to accurately evaluate the degree of processing that is required to integrate wheat-based ingredients into widely consumed food products, it is essential to consider the NOVA classification system.

In more recent years, the NOVA scale, a food classification system implemented to assess foods based on their level of processing, has been adopted to quantify the health value of a given food product or ingredient based on its processing level. The rating system of the NOVA scale has four categories: group 1 being unprocessed/ minimally processed foods, group 2 being culinarily processed foods, group 3 being processed foods, and group 4 being ultra-processed foods (Barrett et al., 2023). While this scale can be a convenient tool to identify which foods are more or less processed, it has villainized processed foods by linking them to increased caloric density, reduced nutritive value, and overall food quality (Petrus et al., 2021). Ironically enough, many food ingredients that are considered “unprocessed” or raw by average consumers are processed in some way to increase their safety and digestibility, in addition to some aspect of their nutritional value, or improve their shelf life or sensory attributes (Barrett et al., 2023). These products, of course, and labelled as processed by the NOVA classification system, hence diminishing their health value due to their processing requirements. Many products that fall into this category are whole-grain products, like oatmeal, whole-wheat bread, and breakfast cereals.

While the NOVA scale does accurately identify which foods available on the market are unprocessed or processed, it does create confusion in both consumers and dietitians alike, since the system naturally aligns processed and ultra-processed foods with minimal dietary value. This is illustrated in the study by Krois et al. (2022), which highlights a significant discrepancy between the whole-grain foods recommended to patients by dietitians and those that should be avoided based on their classification in the NOVA scale. Out of 124 dietitians, only 10 were able to accurately identify wholemeal bread, a food that is widely recognized as whole and minimally processed, as an ultra-processed food, demonstrating the ambiguity faced by professionals and consumers when interpreting the extent of processing that a food product goes through to be safe for consumers (Krois et al., 2022).

This study addresses the controversy surrounding the NOVA classification system, particularly in its approach to assessing the healthfulness of food products based on their level of processing (Krois et al., 2022). It also brings awareness to the common misconception that all processed foods are inherently unhealthy, since the majority of “whole” foods must be processed in some way to remove harmful, antinutritive compounds and contaminants to make them digestible by human standards (Petrus et al., 2021). This is especially the case with wheat-based products, such as whole wheat bread or crackers, which require processing both on account of their ingredients, i.e., whole wheat flour, and on account of their production, i.e., cooking, to be considered edible and food safe. Most consumers and even food professionals do not realize that any of the cooking or combining practices that are used to prepare food ingredients and integrating them into a final food product, technically turns those foods into processed foods, further complicating the public's understanding of what constitutes a “healthy” or “natural” food choice (Petrus et al., 2021). Overall, when considering the health of different foods, specifically foods made from wheat ingredients, it’s important to remember that some level of processing is necessary to complete to make the food digestible by human standards.

Section 3. Enhancing Wheat Digestibility via Processing: Mitigation of Antinutritional Factors

As discussed above, a wheat kernel contains three main components: bran, endosperm, and germ. Of these components, the wheat bran contains the most soluble and insoluble dietary fiber within the kernel, with up to 63% of the bran’s makeup being from dietary fiber (Onipe et al., 2015). This dietary fiber is constructed of mostly insoluble fiber elements, with approximately 96% of the fiber in wheat bran being insoluble, or unextractable within the human intestinal tract, and less than 5% of the fiber being soluble dietary fiber (Andersson et al., 2017). Both soluble and insoluble dietary fibers are important aspects of one’s diet, each with its own role. Soluble fiber is made mostly of components such as pentosans, pectin, gums, and mucilage and solubilize water in the digestive tract (Bader Ul Ain et al., 2019). These components induce rapid fermentation and decomposition of the short-chain fatty acids and absorption of probiotics that are responsible for sustaining a healthy gut microbiome and supporting healthy blood glucose level (Bader Ul Ain et al., 2019).

The insoluble fiber within wheat bran is made up of arabinoxylan (a hemicellulose), cellulose, and lignin (Andersson et al., 2017; Bader Ul Ain et al., 2019). While these components can be helpful in bulking stool and preventing constipation, they do not solubilize water in the digestive tract and can be difficult for the body to process in high levels, such as in raw wheat, or for sensitive individuals (Bader Ul Ain et al., 2019; Cozma-Petruţ et al., 2017). Although increasing daily dietary fiber intake is generally beneficial for healthy individuals, consuming raw wheat to achieve this can lead to digestive issues due to the presence of antinutritional factors naturally found in wheat bran, which will be discussed below.

Section 3a. Phytic Acid

The foremost antinutritional factor found within the wheat kernel is phytic acid, which is primarily localized within the bran, specifically the aleurone layer. Endosperm, which is separated from wheat bran and germs during milling, contains virtually no phytic acid and is more digestible (Muhammad et al., 2010). Phytate, or phytic acid, is the primary storage form of phosphorus and is instrumental in supporting a seedling's growth in the beginning stages of the growing cycle for many grains, including wheat (Kumar et al., 2023). Phytic acid also acts as a chelator for divalent cations such as iron, zinc, and calcium, binding them from performing their function within the body; therefore, reducing their bioavailability (Muhammad et al., 2010). Phytate is also not bioavailable to humans, since the enzyme phytase isn’t present in the plant, hindering any beneficial effect it may have on the human body, and most commonly causes micronutrient deficiencies for iron and zinc (Ram et al., 2020). Various techniques, such as heating, soaking, fermenting, can be used to remove the aleurone layer and phytic acid, or to use molecular plant breeding techniques to find cultivars of wheat that contain lower levels of phytic acid and still deliver the same yields (Venkatasubbaiah & Konasur, 2020).

Section 3b. Protease inhibitors/ ATIs

Other antinutritional factors present in raw wheat include protease inhibitors (mainly trypsin inhibitors), lectins, tannins, alkaloids, and oxalate, all of which contribute to general dysfunction in the body and are mostly concentrated in the bran (Chinma et al., 2024). Of these, protease inhibitors tend to cause the most undesirable effects on the human body after phytic acid. Protease inhibitors are compounds that inhibit the actions of proteases, which are enzymes responsible for carrying out proteolysis via the hydrolysis of peptide bonds, initiating protein digestion (Junker et al., 2012). While a healthy balance of proteases and protease inhibitors support even protein digestion, an imbalance of the two can cause varying gastrointestinal issues, including intestinal inflammation via the release of proinflammatory cytokines in healthy individuals and celiac-patients, as well as severe stomach discomfort and pancreatic hypertrophy or hyperplasia (Junker et al., 2012; Ram et al., 2020).

Protease inhibitors are found widely throughout cereals and grains, but the main variety present in wheat is trypsin inhibitor, which is commonly coupled with amylase inhibitor when described, since the two are both types of isoforms (Geisslitz et al., 2022). Amylase inhibitors are aligned with trypsin inhibitors in that they block the degradation and absorption of starch, which can be a positive in some cases, but, coupled with the trypsin inhibitor, can cause digestive issues in most individuals (Thakur et al., 2018). Colloquially called ATIs (amylase/ trypsin inhibitors), these proteins can cause issues and promote inflammation in those who have celiac disease and nonceliac gluten sensitivity, as well as in mice with prospective colitis (Junker et al., 2012; Pickert et al., 2020; Reig-Otero et al., 2018). ATIs have also been shown to influence the development of baker's asthma and baker's eczema, both allergy responses in individuals who have consistent exposure to raw wheat flour, demonstrating the importance of wheat processing, even past the point of wheat milling, since these proteins are found in the endosperm, which usually contains a lower concentration of antinutrient factors than the wheat bran (Geisslitz et al., 2019; Gómez et al., 1990). The utilization of moist heat is one of the most effective cooking methods to reduce protease inhibitor activity within wheat (Pandey et al., 2023).

Section 3c. Lectins

Lectins, or hemagglutinins, are storage carbohydrate-binding proteins that are extremely prevalent in raw or unprocessed grains, including wheat. Their botanical function is to help protect the plant from external invaders, such as pests and pathogens, that affect the plant's overall health and well-being (van Buul & Brouns, 2014). In wheat, these compounds are primarily found within the germ and are defined as 'wheat germ agglutinin' with wheat consumption and health concerns, which exhibits a strong affinity for the intestinal epithelium, where its binding activity can lead to cellular damage and increased intestinal permeability, commonly referred to as "leaky gut" within the health industry (van Buul & Brouns, 2014). This compromised barrier function impairs nutrient absorption and may contribute to systemic inflammation, alongside potentially interrupting glucose and insulin receptor signaling, which can contribute to further autoimmune disease, such as celiac disease (Pandey et al., 2023; van Buul & Brouns, 2014). Despite the concerns associated with the ingestion of these antinutrients, it is easy to avoid this through processing wheat, since it's been shown that processing significantly affects the content of lectins found in wheat (Pandey et al., 2023).

Section 3d. Tannins

Tannins, a type of phenolic compound, are another antinutritonal factor found in unprocessed wheat in the seed coat (Ram et al., 2020). Tannins act as an antinutrient due to their ability to either bind or precipitate proteins, amino acids, and alkaloids, which can impair the body's ability to properly process and utilize some of these nutrients, although, in the case of alkaloids, this is a positive since alkaloids are also considered an antinutritional factor in wheat. These compounds can also inhibit digestive enzymes like amylase, decreasing the efficiency of starch alongside protein digestion (Thakur et al., 2018). As a result, the level of tannins found within unprocessed wheat, specifically the bran, can negatively impact the body's nutrient utilization. Tannins have also been shown to form complexes with B vitamins, reducing the bioavailability, and are suspected to limit iron absorption, contributing to iron deficiency (Delimont et al., 2017). Processing methods such as soaking and fermentation are commonly used to reduce tannin content and improve the nutritional quality of wheat products. Thermal processing is not recommended since phenolic compounds are generally heat-stable, so separating the main mode to remove tannins from the wheat kernel is through milling (Ram et al., 2020; Thakur et al., 2018).

Section 3e. Alkaloids

Alkaloids are considered to be antinutritional factors in unprocessed wheat due to their influence on the human nervous system. While these bioactive compounds occur naturally in approximately 20% of plants, the alkaloids found within the wheat kernel are formed externally as a part of the fruiting body, or sclerotium, of the fungal species *Claviceps purpurea,* commonly known as Ergot (Pandey et al., 2023). The effects of the *Calviceps* genus have been of economic and physiological importance for consumers of wheat for centuries, with the effects of its alkaloids being a primary antinutritonal factor within wheat if present. If a wheat plant is infected with Ergot, it takes about five weeks for the sclerotia to reach maturity within the developing kernel, at which point it harbors a reservoir of mycotoxins, known as ergot alkaloids (Pandey et al., 2023; Ram et al., 2020).

There are six commonly produced ergot alkaloids: ergonovine, ergosine, ergotamine, ergocornine, a-ergokryptine, and ergocristine, alongside their corresponding -inine epimers (Fajardo et al., 1995). Since the primary function of alkaloids in plants and fungi is to act as a chemical deterrent against biotic stressors such as insects and herbivores, they can be extremely toxic in high quantities, interrupting a variety of normal metabolic processes, the majority of which are related to neurotransmitters and modified electrochemical firing (Panaccione et al., 2012). The chemical structure of these different alkaloids and the amount of vulnerable neurotransmitter receptors influence their degree of toxicity, meaning that the symptoms associated with ingestion of these alkaloids can vary (Panaccione et al., 2012). Separating wheat kernels containing the Ergot sclerotia can be difficult, although highly contaminated kernels differ visually from healthy ones. The best way to avoid ergot contamination for a wheat-based ingredient, like flour, is to thoroughly clean and remove the contaminated kernels, which is best achieved through density-dependent or specific gravity kernel separation, which can be time-consuming and costly if the wheat is heavily infested (Berraies et al., 2024; Fajardo et al., 1995). This can help to remove a large percentage of the ergot alkaloids from within the kernels, but will not rid the wheat of them entirely, making pre-harvest control methods an essential addition to management.

Section 3f. Oxalates

The last notable antinutrient present in unprocessed wheat kernels, in both Durum and Common wheat, is oxalate. Oxalate is an organic acid that interacts with a variety of essential minerals, forming salts and esters which, depending on the mineral, can decrease their absorption in the body (Pandey et al., 2023). When in combination with calcium, in particular, oxalates can form calcium oxalate, which is one of the primary factors that contribute to the development of kidney stones if they are not excreted before entry into the urinary tract (Pandey et al., 2023; Siener et al., 2006). Even when soluble oxalate salts are formed, specifically with minerals potassium and sodium, they are still quite insoluble at the intestinal pH, therefore decreasing their usability within the body (Pandey et al., 2023). The best methods to reduce the amount of oxalates within wheat are through processing, since this compound is concentrated in the outer layers of the kernel, with wheat bran in particular containing 457.4 mg/ 100g, making it an extremely high oxalate component in the kernel, according to Siener et al., 2006 (Siener et al., 2006). With the amount of oxalate concentrated within the wheat bran, consuming high quantities of whole, unrefined grains can increase one's chance of developing kidney stones and other related complications (Siener et al., 2006).

Section 3g. Gluten

Along with the apparent antinutritional factors discussed above, another arguable antinutrient is gluten, an important storage protein in wheat (Geisslitz et al., 2019). Albeit gluten's extremely important rheological role in dough, it has faced significant criticism due to its perceived negative effects on digestion and its association with systemic inflammation. However, these adverse effects are typically limited to individuals with celiac disease or other medically diagnosed gluten-related disorders, alongside those who are following a low FODMAP diet (Cozma-Petruţ et al., 2017). For the general population, there is limited scientific evidence supporting the exclusion of gluten from the diet, and its removal from wheat products can significantly compromise both their quality and nutritional value due to the associated reduction in total wheat protein content (Cozma-Petruț et al., 2017). So, given gluten's critical role in the production of high-quality wheat products and the lack of scientific evidence linking it to adverse health effects in healthy individuals, its classification as an anti-nutritional factor remains somewhat subjective. Nonetheless, it represents an important consideration in the broader evaluation of wheat's nutritional and functional profile.

Table 1. Description of nonnutritive agents present in Common Wheat (*Triticum aestivum*), including their location in the wheat kernel, effect on the human body, and removal or control techniques.

Nonnutritive Agent of Common Wheat (*Triticum aestivum*)	Location in Wheat Kernel	Effect on the Body	Removal/ Control Tactic
	Antinutrients:		
Phytic Acid	Wheat bran, localized in the aleurone layer (Muhammad et al., 2010)	Chelator of essential micronutrients- causing deficiencies (Pandey et al., 2023; Ram et al., 2020)	Kernel processing: milling, heating, soaking, fermenting. Or molecular plant breeding and genetic biofortification techniques (Pandey et al., 2023; Venkatasubbaiah & Konasur, 2020)
Protease Inhibitors/ ATIs	Wheat endosperm (Gómez et al., 1990)	Protease inhibition, causing reduced protein digestion, and reduced starch digestion due to amylase suppression, intestinal inflammation, or baker's eczema in	Moist heat treatment, cooking (Pandey et al., 2023)

		severe cases (Geissleitz et al., 2022; Gómez et al., 1990; Junker et al., 2012; Reig-Otero, 2018; Pickert et al., 2020)	
Lectins	Wheat germ (van Buul & Brouns, 2014)	Development of leaky gut (caused by cellular damage in the intestines and increased intestinal permeability), reduced nutrient absorption, systemic inflammation, and in severe cases, celiac disease (van Buul & Brouns, 2014)	Milling- separation of bran from endosperm (Pandey et al., 2023)
Tannins	Seed coat, in testa (Ram et al., 2020)	Bind to biologically important macronutrients (proteins), inhibit digestive enzymes (amylase, protease), binds to vitamins and minerals (mainly iron), reducing their bioavailability (Thakur et al., 2018; Delimont et al., 2017)	Milling- separation of bran from endosperm, soaking, and fermentation (Thakur, 2018; Ram et al., 2020)
Alkaloids	Entirety of wheat kernel, if contaminated (Fajardo et al., 2024)	Toxicity: seizures, psychosis, nausea, vomiting, gastrointestinal distress, and reduced blood circulation (Berraies et al., 2024)	Physical Processing: separation of contaminated kernels from normal kernels using a specific-gravity separator (Berraies et al., 2024; Fajardo et al., 1995)
Oxalates	Wheat bran (Pandey et al., 2023)	Kidney stones, reduced mineral absorption (Pandey et al., 2023; Siener et al., 2006)	Milling- separation of bran from endosperm and ingesting along with calcium rich foods (Siener et al., 2006)

Section 4. Ensuring Food Safety Through Wheat Processing: Elimination of Fungal Pathogens and Mycotoxins

Wheat is a foundational food across the global food system and is responsible for over 20% of the world's calorie and protein consumption (Hawkesford et al., 2013). It is projected that there will need to be a 40% increase in wheat production globally to sustain the growing population and meet nutrient requirements, and there is concern that with the current methods of growing and cultivating wheat, this will not be possible. One of the largest concerns is three fungal pathogens that currently affect the growth, yield, and nutritive value of wheat crops (Goyal & Prasad, 2010). The most important fungal genera plaguing common wheat crops today are: *Fusarium* spp., *Aspergillus* spp., and *Penicillium* spp., all of which harm the health of the wheat plant, decreasing its kernel yield, alongside producing mycotoxins that are harmful to human health if ingested. Mycotoxins are secondary metabolites of filamentous fungi and are regulated by different regulatory agencies based on their growing location (Figueroa et al., 2017). In the US, the FDA regulates the mycotoxin amount in foodstuffs (*FungalDiseaseandMycotoxinReference2017.Pdf*, 2017).

The technological baking properties associated with wheat are also affected by two of these fungal pathogens, *Aspergillus* spp. and *Penicillium* spp., due to their effect on the sulfur speciation of low molecular weight subunits of glutenin, a primary component in the development of gluten in wheat products (Prange et al., 2005). Mycotoxins produced by all three of the fungal genera mentioned above also affect the nutritional composition of wheat, leading to over 75% change in carbohydrate, protein, and lipid content due to their presence in the kernel, therefore reducing the overall nutritive value of the wheat crop (Awuchi et al., 2020). The crude fiber and ash content were also shifted, with the crude fiber content decreasing by 47.2% and the ash content increasing by 54.9%, according to Awuchi et al. (Awuchi et al., 2020).

Section 4a. *Fusarium* spp.

Fusarium Head Blight (FHB), primarily caused by *F. culmorum* and *F. graminearum*, is the most prevalent and economically significant fungal disease that affects wheat pre-harvest (Różewicz et al., 2021). FHB compromises the commercial value of wheat in two major ways: by reducing grain yield and by contaminating the crop with various sesquiterpenoid trichothecene mycotoxins, commonly referred to as vomatoxins in the milling industry. These compounds are highly toxic to humans and animals and also exhibit phytotoxicity, negatively affecting plant health. One of the hallmark symptoms of FHB is the premature senescence of the wheat head, which causes kernels to appear shriveled and husk-like, a direct result of the damaging effects of these mycotoxins. The other phytotoxic effects of FHB on wheat include stunted growth (further compromising yield), chlorosis, disrupted cell meiosis, and programmed cell death, eventually leading to necrosis (Figueroa et al., 2017; Różewicz et al., 2021).

The most notable mycotoxins/ vomatoxins are trichothecene and zearalenone, with trichothecenes being divided into four groups based on their structure (A, B, C, D), where types A and B are the most common (Różewicz et al., 2021). The only mycotoxin produced by FHB that has any regulatory guidance from the FDA is deoxynivalenol (DON), a type B trichothecene, for which they've set an advisory level of no more than 1 ppm of DON in finished wheat products for human consumption and no more than 5 ppm in animal feed (*FungalDiseaseandMycotoxin Reference2017.Pdf*, 2017). The other FHB mycotoxins that are surveilled in the wheat industry are fumonisims and nivalenols (Tola & Kebede, 2016).

While the main control methods for mitigating mycotoxin contamination in wheat are employed through pre-harvest techniques, namely fungicide applications or the use of FHB-resistant cultivars, most of which don't uphold the same yields and characteristics of common wheat cultivars, the most effective means of controlling mycotoxin contamination in wheat is through post-harvest processing techniques (Figueroa et al., 2017; Różewicz et al., 2021). The most effective post-harvest processing method is cleaning and sorting the wheat kernels using a gravity separator, followed by milling. This is important because the bran often contains higher levels of mycotoxins, underscoring the criticality of processing wheat before incorporating it into food products or eating it (Tibola et al., 2016).

Section 4b. *Aspergillus* spp.

Another important genus of fungal pathogens of wheat is *Aspergillus*, which mostly occurs post-harvest and during storage but can also occur when a wheat plant is under stress (*FungalDiseaseandMycotoxinReference2017.Pdf*, n.d.). The most prominent species associated with *Aspergillus* in wheat is *Aspergillus flavus*, with *A. parasiticus* and *A. nomius* being important but less notable. All of these *Aspergillus* species produce the well-known mycotoxin, 'aflatoxin,' the name of which is a composite of the scientific name and the word toxin (a + fla + toxin) (*FungalDiseaseandMycotoxinReference2017.Pdf*, 2017; Tola & Kebede, 2016). There are more than 20 different types of aflatoxins, with aflatoxin B1 having toxicity in humans, particularly so since it is categorized as a Group 1 carcinogen according to the International Agency for Research on Cancer (Gong et al., 2024).

Aflatoxins can cause a host of harmful effects on the human body, with prolonged exposure and ingestion of these toxins causing aflatoxicosis, which includes nausea, vomiting, convulsions, and liver failure, on top of impaired food digestion and nutrient absorption, immune system suppression, and liver cancer (Dhakal et al., 2023; Gong et al., 2024). Ochratoxin A is another mycotoxin synthesized by species of *Aspergillus*, most notably *Aspergillus ochraceus* and *Aspergillus niger*. It commonly manifests in wheat following harvest, primarily due to suboptimal storage conditions promoting fungal growth, and is relatively new in the sphere of toxicology research (Bui-Klimke & Wu, 2015). Ochratoxin A is also produced by *Penicillium* spp., a fungal genus in which its production is more commonly observed than in *Aspergillus* spp. (*FungalDiseaseandMycotoxinReference2017.Pdf*, 2017).

Since aflatoxin is the mycotoxin of greatest concern from the *Aspergillus* genus, it is the most commonly screened and treated for. Many pre-harvest and post-harvest methods are used to mitigate aflatoxin contamination in wheat, including chemical, biological, and physical treatments or methods (Gong et al., 2024). Of these three types of treatments, the most commonly used within the food industry are physical methods, specifically sorting the contaminated kernels from the rest of the grain harvest using visual inspection and density measurements to determine which kernels to discard. Another physical method for reducing aflatoxin contamination in wheat is hulling, which helps remove the outer layers where aflatoxin concentrations are typically higher (Sipos et al., 2021). Cleaning and heating have also been shown to reduce aflatoxin toxicity in wheat, particularly when the grain is wet compared to dry during thermal processing (Hwang & Lee, 2006). These findings highlight the importance of properly processing wheat to ensure a safer final food product, as well as meet FDA standards, which considered food with greater than 20 ppm of aflatoxin to be adulterated (21 USC 342: Adulterated food, 2025).

Section 4c. *Penicillium* spp.

The third fungal genus responsible for mycotoxin contamination in wheat is *Penicillium*, which primarily affects the grain during storage. The species of greatest concern belonging to this genus is *Penicillium verrucosum*, which is the primary producer of ochratoxins A, B, and C in wheat post-harvest (Awuchi et al., 2020). Of the three types of ochratoxins, ochratoxin A has been linked to a variety of significant health risks, principally nephrotoxicity, leading to Balkan endemic nephropathy, chronic interstitial nephropathy, and tumor development in the urinary tract (Bui-Klimke & Wu, 2015; el Khoury & Atoui, 2010). This mycotoxin is also considered to be neurotoxic, hepatotoxic, and immunotoxic, showcasing the danger of consistent exposure to these compounds, especially since they occur post-harvest and can remain stable under ambient and cooled food storage conditions (el Khoury & Atoui, 2010).

It is presumed that the mycotoxins produced by *P. verrucosum*, mainly ochratoxin A, are concentrated in the outer parts of the wheat kernel, i.e., the bran; milling can be a beneficial tactic to reduce the level of mycotoxin within the wheat (Osborne et al., 1996; Scudamore et al., 2003). Additional techniques, including preliminary cleaning and scouring the kernel, have been shown to reduce the amount of ochratoxin A in wheat, with the scouring technique eliminating up to 44% of ochratoxin A from the kernel before milling. Moreover, when used in combination with milling, both methods can remove up to 75% of ochratoxin A from the wheat flour (Scudamore et al., 2003). This being said, refined flour naturally will contain less ochratoxin A and mycotoxins in general than whole wheat flour if there was any contamination in the wheat kernels used to make the flour.

Section 5. Meeting Dietary Requirements: Fortification of Processed Wheat with Essential Micronutrients

While wheat processing is imperative to remove harmful antinutrient factors and fungal pathogens, it is also used to help reinforce the nutrient value of wheat and improve its overall storage capacity. Both micro- and macronutrients are enhanced through the processing of wheat, either through fortification or by increasing the bioavailability of wheat proteins and starches that are key components in wheat's nutritional value. This is exemplified in the nutritional capacity of diets commonly found in developing countries, where wheat processing is not as widely evolved as it is in developed countries (Dixon et al., 2009). Since wheat is incorporated into the diet in different ways in these countries compared to developing countries, there are different nutritional needs met in these circumstances, while others are found sparingly in the diet, leading to deficiencies and overall poor health. Examples of these nutrients include the micronutrients explored in this section, as well as macronutrients, such as protein, when wheat is consumed as a primary portion of one's diet (Henley et al., 2010). This highlights the importance of wheat processing, both through pre- and postharvest techniques, as well as through breeding effects, to supply a more complete nutritional profile for those who rely more heavily on wheat as part of their diet (Dixon et al., 2009; Müller & Krawinkel, 2005).

In the U.S., the micronutrients that are mandatory to fortify wheat flour with include iron and B vitamins; thiamin (B1), riboflavin (B2), niacin (B3), folic acid (B9), and, on occasion, calcium (Questions and Answers on FDA's Fortification Policy Guidance for Industry, 2015). This mandatory fortification policy was first implemented in the early 1940s as a public health measure in response to widespread micronutrient deficiencies, particularly pellagra, a disease caused by niacin deficiency that was prevalent in the southern United States. The fortification of wheat flour with B vitamins significantly reduced the incidence of pellagra and demonstrated the effectiveness of food-based nutritional interventions (Mannar & Hurrell, 2018). Although this disease is no longer prevalent in the U.S., it is still common throughout developing countries, alongside many other micronutrient deficiencies, such as vitamin A and zinc (Müller & Krawinkel, 2005). These micronutrients can serve as supplementary fortificants and offer significant benefits when added to milled flour, particularly in developing countries where deficiencies are somewhat widespread, although these aren't likely to be fortificants for wheat flour in the U.S. (Akhtar et al., 2011).

Section 5a. B Vitamins

When evaluating the vitamin and mineral content of a wheat kernel, the main areas that contain these micronutrients are in the wheat bran and the wheat germ, both of which are effectively removed during the milling process. This may seem counterintuitive, but separating these components from the endosperm is a highly important process when it comes to the reduction of lipid oxidation, antinutrient factors, and fungal pathogens. Despite this being a necessary process for food safety, milling eliminates a large portion of the preexisting vitamins and minerals present within the kernel. To help remedy this, fortification processes have been added to the processing procedure for refined wheat flours. As mentioned previously, the US mandates fortification of iron and many different B vitamins, including folic acid, thiamin (B1), riboflavin (B2), and niacin (B3) (FDA, 2015). B vitamins are water-soluble vitamins that act as enzyme cofactors, which facilitate the biosynthesis of DNA and RNA, alongside the synthesis of neurotransmitters and their respective pathways (Hanna et al., 2017; Kennedy, 2016). A deficiency in these types of vitamins is a major influencer in the development of neurological disorders and other conditions, such as depression, anxiety, and fatigue, and is considered a "hidden hunger" within populations eating enough calories (Kennedy, 2016; Lowe, 2021). These symptoms are more commonly associated with prolonged deficiency of vitamins B1, B2, B3, and folic acid, but low-grade, or marginal, deficiency of these vitamins can create dermatitis, angular chelitis, sleep disturbances, eye irritation; with folic acid specifically contributing to neural tube defects, like spina bifida, demonstrating the necessity of supplementing these vitamins in the diet via refined flour fortification (Copp et al., 2015; Hanna et al., 2017).

Section 5b. Iron

Iron deficiency anemia (IDA) is also considered a "hidden hunger" and is the most common micronutrient deficiency in the world (Ahmed et al., 2014). Clinically, IDA is defined as a deficiency in red blood cells or hemoglobin levels that are insufficient to meet the body's physiological needs, resulting in a reduced capacity to transport oxygen throughout the body (Field et al., 2020). IDA can cause a range of health issues, including extreme fatigue, weakness, poor concentration, reduced physical endurance, and increased susceptibility to infections, significantly impacting overall well-being and daily functioning (Ahmed et al., 2014). It can also cause growth and development issues in growing children and adults, particularly women (Bathla & Arora, 2022). One of the main ways by which this is addressed is by fortification of frequently eaten foods, such as wheat flour. By fortifying milled wheat with iron (usually ferrous iron), a widely consumed staple food becomes a valuable vehicle for improving iron intake across populations (Akhtar et al., 2011). This not only helps prevent IDA and its associated health risks but also supports overall well-being and productivity, making iron fortification a key public health strategy.

Additionally, iron intake from fortified refined flour is more effective than from whole wheat flour with naturally occurring iron, as the fortified flour contains higher levels of iron in a more bioavailable state, without the effect of antinutrients or excessive dietary fiber that can bind to iron and excrete it from the body (Reinhold et al., 1981). While whole wheat flour may contain more iron than refined fortified flour, its high phytate content significantly hinders iron absorption. Whole wheat flour contains 6–10 mg/g of phytates, compared to only 2–4 mg/g in refined flour. Phytates bind to iron through chelation, making it less available for absorption in the body (Febles et al., 2002; Zimmerman, 2013). This inhibitory effect extends to other essential micronutrients as well, such as zinc and calcium, which are crucial for bodily functions and healing (Zimmermann, 2013).

Section 5c. Other Micronutrients (Vitamin A, Calcium, and Zinc)

Other micronutrients, such as calcium, vitamin A, and zinc, have also been considered as fortification options in refined wheat flour, as well. Calcium fortification is an option for refined wheat flours in the US, but this is up to the discretion of the miller, in which, if the flour is acidified with monocalcium phosphate within the limits specified for phosphated flour or enriched with calcium, then it must reach at least 960mg per pound of flour. If this value is not reached, then no calcium should be added to the nutrition label (*21 CFR §137.165 -- Enriched Flour.*, 1998). Vitamin A and zinc are other important micronutrients to include in refined wheat flour in developing countries, where wheat serves as a key source of nutrients and energy, and there are lacking amounts within the diet (Akhtar et al., 2011). Vitamin A deficiency causes many symptoms related to eyesight, with a major symptom of deficiency being night blindness, and in severe cases, blindness (Hodge & Taylor, 2023). Both vitamin A and zinc deficiency can lead to poor wound healing and lowered immunity, making these micronutrients extremely crucial in preventing poor health (Hodge & Taylor, 2023; Prasad, 2013). Since wheat flour is widely consumed, especially in developing countries, where diets lack diversity, fortification provides a practical and efficient way to deliver these critical nutrients to large segments of the population without the negative effects of antinutrient factors or fungal pathogens.

Conclusion

Over the years, numerous advancements have been made in wheat processing techniques to effectively incorporate wheat-based ingredients into a wide range of food products. These techniques encompass both fundamental processes that ensure wheat products are safe and digestible for human consumption, as well as modern advancements that have revolutionized how wheat-based foods are produced and delivered to consumers in a way that increases their food safety and nutrient value. While whole wheat is often idealized for its "natural" state, a closer examination reveals that although processing diminishes the nutritional composition of wheat but enhances both its digestibility, safety, and nutritional potential. This review underscores the importance of demystifying common misconceptions surrounding whole versus refined wheat products and highlights the necessity of processing in making wheat a reliable and health-promoting staple in the human diet. As global populations continue to grow and dietary trends increasingly emphasize minimally processed foods, it is essential to promote a scientifically grounded understanding of food processing. Rather than viewing processing as inherently detrimental to wheat as a food source, its role in improving food safety through the removal of harmful mycotoxins, promoting its digestibility through the elimination of antinutrient factors, and enhancing the bioavailability of essential micronutrients through fortification, must be communicated to consumers and health professionals alike. Clear, evidence-based communication is key to reshaping public perception and ensuring that consumers make informed decisions about the foods they eat, particularly when it comes to foundational staples like wheat.

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