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REVIEW ARTICLE

A review of gluten and sorghum as a gluten free substitute

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ABSTRACT

The review explores the role of gluten in food products, its associated health issues, and the growing market for gluten-free alternatives. Gluten, a protein in wheat, barley, and rye, is widely used in the food industry for its binding and stabilizing properties. Increasing gluten intolerance, especially in those with celiac disease, has boosted demand for gluten-free options like sorghum. Sorghum, a gluten-free grain, offers high protein and fiber content but also contains antinutritional factors like tannins, phytates, and protease inhibitors. Various processing techniques, such as dehulling, soaking, fermentation, and heating, have been developed to address these factors. Future trends in sorghum are expected to focus on innovative processing methods to enhance its nutritional value. This review also provides a detailed examination of gluten, its functions in foods, health concerns, gluten-free products, sorghum-based foods, antinutritional properties, processing technologies, and future opportunities.

Keywords: grain sorghum (GS); gluten free; prolamins; celiac disease

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1. Introduction

Gluten, a protein found in wheat, barley, and rye, contributes to the flexibility of dough and texture of baked goods dough. Gluten has a substantial impact on the texture and structure of baked goods, as well as their flavor and appearance[1]. For individuals with celiac disease, however, gluten can pose a health risk. Gluten consumption results in celiac disease, an autoimmune disorder that affects the small intestine. Gluten consumption by individuals with celiac disease can damage the lining of the small intestine, resulting in nutrient malabsorption and other health complications[2]. Gluten sensitivity is increasingly recognized as a health concern alongside celiac disease. Gluten sensitivity is a non-celiac condition characterized by abdominal pain, bloating, and fatigue, which is triggered by the consumption of foods containing gluten[3]. Gluten-free diets have gained popularity among those with celiac disease and gluten sensitivity, as well as those who follow a gluten-free diet for other reasons[4]. In recent years, the market for gluten-free products has expanded significantly, and consumers now have numerous options. In addition, opportunities exist for the use of gluten-free grains like sorghum, chickpea, buckwheat, potato starch and arrowroot starch in the production of gluten-free products. Sorghum has been found to be a suitable substitute for wheat flour in gluten-free bread, pasta, and other products, and it is rich in protein and fiber[5].

Sorghum is a plant that uses the C4 pathway during the dark reaction, with high photosynthetic efficiency[6] and belongs to the

Andropogoneae family, the Panicoideae subfamily, and the Poaceae family (grasses)[7]. Sorghum is grown in the semiarid and arid regions of the Middle East, Sub-Saharan Africa, Asia, Australia, and Central and North America[8]. As of January 2021, the annual global production of sorghum cereal was 61.62 million metric tons (MMT)[9]. Sorghum cereal is a staple in parts of Asia, South Africa, and other low-income regions, as well as a forage and fodder crop for cattle[10]. Except for Antarctica, grain sorghum grows on every other continent. After barley, oats, and rice, it is the world's fifth most important cereal crop. Even though grain sorghum was first grown in Africa and is still grown there, the United States is the largest producer of sorghum; in 2017/2018, they produced 9.24 MMT, while Australia only produced 1.44 MMT; however, this is expected to increase to 2 MMT in 2018/2019 which could put Australia among the top ten countries that produce the most sorghum in the world[11]. Grain Sorghum is not as widely known or utilized as maize, wheat, rice, or barley as a human food. Nonetheless, it is a staple in some regions of the world. Nigeria, the United States of Mexico, and India are the leading producers of sorghum, followed by China, the Argentine Republic, and Brazil (**Table 1**).

The cereal grain sorghum, which has gained attention as a potential alternative to other grains such as wheat and maize due to its resilience in harsh growing conditions and its ability to adapt to different environments, has many other potential uses beyond gluten-free products[12]. Sorghum is a good source of proteins, vitamins and minerals with all trace elements. It contains (0.119/100 g) moisture, (0.104/100 g) protein and a lower fat content of (0.019/100 g). Fiber and mineral content are (0.016/100 g), and it is also rich in dietary fiber (0.143/100 g). It provides 349 kcal of energy, and 72.6 g of carbohydrates[13]. The amylase composition of the sorghum cereals ranges from 21.2% to 28.2%, and starch makes up the bulk of the grain's carbohydrates. Sorghum has a calcium content of 25 mg, phosphorous content of 222 mg, and iron content of 4.1 mg (per 100 g of edible portion), respectively[14].

Sorghum treatment processes like fermentation, malting, soaking, extrusion, micronization, and enzymatic treatments use warm air, pressure, or enzymes to disintegrate antinutritional factors and improve nutritional value[15]. These techniques have been shown to improve the digestibility and bioavailability of sorghum, making it a more nutrient-dense food source[15]. Due to its unique properties, sorghum has the potential to be used in a variety of applications in the future. Due to the absence of gluten, the grain can be used to produce gluten-free foods, such as gluten-free bread and pasta. Recent research has demonstrated that sorghum can be successfully utilized in the production of gluten-free bread, noodles, and pasta; however, these products have not yet entered commercial production[16]. There are numerous opportunities for sorghum, but it has yet to reach the full potential of its use as an alternate source of nourishment.

Table 1. Sorghum grain output in the 7 top sorghum-producing nations from 2018–2021.

Sorghum production (tons)			
Country	**2018–2019**	**2019–2020**	**2020–2021**
USA	9271.001	8672.994	9474.002
Nigeria	6720.996	6664.995	6899.992
Mexico	4699.997	4299.992	4499.999
India	3474.998	4732.991	3849.992
China	2908.996	3599.999	3549.995
Argentina	2499.992	2499.992	3199.994
Brazil	2177.000	2254.000	2099.996

2. Gluten

Gluten is a protein composite found in certain grains such as wheat, barley, and rye[17]. Gliadin and glutenin make gluten. Gliadin, a prolamin, and glutenin, a glutelin, are wheat storage proteins[18]. Wheat protein is 80%–90% gliadin-glutenin complex, which is rich in glutamine and proline[19]. Because they share amino acids with wheat gliadin-glutenin complex, rye's secalin and barley's hordein are also called gluten[19]. These cereals store prolamins. Triticeae tribe members rye, barley, and wheat share botanical similarities. Rye and barley have less gluten. Oats are often gluten-free. Oats are in the Aveneae tribe, not Triticeae, despite their close relationship[20]. Due to their amino acid makeup and avenin content, they differ from gluten proteins. Avenin is a low-glutamine, proline-poor storage protein (10%–15%)[21]. Oats are typically regarded as gluten-containing cereal due to cross-contamination from being processed in the same facility as wheat and other cereals[22]. Rice, millet, maize, and sorghum are not gluten-containing cereals because they have different amino acid compositions than wheat, rye, barley and do not include celiac-reactive peptide sequences[21]. Glutamine and proline content of different cereals were mentioned in **Table 2**. The highest proline content was found in Barley (13.03) and the lowest was observed in rice which is on par with millet. While the highest glutamine was recorded in wheat at about 31.1, the lowest was observed in rice.

Table 2. Glutamine and Proline content of various cereals (% total amino acid).

	Cereals	Glutamine	Proline
Gluten cereals	Wheat	31.05 ± 0.07^{d}	12.50 ± 0.14^{bc}
	Rye	27.76 ± 3.6^{cd}	12.63 ± 0.15^{c}
	Barley	23.93 ± 0.77^{bc}	13.03 ± 1.10^{c}
Non-gluten cereals	Oats	18.13 ± 3.03^{b}	11.60 ± 4.60^{bc}
	Rice	15.96 ± 2.37^{a}	5.90 ± 0.65^{a}
	Millet	17.40 ± 1.0^{a}	5.96 ± 1.34^{a}
	Corn	19.00 ± 0.43^{a}	8.60 ± 1.91^{ab}
	Sorghum	21.63 ± 2.26^{a}	10.03 ± 1.34^{bc}

Values represent the average of triplicate ± standard deviations. Different letters in the same column represent a statistically significant difference ($p < 0.05$) among different cereals.

3. Function of gluten in food

Many wheat-based foods depend on gluten. Gliadin and glutenin, which make up gluten, have different functions. Gliadin increases dough viscosity, while glutenin especially high molecular weight subunits gives dough elasticity[23]. Gluten provides a robust protein network that allows the dough to stretch or expand without breaking or tearing[23]. Higher molecular weight secalin and D-hordein are comparable to higher molecular weight glutenin subunits, but their lesser numbers prevent them from forming a strong protein network for highly leavened bread[24].

4. Health issues caused by gluten

Foods that contain gluten are a cornerstone in the diet of the majority of the world's population; nonetheless, these foods have the potential to have negative impacts on the health of certain individuals. The ingestion of these meals has the potential to bring on a wide variety of gastrointestinal, systemic, and even psychological problems[25]. Celiac disease (CD), wheat allergy (WA), and non-celiac gluten sensitivity (NCGS) are the three most common health conditions that are linked to gluten consumption. While the pathogenesis of CD and WA have been well investigated, the pathogenesis of (NCGS) is not yet completely understood[26].

4.1. Celiac disease (CD)

Gluten in the diet causes a chronic inflammatory bowel condition known as celiac disease in those who are genetically predisposed individuals[27]. Gliadin-induced inflammation causes small intestinal mucosa lesions[29]. Celiac disease is typically diagnosed by serological testing for celiac-specific antibodies and small intestinal biopsies[29,29]. Irritable bowel syndrome (IBS) and celiac disease share symptoms of malabsorption, tiredness, and anemia, among others[30]. Due to intestinal inflammation, celiac disease patients are more likely to acquire IBS, and IBS patients are more likely to develop CD[31].

The global seroprevalence of celiac disease is 1.4% while the prevalence of biopsy-confirmed celiac disease is 0.7%, according to a recent study by Marston et al.[32]. It was also reported that children are more susceptible than adults and that the illness affects more females than males. Celiac disease was also more prevalent in Europe, Oceania, and South East Asia. It can be controlled with a lifetime, stringent gluten-free diet (GFD)[31].

4.2. Wheat allergy (WA)

Wheat gliadin causes Immunoglobulin E (IgE) mediated wheat allergy[33]. An increased IgE to gliadin antibody test confirms the allergy[34]. Wheat-based meals cause symptoms between minutes to hours, like most food allergies. These include skin rash, wheezing, itching, and swelling in the mouth, nose, throat, and eyes, IBS-like symptoms, and anaphylaxis in particularly sensitive people[35]. WA patients may have duodenal mucosa lesions[36,37]. 1% of the world's population has wheat allergy (WA)[28]. Although WA and CD have completely different pathogenic processes, in rare circumstances both disorders might arise in the same person. Those with anaphylaxis must avoid wheat for life, but those with non-life-threatening wheat allergy can reintroduce wheat after 6 years[36,37].

4.3. Non-celiac gluten sensitivity (NCGS)

Non-celiac gluten sensitivity (NCGS) refers to less well-characterized disorders connected to gluten intake[38]. After CD and WA are ruled out, it defines a condition caused by gluten-containing meals. This disorder includes gastrointestinal, systemic, and psychological symptoms, including abdominal pains, diarrhea, nausea, bloating, flatulence, dermatitis, eczema, headache, chronic weariness, muscle pain, numbness in the hands and feet, mouth ulcers, anemia, and anxiety and depression[28,31]. NCGS's gastrointestinal symptoms are similar to IBS's, hence it may be a variant of IBS[36,37]. NCGS, unlike CD and WA, is not caused by gluten. Fermentable oligo-, disaccharide-, mono-, and polyol-rich foods (FODMAPs) can cause IBS[36,39]. FODMAPs pass through the small intestine undigested and ferment in the large intestine, causing IBS symptoms. Wheat, rye, and barley contain fructans, and fermentable oligosaccharides. In fact, wheat fructan was found to cause more IBS symptoms in self-reported NCGS patients than gluten[40]. NCGS development may involve ATIs. ATIs are starch and protein-resistant proteins[41]. They naturally defend cereals, pseudocereals, and legumes from parasites and pests in the endosperm[42]. ATIs help the plant; however, they worsen gastrointestinal symptoms in NCGS patients with intestinal inflammation[43].

NCGS's mechanism is unknown, and there is no standard diagnostic approach due to the lack of biomarkers[42,43]. NCGS is not as well-defined as CD and WA, hence, its prevalence is unknown, and however, multiple sources say it may range from 0.6% to 6% of the world population[44]. A low FODMAP diet may be better for NCGS patients' gastrointestinal problems than a gluten-free diet (GFD)[45]. Due to recent findings that fructan and other FODMAPs cause NCGS, gluten may be a marker for the symptoms but not the cause. If NCGS is renamed, it may be necessary to reconsider whether gluten-free foods are appropriate for patients.

5. Gluten-free food products

Gluten-free (GF) foods are those carefully produced for people with gluten sensitivity, according to the Codex Alimentarius Standard for Foods for Special Dietary Use for Persons Intolerant to Gluten–CODEX STAN 118-1979[46]. GF foods are manufactured from wheat, rye, barley, or oats that have been processed to eliminate gluten, or from ingredients that do not contain these grains. The Enzyme-linked Immunoassay (ELISA) R5 Mendez method must be used to assess the gluten level in food products in both cases. The Codex also indicates that most but not all people with gluten intolerance can tolerate oats and proposes that GF goods contain oats that are not contaminated with wheat, rye, or barley[47].

5.1. Increase in demand for gluten-free foods worldwide

The number of persons diagnosed or self-diagnosed with gluten intolerance is rising worldwide, boosting demand for gluten-free and wheat-free foods. Because gluten-free (GF) foods are seen to be healthier than gluten-containing ones, more non-gluten-sensitive people are adopting a (GF) diet because of health reasons, weight loss, fad diet and perceived benefits[48]. In Australia, 1 in 10 persons avoid wheat-based goods to avoid ailments they believe are linked to wheat consumption[49].

Gluten avoidance has also increased globally, especially in Asia Pacific. GF food products' market expansion is shown by rising demand from 2014 to 2020. In the Asia Pacific (including Australia), gluten-free food market was expected to grow at the rate of 8.8%[50]. Alternative GF foods including wholegrain rice, ancient grains like sorghum, millets, and teff, pseudo cereals like quinoa, amaranth, and buckwheat, and legumes like beans, peas, and lentils are also becoming more popular. Unsaturated fatty acids, polyphenols, phytosterols, and fiber are abundant in these crops[51].

5.2. Gluten-free products available in the market

Nowadays, it is not hard to find gluten-free alternatives to foods that contain gluten. The market for gluten-free (GF) cookies, salty snacks, and meat products made with cereals is already well-established, but there are still opportunities for the use of various alternative flours, such as rice flour, corn flour, chickpea flour, sorghum flour, almond flour, and coconut flour, in gluten-free product development[51]. These flours have unique properties and can be combined to create flour blends that enhance the texture and flavor of gluten-free baked goods such as gluten-free pasta, cookies and bread[52]. Cereal-based staples like bread, pasta, and noodles, as well as ready-to-eat breakfast cereals, are probably the most popular products[53]. There are also gluten-free versions of bakery products like biscuits, cakes, and cereal bars[54]. Pre-packaged gluten-free mixes for pancakes, waffles, muffins, and various delectable treats are widely accessible in global markets[55]. When it comes to condiments and salad dressings, many are inherently devoid of gluten, also for beer aficionados who prefer a gluten-free option, there is an array of choices crafted from alternative grains such as sorghum, rice, or corn[56]. Notable brands like Omission, Redbridge, and New Planet are known for their gluten-free beer offerings. Gluten-free crackers, made from ingredients like rice, almond flour, and quinoa, make for an excellent snack or a delightful accompaniment to a daily diet[53]. Other less obvious gluten-containing foods like cured meats and sausages, candy, chips/crisps, and malted beverages are also available in gluten-free versions, but they should be labelled correctly to show that they are gluten-free[57,58]. Potential buyers should go through ingredient lists and seek products certified by organizations like the Gluten-Free Certification Organization (GFCO) or the Celiac Support Association (CSA) is indeed an essential practice for individuals with gluten sensitivities or celiac disease. These certifications can provide assurance that the product is gluten-free and meets certain standards.

Gluten-free (GF) foods are often considered healthier than gluten-containing ones. However, one study indicated that the mean calorie, salt, saturated fat, and total sugar contents of most (GF) items available in supermarkets are not considerably better than those of conventional products[53]. Also, gluten-free (GF) products have less protein than regular ones. The majority of GF products contain high-carbohydrate, low-protein wheat alternatives such as white rice flour, maize flour, maize starch, and potato starch. Low dietary fiber content and increased carbohydrate digestibility are commonplace in gluten-free goods that rely heavily on refined flours and/or starches[55]. As a matter of fact, they typically contain fewer dietary fibers than their conventional equivalents[59]. Obesity and its associated diseases, such as type 2 diabetes mellitus and cardiovascular disease, have been related to the overconsumption of high-carbohydrate, low-fiber meals[60]. Individuals with celiac disease, wheat allergy, or NCGS, as well as those who avoid gluten for other health reasons or out of personal preference, may be at a higher risk of becoming obese if they consume an excessive amount of low-fiber gluten-free (GF) foods. So, while those with gluten sensitivities or intolerances can safely consume current gluten-free (GF) food products, they do not seem to be considerably healthier than gluten-containing foods. This opens the door for the creation of gluten-free cereals that are high in fiber and phytonutrients and have a low glycemic index (meaning they digest slowly). Therefore, one such chance is presented by sorghum.

6. Opportunities for sorghum-based foods

Grain sorghum (GS) is a cereal that is naturally gluten-free. Prolamin (7%–9% by weight) is the primary storage protein in GS, just as it is in many other types of cereal grains. In contrast to gluten, secalin, and hordein, the kafirin (sorghum prolamin) proteins found in GS do not cause patients with CD or other kinds of gluten intolerance to exhibit any symptoms[61]. As an inhibitor of protein and starch digestion, kafirins perform functions analogous to those of ATIs. In the presence of wet heat, kafirins interact with both each other and proteins that are not kafirin to build complex protein matrices that are resistant to being digested by enzymes[58]. These protein matrices bind with starch granules in the endosperm, preventing amylases from doing their job[62].

There is currently no conclusive evidence linking kafirins to intestinal inflammation. In contrast, a recent study found that kafirins, a commonly used model for evaluating the anti-inflammatory properties of chemical compounds, block lipopolysaccharide-induced inflammation in THP-1 human monocytes[58]. The research indicated that kafirin's antioxidant capacity is linked to its anti-inflammatory benefits. This finding may imply that kafirins, in contrast to amylase/trypsin inhibitors (ATIs), do not increase gastrointestinal symptoms in people with NGCS. However, this idea must be tested further in order to be confirmed. Despite a lack of evidence, GS has been labelled as a low FODMAP cereal[58,61] confirming or refuting (GS) low FODMAP designation requires looking into its FODMAP and fructan content.

In addition to not containing gluten, many studies have found that components of GS, when consumed on a regular basis, may prevent obesity, type 2 diabetes, and cardiovascular disease[63]. Due to the fact that GS has a low starch digestibility, it contains a higher proportion of slowly digestible starches (SDS) and a lower proportion of readily digestible starches (RDS) in comparison to maize, barley, wheat, rice, and oats; as a result, it is less likely to cause post-prandial glucose spikes[64]. Cooking with moisture and heat may also increase the amount of resistant starch (RS) present in GS[65]. Due to the fact that it cannot be digested by humans, RS is functionally categorized as a type of dietary fiber. Therefore, it may be helpful in the management of weight by decreasing the energy density of food and increasing satiety, increasing lipid oxidation, and regulating the production of metabolic hormones such as leptin (a hormone that inhibits hunger) and adiponectin, which has insulin-sensitizing, anti-atherogenic, and anti-inflammatory properties[66]. In addition, it has been demonstrated that the oil fraction of the GS lipid content has cholesterol-lowering capabilities, which is important for the maintenance of cardiovascular health[67].

Consuming GS has been shown in a number of studies to be associated with an increase in both the population and the diversity of gut flora, in addition to an increase in the production of short-chain fatty acids (SCFA). One study found that the addition of GS RS to a high-fat meal resulted in a considerable increase in the population of lactobacilli and bifid bacteria in obese mice. This increase was compared to a high-fat diet that did not contain resistant starch (RS)[68]. The addition of wholegrain GS-based morning cereal was shown in another study to result in an increase in the relative abundance of beneficial gut bacteria as well as the synthesis of short-chain fatty acids (SCFA) (particularly acetate) in a baby gut microbiota model system after the supplementation of said cereal[69]. The increased polysaccharide content of GS was connected with this alteration. The polyphenol content of GS pericarp (particularly condensed tannins and 3-deoxyanthocyanins) has also been demonstrated to increase the variety and number of intestinal bacteria in mice. This was discovered through experiments[70].

7. Types of food products made from sorghum

7.1. Traditional ways of consuming sorghum

Traditional cuisines are made with grain sorghum (GS) in Africa and India, where it is produced for human consumption. Cooking entire grains in water is comparable to cooking rice. Boil the grains whole or decorticate before cooking. Milling grains into flour is the most common preparation method. Gruels, pancakes, dumplings, couscous, and flatbreads can be made with the flours[71]. Sudanese kisra and Indian jowar roti, both flatbreads, are eaten with meat or vegetable side dishes. Sorghum flour, water, and seasonings like salt and sugar make these dishes. The grains can also be burst or puffed and eaten as a snack or used to make traditional alcoholic drinks[56]. Sorghum consumed in different forms in different countries is consolidated in **Table 3**.

Grain sorghum (GS) flour is limited in food use. Due to the lack of gluten, GS flour has poor rheology[72]. Gluten gives wheat flour its elasticity and cohesion for doughs and batters. Thus, doughs made with (GS) flour lack elasticity and break apart quickly[73]. GS flour products are dry and crumbly, so more moisture is needed to obtain a good texture[74]. Whole grain sorghum (GS) imparts grittiness due to its tougher pericarp than most cereal grains[75]. GS tannins may also cause bitterness and astringency[76]. Low-tannin cultivars have a more neutral flavor; therefore, this is not an issue. GS has sluggish protein and carbohydrate digestion. The proteins also lack lysine, an important amino acid that helps the body synthesize protein[75].

Sorghum-based dishes are prepared using conventional methods. These methods include soaking and/or germination before milling, fermentation with naturally occurring bacteria, and alkali treatment with wood ash[77]. These approaches improve dough/batter quality and palatability, increase nutritional availability, and reduce anti-nutrients such as tannins and phytic acid. Lysine is scarce in GS; therefore, these approaches do not boost its availability. By adding lysine-rich legumes to GS, this can be solved[78].

Table 3. Types of food products made from sorghum in global level.

Country of origin	Food type	Food name	References
India	Main meal	Annam	Khoddami et al.[9]
China		Kaoliang mi fan	
Botswana		Lehata wagen	
Ethiopia		Nufro	
India	Snacks	Popped sorghum	Sathe and Mandal[79]
China	Breakfast	Noodles	Aruna et al.[80]
India		Idli	
India		Upma	
India	Sweet	Kesari	Cayres et al.[81]
India		Laddu	
Nigeria	Beverages	Pito	Khoddami et al.[9]
China		Baijiu	
Ghana		Obiolor	
India	Ferment products	Bhakri	Sathe and Mandal[79]
India		Dosa	
Sudan		Kisra	
Ethiopia		Injera	
China		Mantou	

8. Sorghum in modern food products

Some effort has been made to popularize grain sorghum (GS) in gluten-free (GF) food products in industrialized nations, particularly in the US and Australia. Options are still limited to a few product categories. GS flour and pearled (decorticated) grains are available in health food stores, although not as readily as quinoa and buckwheat. Australian shops sell a gluten-free breakfast cereal made of 96% wholegrain sorghum[82]. GF breakfast cereals and snack meals with blends of wholegrain sorghum (15%–24%) and other cereal grains are sold in regular US and Australian shops. Unfortunately, modern food items, especially in industrialized countries, have not fully utilized GS as a GF food source. GS's texture, color, and astringency (especially tannin-rich types) make it seem inferior and a poor man's crop[82]. No gluten-free (GF) items made with GS, such as leavened bread, noodles, and pasta, have been commercialized[71] due to a lack of technology dissemination and government policy backing[9].

Unless customers know that new GF food products have significant benefits, it will be difficult to introduce them. GS's health risks are well-known yet underreported. Instead of emphasizing its GF status, its other nutritional or health benefits can be promoted. Obesity and digestive disorders have increased demand for functional food items with terms like whole grain, high fiber, and cholesterol-reducing, and GS has the ability to supply them[84].

9. Antinutritional properties of sorghum

Sorghum is a commonly farmed grain that is an important source of nutrition for millions of people worldwide. Like many other grains, sorghum includes chemicals with antinutritional qualities, which may reduce its nutritional benefit and also have negative effects on human health.

Sorghum is rich in tannins, and plant polyphenols that can bind to proteins, reducing their digestibility. Tannins can also hinder the absorption of minerals like iron and zinc. Studies have shown that tannin-rich sorghum consumption can lead to impaired iron absorption and potentially cause anemia[85]. It also contains substantial amounts of phytic acid, which binds to essential minerals such as iron, zinc, and calcium, limiting their bioavailability. This can result in mineral deficiencies and stunted growth, as demonstrated in studies involving pigs fed sorghum-based diets[86]. A research study conducted by Abdel Rahman and Osman[87] investigated the presence of antinutritional components like tannins and phytic acid in various sorghum varieties and examined how traditional processing techniques affect their reduction. The findings of the study revealed that traditional processing methods, such as soaking, malting, and fermentation, led to a substantial decrease in antinutritional factors within sorghum. Sorghum includes protease inhibitors, which interfere with the activity of digestive enzymes and reduce protein digestibility. This, in turn, can hinder growth and weight gain in animals consuming sorghum-containing diets[88]. In some sorghum varieties, cyanogenic glycosides are present. When consumed, these compounds can release cyanide, leading to respiratory distress, seizures, and even fatality. Ensuring low levels of cyanogenic glycosides in sorghum is crucial for safety[89].

To enhance sorghum's nutritional value and safety, thorough research into its antinutritional properties is crucial. This may involve studying genetic and biochemical processes related to compounds like tannins, phytic acid, protease inhibitors, and cyanogenic glycosides. Understanding these mechanisms may inform mitigation strategies, such as selective breeding and innovative processing techniques. Investigating the health impacts, especially on nutrient absorption and well-being, is essential. Interdisciplinary collaboration among researchers, agronomists, and food scientists is vital for progress.

10. Sorghum processing technologies

Processing is the technology used to transform the grain into an edible form, improving its quality. When using cereals and millet as food, processing plays a vital role[15]. Various processing technologies are employed in the production of food products for the purpose of enhancing nutritional profile, sensory attributes, and convenience. The bioavailability of micronutrients in plant-based diets can also be increased through the use of a variety of traditional processing and preparation techniques[90]. The terms thermal processing, mechanical processing, soaking, fermentation, and germination/malting all refer to different types of processing. These approaches seek to improve the physiochemical accessibility of nutrients, reduce the presence of anti-nutrients such as phytates, or raise the content of compounds that enhance bioavailability[91].

Food processing operations in sorghum involve primary and secondary processing steps. To maintain the quality of the grain, primary processing is essential to ensure the quality of processed foods. This process eliminates stones, hay, glumes, animal manure, and other debris. Grading and sorting are utilized to eliminate grains that are too large, too small, immature, or of poor quality[92]. Secondary processing is a series of processes in which primary-processed raw materials are transformed into ready-to-eat and ready-to-cook products[93]. As a commercially processed food, sorghum is less prevalent in India, this is due to a lack of processing technologies, a dearth of machinery, and inconsistent grain availability, among other factors. In semiarid areas, grinding and milling are performed by hand, and unfermented baked goods and fermented foods are used to prepare sorghum-based foods. These processes are labor-intensive and almost exclusively performed by manual operations, hence final goods are of low quality[94]. To obtain consumable sorghum products, the grain must undergo processing. As with other cereals, there is no established technological information on the industrial processing of sorghum. Milling, popping, fermentation, and malting are the most frequent sorghum processing techniques. Sorghum processing uses extrusion, baking, brewing, and wet milling for starch separation[61]. This processing has increased the shelf life, value addition, end-product utilization, and sorghum/millet consumption. Some of the reported processing techniques for sorghum are presented in **Table 4**.

One of the primary processing technologies includes dehulling. Dehulling is also called decortication or debranning[95]. It is done to remove the outer layer known as the pericarp. Pestle and motor or hand-pounding dehull grains. This approach wastes grains and does not entirely remove the husk. Poorly dehulled grains cannot produce high-quality flour[96]. The removal of sorghum's collagenous layers can be accomplished mechanically. The prototype dehuller uses grinding discs for abrasive dehulling. The feeder lowers the grain into the dehulled chamber, where grinding stones dehull it through the assessment door[95]. After that, the grain is expelled from the machine through a door located at the bottom of the machine designated for that purpose. Pearling sorghum grain eliminates bitterness and improves palatability when ground into flour[97]. Kernels with hard endosperm or a lot of endosperms are better for dehulling and give higher yields. Soft endosperm kernels have lower yields and higher operating losses. Nevertheless, steaming delicate endosperm kernels for a few minutes may harden them enough to be separated from the hull[98]. In this process there is a loss of nutrients due to the pericarp, which contains fiber and minerals, being removed, and the grain's coarseness is also removed. To minimize the loss of nutrients partial dehulling is done. Dehulling after hydrothermal treatment helps in the redistribution of micronutrients in the endosperm. This method is used to soak, steam, and dry paddy[95,95]. This technology is used by rice-growing nations like India, Sri Lanka, Pakistan, Indonesia, Nepal, and Bangladesh. Pre-treatment is required prior to removal of the hull to (a) loosen the hull, (b) ease milling, (c) reduce breakage and (d) improve the quality of splits[99].

In most cases, hydrothermal treatment will result in the endosperm becoming harder. This will, in turn, result in increased milling yield recoveries and a reduction in breakages and operational loss[98]. The grain is rehydrated through a process that involves soaking it in normal or hot water in order to achieve the desired temperature. After the grain has been soaked, it is heated in steam until the starch granules become gelatinized, then the dried grain is milled[100,101]. Parboiling could be a good way to increase the dehulling yield of millets, just as it has been one of the best ways to increase the yield of rice[102]. The three steps of the parboiling process are soaking, boiling/steaming, and drying. These three steps in the parboiling process make the rice grains harder, which makes them easier to mill[103]. The use of hydrothermal treatment in grain sorghum can help to reduce the nutrient loss that occurs during milling[95], especially by redistributing nutrients and heat-stable vitamin B complex from the grain's outer layers to its inner layers[104]. The Directorate of Sorghum Research has regulated and perfected the methodology for parboiling sorghum. The grain is steeped in water to increase its moisture content, followed by 15 min of steam cooking. It is then dried and utilized for further dehulling and grinding. By employing this method, dehulling and milling yield rates are raised while breakages are decreased[105].

Sorghum processing technologies and equipment are not widely available. Research and Development institutions have created laboratory designs and early versions of machinery as well and agricultural universities have created lab models and prototype machinery, but there is a limited supply of sorghum processing technology and machinery[106]. In Nasik, Maharashtra, and Theni, Tamil Nadu, tiny millets are sold in considerable quantities. These mills are capital-intensive, and their yield is just between 50%–52%. Therefore, the creation of an integrated processing mill that can meet the needs of private enterprises, farmer-producer organizations or individual farmers may be a feasible option[107]. A reliable unit would boost economic development and benefit individual businesses and the local community.

Table 4. Different processing technologies of sorghum and their findings.

Processing types	Key findings	References
Soaking	The process of soaking sorghum grains activates enzymes and breaks down stored food reserves, effectively reducing antinutritional components.	Desta et al.[108]; Rashwan et al.[77]
	Soaking boosts the flavonoid levels in sorghum grains, without impacting total phenolics and condensed tannin. The rise in total flavonoids may result from the liberation of previously bound phenolic compounds as water enters the cell walls.	Xiong et al.[109]
	Soaking sorghum in a 1% alkaline solution leads to flour with increased carbohydrates, better water and oil absorption, higher pH, lower bulk density, and decreased hydrogen cyanide levels compared to untreated and water-treated sorghum flours.	Ocheme Boniface and Esther Gladys[110]
	A notable decline in total flavonoids, total phenols, β-carotene, vitamin-E, and antioxidant activity was evident in sorghum grains soaked for 20 hours in comparison to raw sorghum.	Afify et al.[111]
Wooden ash treatment	Wood ash extract treatment was applied to high-tannin sorghum, effectively reducing tannin levels while preserving the grain's nutrient content.	Kyarisiima et al.[112]
	During the wood ash treatment, the respiration of germinated grains leads to a dry matter loss of approximately 20%.	Rashwan et al.[77]
	The tannin content decreased by 39.5% (from 47.3 to 28.6 g catechin equivalent/kg), and metabolizable energy increased by approximately 7.3% after treating sorghum grains (SGs) with wood ash extract. Additionally, diets with germinated SGs, soaked in ash extract, exhibited improved ileal digestibility for dietary protein and fat when compared to untreated grain diets.	Kyarisiima et al.[113]
	Soaking sorghum grains for 24 h with added wood ash extract decreases tannin levels by 50.2%. This decline may result from tannin hydrolysis, depolymerization in an alkaline environment, or the interaction of tannins with abundant cations like potassium, sodium, and calcium found in wood ash extract.	Benhur et al.[114]
Germination	The researchers examined the impact of a 20-h soak followed by 72 h of germination on phytate levels and mineral bioavailability in sorghum. The phytate content decreased significantly, likely due to the action of enzymes formed both externally and within the grain during germination. This reduction led to a notable enhancement in the bioavailability of iron and zinc.	Afify et al.[111]
	Protein solubility, in vitro protein digestibility, and free amino acid levels showed substantial improvement, while cross-linked kafirin and cross-linked glutelin were reduced. This likely occurred because of the activation of proteolytic enzymes, intrinsic amylases, proteases, phytases, and fiber-degrading enzymes, which collectively enhanced nutrient digestibility.	Afify et al.[115]
	Following a 3-day germination period, sorghum flour displayed notable reductions in both loose and packed bulk densities, as well as an increase in water absorption capacity and oil absorption capacity. Moreover, swelling, foaming, and emulsion capacities significantly improved, indicating enhanced functional properties–with swelling capacity reaching 23.2 mL/g, foaming at 16.2%, and emulsion at 65.5%.	Ocheme et al.[116]
	Germination led to a significant increase in hydrogen cyanide (HCN) content in various sorghum varieties. The HCN content in ungerminated samples ranged from 11.7 to 14.7 ppm, while in germinated samples, it ranged from 141.3 to 163.4 ppm after 48 h at 23 °C.	Chove and Mamiro[117]

Table 4. (*Continued*).

Processing types	Key findings	References
	The research suggests that HCN content can be decreased by shortening the germination time, combined with other processes such as alkaline soaking or nixtamalization.	Desta et al.[108]; Rashwan et al.[77]
Fermentation	Traditional fermentation (TF) of sorghum led to a significant increase in in vitro protein digestibility and a notable decrease in enzyme inhibitory activities. Trypsin inhibitory activity decreased by 31%–58%, amylase inhibitory activity reduced by 74%–75%, and tannin content decreased by 15%–35% during fermentation.	Osman[118]
	Traditional fermentation (TF) of sorghum significantly decreased tannin content by about 52.7%–56.9%, while phytic acid content was reduced by more than 50%. Trypsin inhibitory activity levels were reduced by approximately 76.5%–87.4%. This reduction in antinutritional factors, including phytates, phenols, tannins, and enzyme inhibitors, may result from the action of exogenous and endogenous enzymes, such as phytase and tannase, formed during the fermentation process, as indicated by Afify et al.[111].	Cardoso et al.[119]
	The Lactic acid bacterial fermentation (LABF) process significantly increased the γ-amino butyric acid content in red and white sorghum, by 20% and 30%, respectively. The intestinal bio accessibility of γ-amino butyric acid was found to be 30% for both types of sorghum. In red sorghum, there was an increase in the free form of ρ-coumaric acid, but the contents of caffeic, ferulic, and sinapic acids decreased. Conversely, white sorghum exhibited high levels of free ρ-coumaric and sinapic acids.	Aleminew et al.[120]
Nixtamalization or lime cooking (i.e., $Ca(OH)_2$, NaOH)	Nixtamalization (using 1% lime) of sorghum resulted in sorghum flour with increased protein content, enhanced water and oil absorption capacity, higher pH, greater hygroscopicity, and elevated levels of phytate and trypsin inhibitor compared to the untreated sorghum.	Cabrera-Ramírez et al.[121]
	The ash, tannin, and hydrogen cyanide (HCN) content in nixtamalized sorghum flour were notably lower when compared to untreated sorghum flour and water-treated sorghum flour.	Annapure et al.[122]
	Nixtamalization significantly increased the bio accessibility of non-digestible protein fractions by 5.26% in red sorghum and 26.31% in white sorghum. This enhanced bioavailability appears to influence genes and proteins related to apoptosis, proliferation, cell cycle regulation, and inflammation, offering potential protection against various stages of colon cancer. Additionally, the nixtamalization process improved sorghum protein accessibility, depolymerized condensed tannins, and disrupted protein-tannin complexes[123].	Castro-Campos et al.[124]
	Alkaline cooking positively altered the bioavailability of sorghum compounds, increasing their concentrations and reducing anti-nutritional factors like tannins, consequently enhancing antioxidant capacity. Among the techniques, nixtamalization was the most effective in reducing tannins by 74.3%, and gallic acid emerged as the most bioaccessible phenolic compound at 6359 µg/g.	Luzardo-Ocampo et al.[125]
Irradiation	The study investigated the impact of gamma irradiation on sorghum's nutritional quality. Sorghum samples were exposed to two different doses using a Cobalt-60 package irradiator (0 and 2 kGy). The results showed a noteworthy decrease in phytic acid and tannin content in the irradiated sorghum grains.	Hassan et al.[126]
	Irradiation substantially reduced tannin and phytate levels by approximately 28%–86% and 39%–90%, respectively, compared to untreated samples. Additionally, it enhanced the in vivo digestibility of dry matter, crude protein, true protein, and gross energy.	Shawrang et al.[127]
	Gamma irradiation is a viable method for decontaminating sorghum flours used in weaning porridge production. A dose of 10 kGy improved the porridge's characteristics while notably reducing α and β amylase activity.	Rashwan et al.[77]

11. Sorghum's potential future opportunities

In comparison to many other agricultural crops such as corn, wheat, oats, and barley, the future revenues, demand, and utilization of sorghum will be influenced by a number of factors. The impact of global change on agricultural output and agriculture, as well as the need for adaptation to these changes, is one of the greatest obstacles for farmers around the world. Another strategy is to breed new cereal kinds that are resistant to climate change. Numerous researchers are therefore interested in exploring and exploiting the sorghum phenotypic variation by examining sorghum's wild counterparts that may have persisted for centuries under harsh climate conditions. The corporatization of sorghum-based packaged foods for unconventional western consumers presents the most difficulty. To raise awareness of sorghum, it is vital to comprehend the limitations of the supply chain and the causes of inadequate cooperation between key players[128].

12. Conclusion

Gluten, a protein found in wheat, barley, and rye, can produce severe effects in individuals with celiac disease, non-celiac gluten sensitivity, and wheat allergy. To avoid symptoms and health issues, those people must avoid gluten. For most individuals without gluten-related diseases, a gluten-free diet has no proven benefits. Sorghum grain has tremendous potential as a valuable gluten-free food ingredient. Its distinctive nutritional profile, gluten-free nature, and adaptable properties make it an excellent choice for manufacturers seeking to create high-quality gluten-free food products. Due to its high levels of dietary fiber, protein, antinutritional properties and essential minerals, sorghum is a nutritious and healthy option for gluten-free diets. It is an attractive alternative to traditional gluten-containing grains such as wheat and barley due to its neutral flavors and ability to mimic the texture of wheat flour. In addition, sorghum's resistance to drought and other unfavorable climatic conditions makes it a sustainable and environmentally friendly crop, making it a socially responsible option for manufacturers. In gluten-free food product formulations, sorghum grain is a promising ingredient. Its potential as a healthy, nutritious, and adaptable ingredient makes it an attractive option for manufacturers seeking to produce high-quality gluten-free food goods that are capable of meeting the requirements and preferences of the expanding gluten-free procurer market.

Conflict of interest

The authors declare no competing interests.

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