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Disorders related with gluten and sources for gluten-free diet

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Abstract
Wheat, a staple cereal crop that provides sustenance and vital nutrients to billions of people worldwide, contains a structural protein known as gluten. While gluten is essential for the dough-making properties of wheat, it can also lead to intolerances in certain individuals, giving rise to distinct conditions such as celiac disease (CD), wheat allergy, and nonceliac gluten sensitivity (NCGS). CD, an autoimmune disorder, arises when the immune system erroneously targets the lining of the small intestine upon gluten consumption. In contrast, wheat allergy involves an immune-mediated allergic response, with specific IgE antibodies produced against wheat proteins. NCGS, a more recently recognized condition, manifests as adverse symptoms following the ingestion of gluten or other cereal components. Notably, NCGS does not entail autoimmune or IgE-mediated immune responses. Although these disorders share a common trigger in gluten, their underlying mechanisms, immune responses, and long-term implications differ significantly. The sole effective treatment for gluten-related disorders lies in strict adherence to a gluten-free diet, which necessitates avoiding all sources of gluten-containing grains. This review aims to provide a comprehensive overview of gluten-related disorders and present sources of gluten-free diets.

Keywords: Gluten, celiac disease, wheat allergy, gluten-sensitivity

Introduction
Cereal crops play a significant role as a primary food source for the human population. Wheat, rice, and barley are among the key cereal crops cultivated globally. These cereals serve as staple foods, providing a substantial portion of the calories necessary for human nutrition. Over 10,000 years ago, gluten-containing grains were introduced into the human diet, and since then, the selection of wheat varieties has focused more on technological aspects rather than their nutritional value. Gluten, due to its technological and sensory properties, is widely used in the food industry (Day *et al*. 2006) [20]. However, in recent decades, there has been an increase in adverse reactions to gluten, likely due to the widespread exposure to gluten-containing grains (Lebwohl, Sanders, and Green 2018) [54]. Gluten-related diseases, such as celiac disease (CD) and IgE-mediated wheat allergy, are well-known conditions associated with the consumption of gluten-containing grains. CD, an autoimmune disease, can cause significant intestinal damage and is influenced by genetic susceptibility factors. Its prevalence in the general population is estimated to be around 0.5%–1% (Cabrera-Chavez *et al*. 2017; Mustalahti *et al*. 2010) [11, 67]. On the other hand, wheat allergy involves an immune response mediated by IgE antibodies, which recognize specific proteins (allergens) and trigger allergic inflammation (Pietzak, 2012) [73]. Nonceliac gluten sensitivity, a recently identified condition, is characterized by symptoms experienced after consuming gluten and/or other cereal components. Improvement is observed when following a gluten-free diet or reducing gluten intake, although it does not involve autoimmunity or IgE-mediated allergy (Fasano *et al*. 2015) [73]. Adherence to a gluten-free diet is currently the only treatment for gluten-related disorders. Pseudocereals, which are gluten-free grains, have gained popularity in modern diets due to their excellent nutritional and nutraceutical value. They are considered important resources for the development of functional foods, and recent research has highlighted their potential health benefits (Joshi *et al*., 2018, 2019) [48-19].

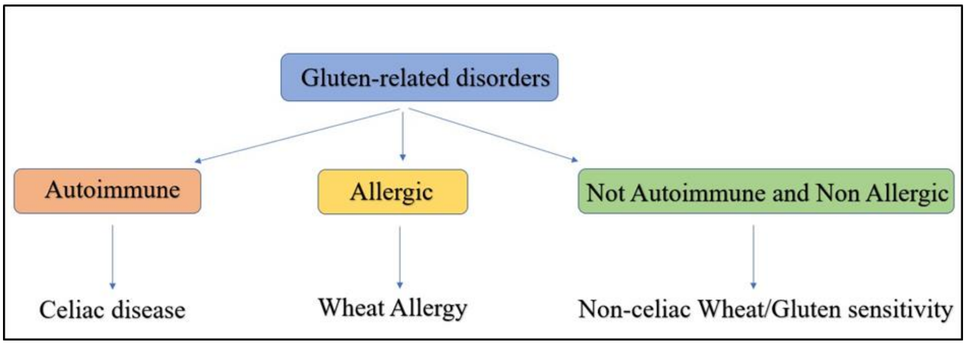

Fig 1: Gluten related disorders

Celiac disease

Celiac disease (CD) is a chronic autoimmune disorder of the small intestine that occurs in individuals who are genetically susceptible and exposed to gluten and gluten-related proteins. The estimated prevalence of CD in the general population ranges from 0.5% to 1% in different parts of the world (Mustalahti *et al*. 2010; Gujral, Freeman, and Thomson 2012) [67, 37]. Genetic factors, particularly major histocompatibility complexes (MHC), play a significant role in determining susceptibility to CD. When individuals with genetic predisposition consume gluten or gluten-related proteins, it triggers an immune response that leads to inflammation and damage in the intestinal tissue. This immune response involves specific T cell populations, proinflammatory cytokines, autoantibodies targeting an intestinal enzyme, and impaired T regulatory cells (Meresse, Malamut, and Cerf-Bensussan 2012) [61].

CD is characterized by immune-mediated enteropathy of the small intestine, and it is primarily caused by the ingestion of gluten proteins found in certain cereals such as wheat, rye, and barley (Freeman HJ *et al*. 2011; Scherf KA *et al*. 2016) [29, 82]. These cereals are closely related to wheat, while more distantly related species do not trigger CD. The involvement of oats in causing CD is a subject of debate (Fric P *et al*. 2011; Comino I *et al*. 2015) [30, 18]. Although oats themselves do not contain gluten, they contain similar proline-rich storage proteins called "avenins" in a small percentage (10-15% of total protein content). Some individuals may exhibit intolerance to oats due to the presence of certain CD epitopes with different structures, albeit at a low intensity (Hardy MY *et al*. 2015; Gilissen LJ *et al*. 2016) [32, 40]. However, ensuring the production of pure, uncontaminated oats that are free from gluten-containing cereals poses a significant challenge in conventional production chains, as there is a high risk of cross-contamination with wheat, rye, and barley during various stages, such as sowing, cultivation, harvesting, milling, and processing of oats (De Souza MCP *et al*. 2016) [22]. Figure 2 illustrates the gluten-rich cereals capable of inducing CD immunogenicity in patients. Both glutenins and gliadins, the protein components of gluten, contain specific amino acid sequences that act as epitopes for CD and are referred to as immunogenic peptides, antigenic peptides, T-cell epitopes, CD-eliciting epitopes, or toxic peptides (Camarca A *et al*. 2009; Singh P *et al*. 2018) [13]. These CD-eliciting peptides are resistant to degradation in the gastrointestinal tract due to their high content of proline and glutamine amino acids.

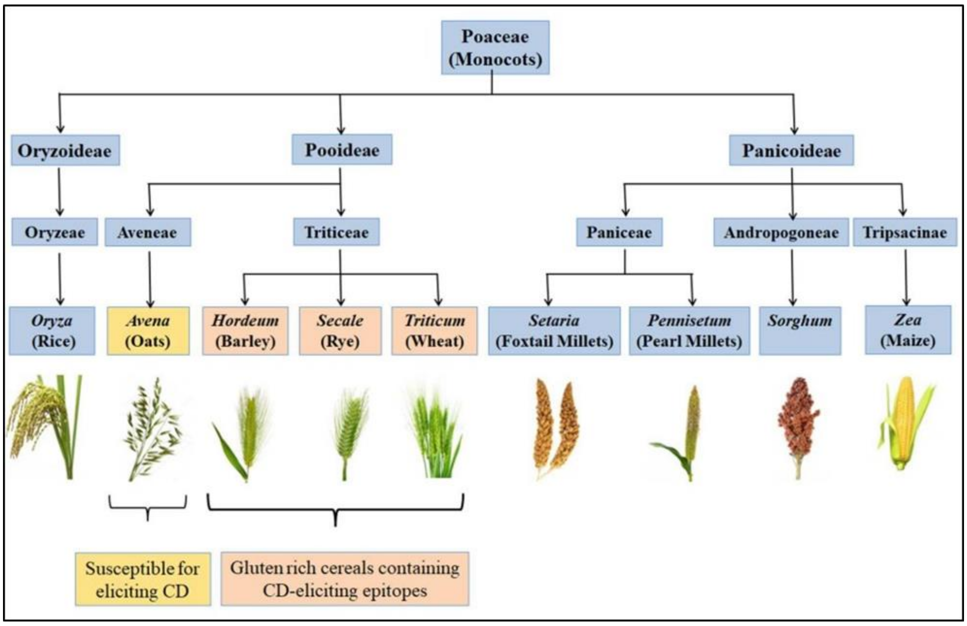

Fig 2: Categorization of monocots and their potential to trigger CD. Cereals rich in gluten, such as wheat, rye, and barley from the Triticeae family, contain epitopes that can elicit CD (highlighted in pink boxes). Oats fall into the category of cereals that have the potential to elicit CD (highlighted in a yellow box), while many other cereals are considered safe for individuals with CD (highlighted in blue boxes) (Sharma *et al*. 2020) [85].

Symptoms: CD is a chronic inflammatory condition that primarily affects the small intestine, specifically the jejunum, leading to villous atrophy. This results in the flattening of the villi in the small intestine, which greatly reduces the surface area available for nutrient absorption as shown in figure 3. As a consequence, individuals with CD may experience malnutrition, deficiencies in vitamins and minerals, and various gastrointestinal symptoms, including abdominal discomfort, bloating, loose bowel movements, and nausea (Green PH *et al*. 2007; Nardecchia S *et al*. 2019) [3, 68].

If left untreated, CD can give rise to several chronic conditions and non-gastrointestinal symptoms. These may include anemia, osteoporosis, fatigue, infertility, eczema, and refractory CD, which is associated with an increased risk of developing lymphoma (Scherf KA *et al*. 2016; Hamer RJ *et al*. 2005) [82, 39]. The symptoms of CD can vary widely and can manifest at any age. There are also certain diseases and disorders that are occasionally linked to CD, such as type I diabetes, Hashimoto's thyroiditis, Grave's disease, Sjogren's syndrome, Down syndrome, Turner syndrome, primary biliary cirrhosis, and neurological disorders like unexplained peripheral neuropathy, epilepsy, and ataxia (Green PH *et al*. 2005; Stordal K *et al*. 2013; Leffler DA *et al*. 2015; Canova C *et al*. 2016) [34, 14, 56, 91].

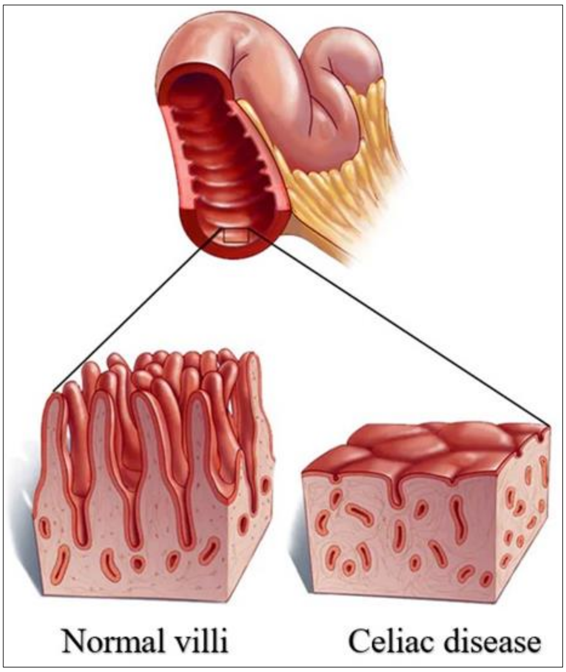

Fig 3: Depiction of healthy villi and CD affected villi

(NCGS) Non-celiac gluten sensitivity

Non-celiac gluten sensitivity, also known as gluten sensitivity, refers to the experience of discomfort or distress following the consumption of gluten and/or other components found in cereals. Unlike celiac disease (CD) and IgE-mediated allergy, nonceliac gluten sensitivity does not involve autoimmune or allergic mechanisms. As a result, it does not typically cause permanent damage to the intestines, and the symptoms can be alleviated by following a gluten-free diet (GFD) or reducing gluten intake (Rotondi Aufiero, Fasano, and Mazzarella 2018) [77].

Although nonceliac gluten sensitivity is believed to involve the innate immune system, the potential harm associated with this condition is generally milder and the symptoms are less severe compared to CD or IgE-mediated allergy. The precise definition of nonceliac gluten sensitivity as an independent disease entity is still a subject of ongoing debate (Reese *et al*. 2018) [75].

Symptoms: Common symptoms experienced by individuals with non-celiac gluten sensitivity (NCGS) include abdominal bloating, pain in the upper or lower abdomen, diarrhea, nausea, aphthous stomatitis, and changes in bowel habits. Additionally, NCGS can manifest with non-gastrointestinal symptoms such as mental fog, fatigue, tiredness, a sense of unwellness, headaches, depression, anxiety, joint and muscle pain, numbness in the legs or arms, and skin rash or dermatitis (Sapone A *et al*. 2012, Biesiekierski JR *et al*. 2015, and Casella G *et al*. 2018) [81, 9, 15].

These symptoms tend to resolve when gluten is eliminated from the diet (Elli L *et al*. 2016) and can overlap with those experienced by individuals with irritable bowel syndrome (Esvaran S *et al*. 2013) [27]. While some symptoms may also be present in celiac disease (CD), it is important to note that CD and NCGS differ in terms of their genetic and immunological responses.

Wheat Allergy

Wheat allergy is an immune response characterized by both IgE-mediated and non-IgE-mediated reactions to various wheat proteins, including gluten proteins, although they are not limited to them. In the case of IgE-mediated wheat allergy, T helper type 2 (Th2) cell response plays a crucial role in the production of IgE antibodies by B cells. When IgE antibodies recognize wheat allergens, they crosslink and activate effector cells of allergy, leading to allergic inflammation. The prevalence of wheat allergy varies across different age groups. Clinical manifestations can range from mild and localized symptoms to severe systemic reactions (Inomata 2009) [45].

Individuals with wheat allergy experience allergic reactions upon consuming, coming into contact with, or inhaling foods that contain wheat. These reactions can be mediated by both IgE and non-IgE mechanisms (Czaja-Bulsa G *et al*. 2017 and Jin Y *et al*. 2019) [19, 47]. IgE-mediated allergic responses occur immediately after food consumption, are specific to the offending food, and can be reproduced in controlled settings (Cianferoni A *et al*. 2016) [17]. They involve the release of histamine, platelet-activating factor, and leukotrienes from mast cells and basophils (Sampson HA 1999 and Lee LA *et al*. 2006) [79, 55]. These allergic reactions can affect the skin, respiratory tract, or gastrointestinal tract. TH2 lymphocytic inflammation plays a role in this process, leading to the production of IL-4, IL-5, and IL-13, as well as the generation of food-specific IgE antibodies by B cells (Cianferoni A, Spergel JM, 2009 and Ortiz C *et al*. 2017) [16, 69]. Both genetic factors and environmental influences contribute to the development of this immune response (Romagnani P *et al*. 2000 and Lack G., 2008) [76, 53]. On the other hand, non-IgE-mediated allergic responses are characterized by chronic infiltration of eosinophils and lymphocytes in the gastrointestinal tract. Various types of wheat allergies include food allergy, wheat-dependent exercise-induced anaphylaxis (which occurs when wheat ingestion is followed by physical exercise but not by wheat ingestion alone), and baker's asthma. Moreover, all these three disorders are differentiated in a table 1 (Sharma *et al*. 2020) [85].

Symptoms: Wheat allergy can manifest with a variety of symptoms, including urticaria (hives), stomach cramps, asthma, allergic rhinitis, abdominal pain, vomiting, and atopic dermatitis (Salcedo G *et al*. 2011 and Cianferoni A *et al*. 2012) [78, 17].

Table 1: Difference in gluten-related disorders

Parameter	Celiac disease	NCGS	Wheat allergy
Definition	Autoimmune disorder due to intolerance to gluten proteins	Disorder due to gluten proteins, FODMAPS in food, ATIs in wheat. Different from CD and wheat allergy	Allergic reaction to wheat containing foods through food ingestion, contact, inhalation of flour dust
Reaction time	Slow (30 min to 24 h)	Slow (several hours)	Immediate
Epidemiology	Affects roughly 1% of population	Affects 0.6–6% of population	0.5–9% in children, 0.2–1% in adults
Antigen	Gliadins from gluten	Gluten proteins, ATIs, FODMAPS	ATIs, Gliadins, Peroxidase, Thiol reductase
Immune response activation	Both innate and adaptive immune response	Innate immune response	IgE mediated immune response
Treatment	Following GFD	Avoidance of gluten, FODMAPS in diet (Gluten challenge)	Avoidance of wheat (contact, ingestion, inhalation)

Sources of gluten free diet

The recommended treatment for individuals with CD is a lifelong adherence to a gluten-free diet (GFD) (Itzlinger, A *et al*. 2018) [98]. Consuming gluten despite the diagnosis can worsen clinical symptoms, cause further damage to the intestines, and increase the risk of various cancers, including small intestinal adenocarcinoma, esophageal cancer, melanoma, and non-Hodgkin's lymphoma (Green, P.H *et al*. 2003) [35]. To achieve the best outcomes, this diet requires the complete elimination of gluten-containing foods, including wheat (gliadin), barley (hordeins), rye (secalins), oats (avenins), and other closely related grains. Despite these dietary restrictions, individuals on a GFD are encouraged to incorporate other nutritious food sources into their diet, such as fruits, vegetables, fish, meat, and gluten-free products.

Rice

Rice possesses several important properties that make it suitable for gluten-free (GF) product preparation. It is gluten-free, has a mild taste, is colorless, hypoallergenic, and contains low levels of protein, sodium, fat, and fiber. Furthermore, rice is rich in easily digestible carbohydrates, making it an ideal ingredient for GF flour (Sivaramakrishnan *et al*., 2004). To achieve viscoelastic properties in rice-based products, additives such as gums, emulsifiers, enzymes, modified starch, or dairy products need to be combined with rice. This is necessary because rice has a relatively low amount of prolamin, which is responsible for viscoelasticity (Sivaramakrishnan *et al*., 2004) [88]. Acidic extruded rice flour bread has been found to exhibit similar crust color and texture characteristics to wheat bread, although it has a lower specific volume (Clerici *et al*., 2009) [70]. Rice noodle products are widely consumed in many Asian countries. Since rice protein does not contribute to the formation of a cohesive dough structure, gelatinized starch plays a crucial role as a binder in rice noodles (Cabrera Chavez *et al*., 2012) [10]. The addition of a protein source such as spirulina can enhance the technological characteristics of rice flour products (Doğan *et al*., 2003) [5]. Flaked rice products can be produced by cooking rice, coating it with skim milk for added nutrition, partially drying it, tempering it, passing it through flaking rolls, and toasting it in an oven. Additionally, both non-waxy and waxy rice can be used to make crackers (Arendt *et al*., 2011).

Oats

Pure oats have high protein, fat, and fiber content, making them a suitable choice for individuals with celiac disease. However, the safety of oats in a gluten-free diet (GFD) has raised concerns due to potential contamination with gluten-containing cereals during various stages of production (Mirmoghtadaie *et al*., 2009; Picarelli *et al*., 2001; Thompson *et al*., 2003) [64, 72, 94]. To ensure uncontaminated oats, strategies need to be implemented.

The Professional Advisory Board of the Canadian Celiac Association, in collaboration with Health Canada, conducted a review on pure oat safety in celiac disease. They recommended limited consumption of pure oats, with a daily intake of approximately 20-25 g (65 ml or ¼ cup dry rolled oats) for children with celiac disease and 50-70 g (125-175 ml or ½ to ¾ cup dry rolled oats) for adults with celiac disease (Rashid *et al*., 2007) [74]. Fermented oat slurry can be used as a yogurt-like product suitable for individuals with celiac disease, lactose intolerance, or a milk allergy (Martensson *et al*., 2001) [59]. Furthermore, oat β-glucans have shown technological feasibility as thickening agents in soups and are well-accepted by consumers (Arendt *et al*., 2011).

Amaranth

Amaranth, characterized by small seeds, stands out with exceptional nutritional value surpassing that of other grains, including cereals, and exhibiting higher fiber and mineral content compared to other gluten-free (GF) grains. Notably, amaranth is rich in lysine, arginine, tryptophan, and sulfur-containing amino acids (Gambus *et al*., 2002) [31]. The use of amaranth flour to fortify cereal-based products, such as GF pasta, has already been explored (de la Barca *et al*., 2010) [21]. Amaranth bread, known for its elevated protein, fiber, and mineral levels, is deemed suitable for individuals with celiac disease (Gambus *et al*., 2002) [31]. Incorporating a combination of popped and raw amaranth flour in bread recipes yields loaves with a higher specific volume and a more uniform crumb compared to other types of GF bread (de la Barca *et al*., 2010) [21].

Quinoa

Quinoa protein stands out for its richness in essential amino acids, particularly lysine, methionine, and cysteine. This makes it an excellent complement to legumes, which are typically low in methionine and cysteine. Moreover, quinoa is a notable source of Vitamin E, B group vitamins, and exhibits high levels of calcium, iron, and phosphorus. It also possesses a favorable fatty acid composition (Schoenlechner *et al*.,

2010) [83]. In the realm of snack production, Dogan and Karwe demonstrated the potential of quinoa in creating a novel and nutritious extruded snack product. Due to quinoa's high lipid content and low amylase levels, the process of extrusion cooking requires a high shear force (Dogan *et al*., 2003) [25].

Buckwheat

Buckwheat seeds are rich in fagopyritols, a type of soluble carbohydrates. Fagopyritols serve as a source of D-chiro-inositol, a compound known for its positive impact on glycemic control in patients with noninsulin-dependent diabetes. Furthermore, buckwheat exhibits a low glycemic index and offers additional health benefits such as blood pressure reduction and support for cholesterol metabolism (Ikeda *et al*., 2006) [44]. When buckwheat flour is used as a substitute for cornstarch in gluten-free (GF) bread, it has been observed to have favorable effects on bread texture and helps delay staling due to its lower starch gelatinization enthalpy (Wronkowska *et al*., 2013) [96]. Incorporating buckwheat in the production of GF crackers yields products that demonstrate acceptable sensory qualities, making it a viable ingredient for such applications (Sedej *et al*., 2011) [84].

Maize

Maize, with its high yields, plays a crucial role in ensuring food availability and promoting food security (Mboya *et al*., 2011) [60]. It is widely recommended as a safe source for producing gluten-free (GF) pasta. Moreover, maize grits or meal can be utilized in extrusion cooking to create a variety of snack products, including curls, puffs, and balls. Additionally, alkaline processed maize can be used to produce fried snacks like tortilla chips. Maize also serves as a key ingredient in the production of breakfast cereals, including flakes, shreds, granules, puffs, and other forms (Arendt *et al*., 2011).

Millet

Millet is a nutritious grain that serves as a good source of various nutrients, including fiber, calcium, and minerals (Singh *et al*., 2012). It contains approximately 7% to 12% protein, with lysine being the limiting amino acid, while tryptophan and threonine are not deficient (Hymavathi *et al*., 2011) [43]. Millet is commonly used to make flatbreads such as injera, kisra (fermented), and roti (unfermented). Injera made from millet has a slower staling process compared to those made from sorghum or other cereals. Teff, a type of millet, has a protein content similar to other cereals (10%-12%) and is notable for its mineral content, particularly calcium and iron. Teff grain is primarily used in making injera (Yigzaw *et al*., 2001) [97]. The slow retrogradation rate of teff starch helps delay bread staling (Arendt *et al*., 2011; Alaunyte *et al*., 2012) [1]. To overcome millet's lysine deficiency, it can be blended with lysine-rich flours like legume flours. Millet is also utilized in the production of various products such as baby foods, snack foods (Hathan *et al*., 2011) [41], breakfast cereals (Srivastava *et al*., 2012) [89], and complementary and infant foods, where germinated, popped, and roasted millet flours are combined with milk solids, legume flour, and other cereals (Griffith *et al*., 1998) [36].

Sorghum

Sorghum is a versatile grain that can be processed into white, pleasant-tasting, and gluten-free flour (Taylor *et al*., 2006) [93]. However, the nutrition quality of sorghum protein is low due to its deficiency in essential amino acids. The process of malting can increase the lysine content and improve the overall protein quality (Anglani *et al*., 1998) [4]. When making sorghum bread, it is important to use soft batters instead of firmer dough to achieve adequate rise and good elasticity without brittleness. This often requires the addition of more water to the bread recipe (Taylor *et al*., 2006) [93]. Sorghum naturally contains polar lipids, soluble proteins, and soluble pentosans, which help in creating liquid films around gas cells and stabilize them. This property makes sorghum suitable for producing bread without the need for additives. However, the addition of hydrocolloids can further enhance the quality of sorghum bread (Taylor *et al*., 2006) [93].

Chestnut

Chestnut flour is rich in high-quality proteins, with 4%–7% essential amino acids. It also contains 20%–32% sugar, 50%–60% starch, 4%–10% dietary fiber, 2%–4% fat, and various vitamins and minerals, including B group vitamins, Vitamin E, phosphorus, magnesium, and potassium. The nutritional value of most gluten-free flours is often lacking in terms of Vitamin B, iron, folate, and dietary fiber. Incorporating chestnut flour into gluten-free recipes can be advantageous for improving the nutritional content (Stoven *et al*., 2012) [92].

However, chestnut bread faces challenges in terms of volume and color due to weak interactions between the components of the chestnut dough, inadequate starch gelatinization, and high levels of sugar and fiber (Stoven *et al*., 2012) [92]. Nevertheless, chestnut flour is better suited for pastry making (Stoven *et al*., 2012) [92]. To address these issues, blending chestnut flour with other flours such as rice flour (Demirkesen *et al*., 2010) [23] and incorporating hydrocolloids like guar gum, xanthan gum, or hydroxypropyl methylcellulose (HPMC) can help overcome these problems (Stoven *et al*., 2012) [92].

Chia flour

Chia seeds and flour have been staple foods in Central America and are gaining attention in the food and pharmaceutical industries due to their nutritional and functional potential. Chia seeds are rich in phenolic compounds, dietary fiber (20%–37%), protein (18%–25%), and oil (21%–33%) containing approximately 60%–63% α linolenic acid.

Studies have explored the incorporation of chia flour in gluten-free (GF) bread formulations. Sandri *et al*. utilized a mixture design and response surface methodology, combining chia flour, potato starch, and rice flour to optimize sensory properties. When whole chia flour was used alone, unsatisfactory physical and sensory properties were observed. However, adding 5%, 10%, or 14% whole chia flour to GF bread containing rice flour resulted in minimal decreases in crumb moisture, crumb firmness, and loaf volume (Sandri LT *et al*., 2017) [80].

Huerta *et al*. found that replacing rice and soy flour with 2.5%, 5.0%, or 7.5% whole chia flour in GF bread did not significantly affect specific volume, baking loss, or sensory acceptability compared to the control (Huerta KM *et al*., 2016). Another study incorporated 2.5%–7.5% whole chia flour into chestnut flour-based GF bread and observed improvements in dough rheological properties such as elasticity, viscosity, and stability with the use of 7.5% chia flour (Moreira R *et al*., 2012 and 2013) [66].

In contrast, Steffolani *et al*. found that replacing 15% of rice flour with whole chia flour in GF bread resulted in reduced specific volume, darker color, increased bread hardness, but did not significantly affect overall acceptability (Steffolani E *et al*., 2014) [90].

Legumes

Breads made from legumes, such as pea isolate, chickpea flour, soya flour, or carob germ flour, have demonstrated favorable sensory profiles and physicochemical characteristics. Carob germ flour exhibited good rheological properties in batters but resulted in bread with poor qualities. On the other hand, bread made from chickpea flour and pea isolate showed positive outcomes in all parameters (Minarro B *et al*., 2012) [63].

In a different study, Gularte *et al*. prepared gluten-free cakes using a combination of chickpea, pea, lentil, and bean flours with rice in a 50:50 ratio. The inclusion of legume flours, particularly lentil, resulted in lower batter viscosity and consequently higher specific volume compared to the control sample. Furthermore, cakes enriched with lentil showed comparable crumb hardness and increased springiness. From a nutritional standpoint, legumes have higher protein content and availability than cereals, making them a recommended option for enhancing the nutritional value of gluten-free cakes (Gularte MA *et al*., 2012) [38].

Tsatsaragkou *et al*. (2014) [95] demonstrated that substituting 15% of rice flour with carob flour led to the production of gluten-free bread with improved crumb structure and color, reduced moisture loss, but harder crumbs and lower specific volume compared to rice bread. The smaller particle size of carob flour contributed to a slower rate of firming (Tsatsaragkou K *et al*., 2014) [95].

Table 2: Various kinds of gluten-free products developed

Product	Ingredients & Supplementation	Result	References
Noodles	Mixture of potato starch, extruded and non-extruded quinoa (red and white flour) and tara gum with or without addition of lupine flour and vegetable proteins	Formulation containing quinoa flour and lupine flour (70:30) in combination with rice protein (12%) and POx-enzyme (1%) showed satisfying noodle quality and high protein and fiber contents	Linares-García *et al*. (2019) [57]
Cookies	20% of popped amaranth flour and 13% of whole grain popped amaranth	Cookies with high protein content and expansion factor and hardness comparable to other GF cookies	Calderón de la Barca *et al*. (2010) [12]
Flatbread	Mixture of quinoa, peanut oilcake and broccoli/beet	Higher protein and mineral contents and acceptance than wheat-based breads	Kahlon *et al*. (2019) [51]
Pasta	Base of rice flour replaced by quinoa and amaranth flours at different concentrations and egg white	Formulation containing amaranth, quinoa and rice flours (10:40:50) exhibited good elasticity and sensory acceptability but poor toughness	Makdoud & Rosentrater (2017) [58]
Wafer sheet	Base of rice replaced by 20%, 40% or 60% corn, chestnut or buckwheat flours	Wafer sheet formulations containing rice-buckwheat flours (60:40) had the closest value of consistency, flow behavior index, hardness and fracturability to wheat-based wafer sheet.	Mert *et al*. (2015) [62]
Cookies	100% quinoa flour	Quinoa cookies produced with optimized variables (fat content, sugar content, baking temperature and time) exhibited good textural and sensory quality and high antioxidant activity	Jan *et al*. (2018)
Bread	Base of rice flour and xanthan gum with 50% of quinoa, amaranth or buckwheat flours	Replacement of potato starch by pseudocereal flours resulted in softer bread crumbs an higher protein, minerals, vitamin E and phenolics contents and antioxidant activity than control GF bread (50% potato starch instead of pseudoceal flours)	Alvarez-Jubete *et al*. (2009, 2010a, b) [2-3]
Bakery products	Base of rice and oat flour replaced by 5%, 10% and 15% of roasted quinoa flour	Addition of up to10% of quinoa flour provided GF bakery products with good sensory attributes	Kaur & Kaur (2017) [52]
Muffins	Base of rice flour replaced by 25%, 50%, 75% and 100% of quinoa flour	Inclusion of quinoa flour up to 75% produced good quality muffins regarding texture and overall acceptability	Bhaduri (2013) [8]
Snacks	Whole grain quinoa flour with spices	Quinoa-based snacks exhibited good water activity, textural and sensory acceptability	Kahlon *et al*. (2016) [50]
Fresh spaghetti	Mixture of dried potato pulp, extruded potato pulp and amaranth flour at different concentrations	Mixture containing dried potato pulp, extruded potato pulp and amaranth flour (65:10:25) provided fresh pasta with higher yield, better color and cooking characteristics than fresh commercial wheat pasta.	Bastos *et al*. (2016) [6]
Beer-like beverage	100% buckwheat or quinoa malt	Buckwheat beers showed similar fermentability values, the wort pH and soluble protein content similar to barley beer Quinoa beer showed similar viscosity and beverage pH to barley beer and highest levels of metal cations	Deželak *et al*. (2014) [24]

Conclusion

These wheat/gluten-related disorders i.e., CD, Wheat allergy and non-celiac gluten sensitivity only affect a small fraction of the global population. Individuals diagnosed with celiac disease (CD) are advised to steer clear of gluten-containing foods and adhere strictly to a gluten-free diet (GFD). Those with wheat allergy must avoid any form of contact with wheat, while individuals with nonceliac gluten sensitivity (NCGS) are also recommended to follow a gluten-free diet (GFD). Following a gluten-free diet is the most feasible solution. Various gluten-free cereals and additives have been utilized in the production of gluten-free products, with the additives playing a role in enhancing the structural integrity and moisture retention of gluten-free baked goods. However, each approach for manufacturing gluten-free food faces certain limitations, such as potential nutrient deficiencies or a decline in functional properties. Further research and investment in infrastructure are essential for the advancement of low-gluten wheat and the subsequent development of food products. Achieving this goal will necessitate modifications in industrial food processing techniques to accommodate the lower gluten content in wheat and its derived products, as this characteristic will be a crucial factor for successful commercialization in the future. Consequently, it is crucial to address issues of taste and weak functional characteristics while ensuring the preservation of nutritional value and safety.

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