

Review Article

Formulation of Gluten Free Bakery Products from Cereals

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Abstract

The increasing number of people diagnosed with Celiac Disease (CD) has created a growing demand for high-quality gluten-free (GF) baked products. As more consumers require or choose gluten-free foods, researchers and food manufacturers are increasingly focused on developing products that are not only safe for individuals with gluten-related disorders but also comparable to conventional wheat-based products in terms of quality, texture, appearance, and overall acceptability. However, producing gluten-free baked goods with characteristics similar to those provided by wheat gluten remains a major technological challenge. This review examines the different ingredients and processing approaches that have been investigated to overcome these challenges. Particular attention is given to alternative gluten-free grains, non-cereal ingredients, and functional additives that can help improve the structure and quality of GF products. These include hydrocolloids, enzymes, and emulsifiers, which can contribute to improving dough or batter stability, gas retention, volume, texture, and other important quality characteristics. Since gluten normally provides the elastic and cohesive network required for the development of many baked products, replacing or compensating for its unique structural and viscoelastic functions requires careful selection and combination of alternative ingredients. The review also considers the application of these ingredients in several important food products, including bread, cakes, muffins, biscuits, crackers, and pasta. Each product presents specific formulation and processing requirements, and the absence of gluten can significantly affect characteristics such as volume, crumb structure, firmness, elasticity, cooking quality, and sensory acceptability. Therefore, developing successful gluten-free formulations requires a balanced combination of ingredients and suitable processing conditions. In addition to technological considerations, the review highlights important nutritional aspects associated with gluten-free products. Some GF formulations may have limitations in nutritional quality depending on the ingredients used, making the selection of nutrient-rich alternatives particularly important. Overall, the review identifies the major technological and nutritional challenges involved in gluten-free product development and discusses potential directions for future research. Continued investigation into innovative ingredients, functional additives, and improved processing technologies will be essential for producing gluten-free foods that are nutritious, appealing, and capable of meeting the increasing expectations of consumers.

Keywords

Bakery, Celiac Disease, Gluten, Pseudo Cereals, Starch

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Received: 21 August 2026; **Accepted:** 7 September 2026; **Published:** 27 September 2026



1. Introduction

Prolamin protein consumption causes celiac disease (CD), an immune-mediated enteropathy in genetically predisposed people. Prolamins contain oligopeptides rich in proline and glutamine that are resistant to gastrointestinal proteolysis. Tissue transglutaminase deamidates these oligopeptides, causing crypt hyperplasia, small-intestinal mucosal atrophy, and loss of nutrients [1]. Celiac disease is brought on by consuming gluten-containing foods like wheat, rye, barley, and probably oats [2]. According to epidemiological studies, approximately 1% of people worldwide suffer from CD. Based on positive IgA anti-TG2 and/or anti-endomysial antibody test results (also known as seroprevalence), a recent meta-analysis found that the pooled global prevalence of CD autoimmunity is 1.4% (95% CI: 1.1-1.7%). With a biopsy-confirmed prevalence of 0.7% (greater in children at 0.9% and females at 0.6%), the estimated global seroprevalence of CD is 1.4%. Prevalence rates confirmed by regional biopsies are 0.4% in South America, 0.5% in North America and Africa, 0.6% in Asia, and 0.8% in Europe and Oceania [3].

The endosperm of wheat, barley, rye, and some oats contains a protein known as gluten. Gliadin and glutenin, which are present in wheat, barley, rye, and other related cereals like triticale, a wheat-rye hybrid, are the main components of this complex mixture of hundreds of similar but distinct proteins. Proteins in other cereals are caused by prolamins, such as hordeins in barley, secalins in rye, or avenins in oats, whereas gliadin is the cause of wheat [4]. High levels of proline and glutamine prevent these proteins from breaking down easily during digestion. This structure makes them highly susceptible to modification by tissue transglutaminase, triggering an immune reaction that leads to intestinal inflammation, tissue damage, and cellular changes in people with celiac disease [5]. Gluten acts as a structural binding agent, providing dough with elasticity, stability, and stickiness for baked goods. Composed of hundreds of monomeric, oligomeric, and polymeric proteins linked by disulfide bonds, it is defined by high glutamine and proline content alongside few charged amino acids [6, 7].

Celiac disease is treated exclusively with a lifelong gluten-free diet, which fully restores small intestine structure and function. However, this strict diet is socially restrictive and poses significant challenges for the food industry in producing appetizing gluten-free alternatives [8].

The food industry struggles to find gluten substitutes that provide the necessary dough elasticity and structure for gluten-free products [9]. Gluten is crucial to all four stages of bread making: mixing, kneading, fermenting, and baking [10]. Akesowan (2016) notes that the easiest way to improve gluten-free goods is adding functional additives (starches, gums, proteins) to flour alternatives (rice, corn, pseudo-cereals), though this often compromises appearance, taste, and texture [11]. Masure et al. (2016) detailed gluten-free bread formulations, including typical recipes using alternative flours,

starches, and additives [12]. Surging demand for gluten-free products led to the development of higher-quality, nutritionally enriched breads, pastas, and baked goods [13].

European Commission regulations define a gluten-free diet as containing less than 20 ppm gluten, while items under 100 ppm are labeled "very low gluten." Today, diverse options—including specialized baked goods, beers, sourdoughs, and beverages—make these diets appealing for celiac patients [14, 15].

Popular across the Americas, Europe, North Africa, and parts of Asia, the gluten-free market was projected to grow from \$4.18B in 2017 to \$6.47B by 2023, led by breads and cookies. Gluten typically provides these foods with their dough elasticity, extensibility, and structural resistance [16, 17].

2. Gluten-Free Grains for Bakery Products

2.1. Cereals

Plant seeds including grains, beans, nuts, and pseudo-cereals—contain essential nutrients for plant growth and human nutrition. While most are naturally gluten-free and offer diverse colors and flavors, none replicate the unique texture and functionality of wheat in baking [18].

2.1.1. Corn (Maize)

Corn is used in gluten-free baking as meal, flour, or starch. Coarse meal adds grittiness to cornbread, while fine flour creates a smoother crumb. White corn starch adds structure, with waxy varieties providing soft gels and high-amylose options yielding stiffer crumbs; starches can also be modified for specific functions [19]. Scientists are studying maize zein (corn gluten) for its functional similarity to wheat gluten. Research shows that removing zein's surface lipids improves its viscoelasticity and overall baking performance [19].

2.1.2. Rice

Rice (*Oryza sativa*) is a key gluten-free grain, classified by size and cooking texture. Amylopectin-rich glutinous rice increases stickiness to alter crumb quality, while high-amylose long-grain rice delays gelatinization and speeds up structural setting in baked goods [20]. Rice flours range from coarse to extra-fine; fine varieties prevent grittiness in low-hydration items like cookies, while medium grinds suit breads and batters. Affordable, hypoallergenic rice protein isolates add nutrition, while stabilized bran prevents lipid oxidation off-flavors. Bland white rice flour contrasts with the sweet, nutty flavor of fresh brown rice flour.

2.1.3. Millet

Millet is a group of small, spherical, gluten-free grains (2-3 mm, similar to mustard seeds). Globally and in the U.S., production relies mainly on four genera: Pearl, Foxtail, Proso, and Finger millet [21]. Studies show all millets contain high phenolic levels, driving their strong antioxidant activity [22].

2.1.4. Sorghum

Gluten-free sorghum (*Sorghum bicolor*) is growing in popularity because it thrives in dry environments and is cheaper than other gluten-free grains [23]. Though less nutritious than quinoa or oats, whole sorghum still provides B vitamins, minerals, and antioxidants. It matches corn in macronutrients, though sorghum's protein is less digestible [24]. Sorghum has a lipid profile nearly identical to corn (over 80% unsaturated) and 70-80% starch, making it a key energy source. Best eaten whole for its fiber, micronutrients, and polyphenols, sorghum is nevertheless often abrasively milled to remove the bran for cleaner, lighter flour [25].

2.1.5. Oats

Oats are used globally for gluten-free products, but their safety for celiac disease remains debated. Oats contain the protein avenin, which triggers reactions in some sensitive individuals with celiac disease [26]. Numerous studies confirm both adults and newly diagnosed children with celiac disease can safely consume oats. The main risk is cross-contamination with wheat, rye, or barley; thus, celiac patients should eat only certified gluten-free oats and stop if symptoms occur. Oats offer proven health benefits like lowering cholesterol, and their unmatched soluble fiber content helps celiac patients meet daily fiber needs [27]. Oats contain nutrients including calcium, magnesium, and zinc that are especially important for celiac patients.

2.2. Pseudocereals

Pseudocereals are non-grass seeds primarily amaranth, buckwheat, and quinoa ground into flour for gluten-free foods. Because their nutritional profiles mirror whole-grain cereals, the FDA classifies whole pseudo cereals as whole grains.

2.2.1. Amaranth

Native to the Americas and now grown in Mexico, Central America, India, and China, amaranth is a drought-tolerant pseudocereal whose seeds require initial moisture to sprout. Superior to wheat in fat, fiber, and protein, its high-quality protein exceeds 14%, making it a top gluten-free flour. It also provides essential calcium and iron. The nutty, off-white flour retains water well due to its fiber and protein content, yielding foods with higher moisture and longer shelf lives.

2.2.2. Buckwheat

Recognizable by its dark, triangular seeds, buckwheat

yields dehulled kernels called groats, which add a nutty, bitter flavor to baked goods. High in unsaturated fat, it is prone to oxidation. Its mucilage acts as soluble fiber, adding viscosity and water binding to gluten-free batters and pasta. Compared to wheat, buckwheat provides superior protein quality and more micronutrients [28]. Like teff, dark buckwheat flour can limit its use in recipes due to its impact on product color.

2.2.3. Quinoa

Quinoa—a relative of spinach and beets—is sold mainly in white, red, and black varieties. Highly nutritious for gluten-free diets, it offers superior protein (~13.5%, exceeding many bread wheat flours) and rich minerals. Its impressive profile stems from a large germ comprising 60% of the seed (versus 3% in wheat). However, its seed coat contains high levels of antinutritional saponins [29].

2.3. Non Cereal Ingredients for Gluten -Free Bakery

2.3.1. Inulin

Chicory-derived inulin is a soluble prebiotic fiber that improves the texture, volume, shelf life, and nutritional profile of gluten-free breads, cakes, and pasta. Unlike maltodextrins, it promotes healthy gut bacteria and supports digestive health [30].

2.3.2. Tubers

The resulting dazzling white powder gelatinizes at lower temperatures than other starches, making tapioca and potato starches ideal for composite gluten-free flours. Overall, tapioca gels are less viscous and cohesive than potato starch gels [31].

2.3.3. Legumes

Legumes including gluten-free beans, lentils, lupines, peas, and peanuts—comprise diverse plants, fruits, and seeds. Because peanuts, soybeans, and lupines are allergens, their use requires care, though soybeans and peanuts are uniquely high in oil (18% and 48%). Bean flours provide rich protein, fiber, and minerals [18].

2.3.4. Enzymes

Enzymes are protein catalysts that improve baked goods' volume, texture, and shelf life. They are either endogenous (naturally occurring in main ingredients) or exogenous (added intentionally). Though widely used in wheat baking, enzymes see limited use in gluten-free products, where their efficacy depends on flour composition and processing conditions. Research mainly focuses on using enzymes to boost the texture and shelf life of gluten-free breads to better match wheat standards. Formulators must verify that enzyme carriers are gluten-free, as some suppliers use wheat- or barley-derived

carriers [32].

Table 1. *Enzymes that are used gluten-free bakery production.*

No	Enzymes	Description	Reference
	α -Amylase	Starch retrogradation (recrystallization) causes the dry, crumbly texture in gluten-free baked goods. Amylases delay this by converting starch to dextrins, extending shelf life	[33]
	Cyclodextrin Glycosyltransferase	It accelerates numerous processes, especially in gluten-free baking Starch breaks down into dextrins and forms cyclic structures	[34]
	Sugar Oxidases	Added to gluten-free doughs to improve gas retention. Oxidizes sugars into lactones and hydrogen peroxide using oxygen. The resulting hydrogen peroxide cross-links proteins via bake-stable disulfide bonds. Increases specific volume in corn- and sorghum-based breads, but not in buckwheat or teff breads.	[35, 36]
	Laccase	Cross-links proteins into larger networks to create gas-retaining structures in gluten-free doughs and batters	[37]
	Transglutaminase	Forms cross-links between L-lysine and L-glutamine to build larger protein networks with altered functional and rheological properties. In gluten-free foods, this helps create structures with better gas retention and improved texture	[38]

2.3.5. Gums/Hydrocolloids

Food hydrocolloids are high-molecular-weight substances (mainly non-digestible polysaccharides acting as fiber) from

plants, seaweed, microbes, or modified biopolymers. By binding water up to 100 times their mass, they improve texture, flavor, gas retention, and shelf life in gluten-free foods lacking viscoelastic properties [39].

Table 2. *Different gum types used in gluten free bakery production.*

No	Type of Gums	Description	Reference
	Xanthan	Most popular gluten-free hydrocolloid; produced via <i>Xanthomonas campestris</i> fermentation. Controls water during freeze-thaw cycles, ideal for frozen-distributed products.	[40]
	Gums from seeds	Guar, locust bean, and tara gums are galactomannans (galactose/mannose polymers). Tara gum serves as a cost-effective hybrid between guar and locust bean gums.	[41]
	Cellulose-Derived Hydrocolloids	Includes CMC, HPC, HPMC, MC, and microcrystalline cellulose. HPC, HPMC, and MC gel when heated and melt when cooled, aiding gluten-free baking.	[32, 42, 43]

2.4. Starches in Flour to Produce Gluten-Free Bakery Products

Wet milling separates pure starch from grains and tubers, providing a neutral flavor and white color ideal for gluten-free foods. However, relying on refined starches (like tapioca, potato, rice, and corn) lowers nutrient density and fiber, poten-

tially harming long-term health. During baking, starch establishes crumb structure; thus, blending flours and starches balances gas retention with proper gelatinization, pasting, and retrogradation [44].
Maltodextrins are glucose chains formed by starch hydrolysis, classified by polymerization degree (DP) and dextrose equivalent (DE = 100/DP). Higher DE values (18-22, indicating lower DP) delay starch retrogradation, boosting volume and extending shelf life in gluten-free breads [45].

3. Preparation of Gluten-Free Breads

Bread is a carbohydrate and micronutrient-rich staple baked from flour, water, yeast, salt, and sugar, often enriched with fat, milk, or eggs. Conventional varieties are characterized by a distinct crust, even crumb, good volume, and golden color. For gluten-free options, rice flour is most popular—favored for its neutral taste, pale color, low sodium, and hypoallergenic digestibility—alongside corn, teff, buckwheat, and amaranth. [46, 47]. Gluten-free corn alternatives include corn flour, meal, starch, masa harina, chips, pasta, tortillas, and baking mixes. [48]. Teff is another viable alternative, containing 80% complex carbs, 11% protein, and 3% fat. It provides essential amino acids, particularly lysine, which wheat lacks [48]. Growing research highlights pseudo-cereals like buckwheat and amaranth as nutritious, fiber- and phenol-rich bread substitutes.

3.1. Gluten-Free Sources of Starch

Starch, the primary plant reserve carbohydrate, occurs as dense, insoluble semi-crystalline granules. Gluten-free baking uses natural or modified starches combined with hydrocolloids to replicate traditional dough viscoelasticity, improving texture, rheology, extensibility, and overall quality [49]. Corn, potato, and cassava starches dominate gluten-free formulations. Most starch granules mix linear amylose (500-600 α -(1, 4)-linked glucose units) and highly branched amylopectin (3×10^5 to 3×10^6 units with α -(1, 4) chains interlinked by α -(1, 6) bonds) [48].

Starches vary in amylose-to-amylopectin ratios (typically 25-28% to 72-75%) and naturally occur as water-insoluble granules of diverse shapes and sizes. [47, 49].

Gluten-free bread relies on starches from corn, tapioca, rice, or potato. Potato starch is ideal: it enhances flavor, retains freshness, and offers high transparency, swelling power, water-binding capacity, and freeze-thaw stability due to esterified phosphate groups and high-molecular-weight amylose. However, its large granules break easily, creating sticky, shear-sensitive doughy [48].

3.2. Conventional and Alternative Sources of Protein in Gluten-Free Breads

Enriching gluten-free bread with alternative (insects, legumes) or conventional proteins (egg, dairy, soy) improves nutrition, viscosity, and dough structure via cross-linking enzymes. For instance, egg white solids boost loaf volume and crumb softness without affecting elasticity. Nutrient-rich flours high in protein, minerals, and fiber—such as rice, buckwheat, sorghum, quinoa, oat, maize, teff, and chia—are widely used base ingredients [50].

3.3. Functional Additives for Gluten-Free Breads

Food hydrocolloids sourced from algae, bacteria, citrus,

seeds, plant exudates, and cellulose derivatives are high-molecular-weight polymers with high water-binding capacity that build viscosity or form gels under specific conditions [51]. Hydrocolloids are added to gluten-free bread to make dough workable and refine final texture. Hydroxypropyl methylcellulose (HPMC) is used most frequently, followed by carboxymethylcellulose (CMC) and methylcellulose (MC), alongside other common choices like xanthan, guar, and locust bean gums. Using X-ray microtomography, Demirkesen et al. (2014) showed that HPMC, CMC, xanthan-guar, and xanthan-locust bean gum blends all produce a cohesive crumb structure. Additionally, adding proteins significantly alters crumb color and texture. Emulsifiers are also incorporated into gluten-free formulations; possessing both hydrophilic and hydrophobic parts, they lower surface tension between immiscible phases, interact with dough components, strengthen the network structure, and create a softer, more stable bread [52].

Gluten-free formulations utilize emulsifiers like lecithin, diacetyl tartaric acid esters of mono- and diglycerides (DATEM), distilled monoglycerides, and sodium stearoyl lactylate (SSL). These compounds strengthen the dough, soften the bread crumb, improve water retention, and reduce retrograded amylopectin levels, which ultimately extends product shelf life [53].

3.4. Strategies for the Development of Gluten-Free Breads

Global recognition of celiac disease and its required diet therapy has driven widespread focus on gluten-free bread creation and formulation. Growing market demand—from both medically necessary celiac consumers and optional dietary choices—has accelerated research aimed at producing gluten-free alternatives that closely mimic the qualities of conventional bread [54, 55].

Lacking gluten transforms dough into a liquid batter, leading to post-baking quality defects compared to wheat breads notably reduced volume, distinct starchy off-flavors, and accelerated staling [53].

4. Formulation of Gluten-Free Cakes and Muffins

4.1. Gluten-Free Cakes

Cakes are specialty baked goods typically consumed as treats, snacks, or celebratory foods, known for their sweet flavor, delicate and tender texture, and appetizing aroma. Although recipes and final products differ, wheat flour serves as the primary base ingredient, though cakes incorporate higher amounts of shortening, sugar, and eggs than standard bread formulations [39]. Cakes are classified into two main categories: shortened (e.g., pound, yellow, and chocolate cakes) and foamed (e.g., chiffon, angel food, and sponge cakes). These

categories are distinguished by the specific techniques used to achieve aeration, structure, volume, and texture: Firstly short-cakes rely heavily on creating a stable fat-liquid emulsion during the batter mixing process. Secondly foamed cakes depend primarily on the natural foaming and aerating properties of eggs to build their structure [56].

Quality cake production depends on the careful selection of ingredients, accurate formulation, and proper control of mixing and baking processes. The ingredients used in a cake play a major role in determining its volume, shape, texture, and overall quality. Flour and eggs provide the basic structure of the cake, while other ingredients can either help expand or strengthen this structure. Sugar, fat, and baking powder contribute to opening or expanding the structure, whereas liquids such as water and milk tend to close or weaken it. Therefore, maintaining the correct balance between ingredients that expand the cake structure and those that limit or close it is essential for producing a cake with desirable volume, shape, and texture [57].

4.2. Gluten-Free Muffins

Muffins are commonly prepared using a combination of wheat flour, vegetable oil or other fats, eggs, sugar, and milk. They are classified as chemically leavened bakery products, meaning that leavening agents such as baking powder or baking soda are used to produce gas and increase the volume of the product during baking. Well-made muffins generally have a moist and tender crumb, a slightly chewy texture, a relatively flat or gently rounded top surface, and a comparatively large volume. These characteristics are influenced by the type and proportion of ingredients used as well as the mixing and baking conditions [58]. Consumers generally prefer muffins that are soft, light, spongy, and have a delicate, tender crumb. Achieving these desirable quality characteristics depends greatly on the proper incorporation and distribution of air throughout the muffin batter. During mixing, air must be introduced uniformly and retained within the batter, while the air bubbles need to remain sufficiently stable to support proper expansion during baking. The formation and movement of convection currents during mixing also influence the distribution of air and ingredients within the batter. Therefore, effective control of air incorporation, air retention, bubble stability, and mixing-induced convection is essential for producing muffins with a soft, spongy structure and a sensitive, tender crumb [59]. The amount of air incorporated into muffin batter can be assessed by measuring its specific gravity. Batter specific gravity is determined by comparing the weight of a given volume of batter with the weight of an equivalent volume of water. The primary purpose of mixing muffin batter is to introduce and distribute air bubbles throughout the mixture, which subsequently contributes to the formation of a porous internal structure during baking. When a greater amount of air is incorporated into the batter, its density decreases because the batter contains more air spaces. Consequently, variations

in batter density can have a significant effect on the final volume of the muffins and the characteristics of their crumb structure and texture [60].

Miranda Villa et al. (2019) also investigated the production of gluten-free muffins using rice flour alone and a 70: 30 blend of rice flour and quinoa flour. The study considered quinoa in both whole and malted flour forms. Their findings showed that incorporating quinoa flour, whether used as whole or malted flour, resulted in a decrease in the specific volume of the muffins while simultaneously increasing their density [61].

4.3. Strategies to Produce Gluten-Free Cakes

Gluten-free cakes are primarily made by replacing wheat flour with individual or blended gluten-free starches and flours, such as corn, rice, cassava, or potato. Because the proteins and starches in these cereal flours and tubers behave differently than those in wheat, achieving traditional cake characteristics requires adjustments. To replicate standard wheat-based cake quality, researchers and bakers use hydrocolloids (like xanthan and guar gum), emulsifiers, enzymes, or processing techniques such as ozonation, extrusion, dry-heat treatment, and roasting. Additionally, non-traditional ingredients like sorghum, water chestnut, baru flour, broken beans, chia, azuki, quinoa, and jambolan flours are utilized alongside added fibers and proteins to enhance the texture, taste, nutritional profile, and overall consumer appeal of gluten-free baked goods.

5. Preparation of Gluten-Free Biscuits and Crackers

5.1. Gluten-Free Biscuits

Biscuits are cereal-based baked products that are primarily distinguished from other similar bakery products by their relatively low moisture content, which generally ranges from about 1% to 5%. The main ingredients used in biscuit production are wheat flour (WF), sugar, and fat. However, by changing the proportions and combinations of these ingredients, manufacturers can produce a wide variety of biscuits with different characteristics, including variations in formulation, processing conditions, crispness, texture, hardness, shape, and overall eating quality. Differences in biscuit formulation and processing are closely associated with dough consistency, which plays an important role in determining the appropriate forming or shaping method. Various molding, cutting, and shaping techniques may therefore be applied depending on the desired type of biscuit. Regardless of the particular cutting or forming technique used, the dough must have adequate cohesion and consistency to maintain its integrity and allow it to be properly shaped during processing [62]. Preparing gluten-free biscuits presents several challenges, especially depending on the specific type of biscuit being made. In a study by Mert

et al. (2015), researchers developed gluten-free wafer-style biscuits by replacing portions of a rice flour base with corn, buckwheat, or chestnut flours at varying ratios (80: 20, 60: 40, and 40: 60). Their goal was to match the textural properties of traditional wheat flour wafers. They found that a 60: 40 blend of rice flour and buckwheat flour produced a consistency closest to standard 100% wheat flour wafers, whereas wafers made solely with rice flour or blends containing corn flour turned out significantly harder [63].

Sarabhai and Prabhasankar (2015) examined how incorporating potato starch (5%) and varying amounts of whey protein (5%, 7.5%, and 10%) impacted gluten-free cookies formulated with Indian water chestnut flour. They found that adding whey protein made the cookies firmer and easier to break. Furthermore, the recipe with the highest protein concentration (10%) received better consumer acceptance than standard control cookies made using conventional wheat flour [64].

Kaur et al. (2015) assessed the physicochemical and sensory properties of gluten-free buckwheat flour biscuits enhanced with 1% concentrations of various gums: guar, acacia, xanthan, and tragacanth. Their findings showed that incorporating any of these gums increased the biscuits' moisture content, physical dimensions (diameter and thickness), and snap resistance. Among all the variations tested, the biscuits made with xanthan gum achieved the highest sensory scores, earning the top ratings for appearance, flavor, and general consumer acceptability [65].

5.2. Gluten-Free Crackers

Crackers are formed from unleavened, unsweetened dough and are thin and crunchy. Three categories of crackers are distinguished by their ingredients and manufacturing processes: Snack crackers (sprayed crackers), soda crackers (saltines or cream crackers), and savory or flavored crackers [66]. Nikolaidis and Labuza (1996) noted that water functions as a plasticizer in crackers, meaning that a higher moisture level reduces the glass transition temperature. Additionally, gluten serves as the primary element driving textural qualities in wheat crackers, such as crispness and overall structural integrity; consequently, increased water content degrades the cracker's crisp texture [67].

Protein isolates and hydrocolloids are frequently incorporated into gluten-free cracker formulations to enhance product quality. Within the dough, hydrocolloids improve gas retention and overall loaf or cracker volume by stabilizing gas cell interfaces during proofing and reinforcing those air pockets so they maintain structural strength throughout the baking process [68].

6. Preparation of Gluten-Free Pasta and Noodles

Pasta is one of the most widely consumed cereal-based

foods worldwide and ranks second only to bread in popularity. Its widespread consumption is largely attributed to its long shelf life, ease of storage, convenience, and the simplicity of preparing meals from it. Pasta and noodles are generally produced from wheat flour or semolina combined with water. During processing, the flour is first hydrated, after which the dough is shaped through processes such as cold extrusion or lamination using rollers. These processes promote the formation and development of the gluten network, which plays a major role in determining the final quality of the product.

The textural characteristics and cooking performance of pasta are important quality attributes and are strongly influenced by the extent and quality of gluten network development. High-quality pasta is generally characterized by desirable firmness and resistance to deformation during cooking, while also maintaining low surface stickiness. In addition, good-quality pasta should retain its structural integrity during cooking and release only a small amount of solids into the cooking water, resulting in minimal cooking loss [69]. During cooking, the proteins and carbohydrates in pasta undergo contrasting physical changes. Heat causes the starch granules to expand and partially dissolve, while the protein undergoes coagulation and transforms into an insoluble state [70]. Gluten plays a vital role in protein coagulation and directly dictates the final texture of cooked pasta. Because gluten is absent, producing gluten-free pasta creates significant technical challenges; without it, the resulting pasta tends to be less cohesive and excessively extensible compared to traditional versions. Consequently, achieving high-quality gluten-free pasta requires carefully selecting alternative raw materials and adapting processing methods to enhance its structural and textural properties [71, 72].

A variety of wheat flour alternatives—such as pseudocereals, legume flours, and vegetable or fruit powders—are used to manufacture gluten-free pasta and noodles, though corn and rice remain the most widely used options. Manufacturing methods differ depending on the format, with traditional pastas typically extruded and Asian noodles sheeted; notably, Asian rice noodles and most starch-based noodles are naturally gluten-free.

In a study on structural properties, Schmiele et al. (2013) evaluated rice flour spaghetti and measured an initial firmness of 4.99 N (tested across 10 noodle threads simultaneously). By replacing a portion of the rice flour with 17% soy protein isolate (SPI), 15% modified egg albumin, and 15% pregelatinized rice flour, they created a protein-enriched pasta with an increased average firmness of 6.42 N. This formulation significantly improved the desirable al dente bite and dramatically reduced cooking loss from 9.84% down to 2.90% [73]. Fiorda et al. (2013) assessed the quality of gluten-free vermicelli-style pasta prepared using combinations of amaranth flour, cassava starch, and a pregelatinized cassava blend (comprising 70% cassava starch and 30% dehydrated cassava pomace). The optimal formulation composed of 60% cassava starch, 30% amaranth flour, and 10% pregelatinized flour

yielded textural properties comparable to commercially available whole wheat pasta [74].

Bilgiçi (2013) examined the chemical composition and sensory qualities of gluten-free noodles produced from various combinations of legumes (chickpea and soybean), pseudocereals (buckwheat and quinoa), and cereals (maize and rice). The researcher found that a formulation combining equal parts chickpea, soy, buckwheat, and quinoa flours (25% each) yielded higher protein, fat, and mineral contents compared to alternative gluten-free blends and the wheat-flour control sample. Meanwhile, the noodle blend consisting of equal proportions of buckwheat, quinoa, corn, and rice flours (25% each) achieved the highest scores in sensory evaluations [71].

D'Amico et al. (2015) investigated how varying drying temperatures (60 °C, 80 °C, and 100 °C) impacted the physical characteristics of two gluten-free pasta formulations—one made from a blend of amaranth, quinoa, and buckwheat, and the other from corn and beans. Their study revealed that applying higher drying temperatures substantially enhanced the textural qualities of both products, with the most pronounced improvement observed in the amaranth-buckwheat-quinoa recipe. Furthermore, elevated drying temperatures decreased cooking loss, demonstrating that high-heat processing helps preserve the overall structural integrity of gluten-free pasta [75].

Ferreira et al. (2016) assessed the production of gluten-free spaghetti using combinations of potato starch with corn, sorghum, and rice flours. Their findings demonstrated that a formulation consisting of 40% sorghum flour, 40% potato starch, and 20% rice flour achieved the highest quality during cooking evaluations, delivering optimal cooking yield, superior weight gain, and minimal loss of soluble solids [72].

In order to boost the protein level, Kahlon et al. (2013) created whole grain, high protein, GF, egg-free pasta using flours from corn, millet, brown rice, sorghum, and whole garbanzo. Compared to millet-garbanzo and sorghum-garbanzo pasta, the sensory acceptance of brown rice-garbanzo and corn-garbanzo pasta was comparable and much greater. It has been claimed that adding corn starch, corn flour, and rice flour to GF pastas improves their texture and cooking capacity [76].

Gluten-free (GF) spaghetti produced from amaranth flour and supplemented with extruded potato pulp has been reported to exhibit improved quality characteristics compared with fresh commercial wheat spaghetti. In particular, the amaranth-based gluten-free spaghetti showed a more desirable colour, lower loss of solids into the cooking water, and a higher cooking yield. It also required a shorter cooking time than the fresh commercial wheat spaghetti, indicating advantages in both processing performance and cooking characteristics [77]. Pasta formulated from cassava starch, amaranth flour, and pregelatinized flour demonstrated favourable cooking, nutritional, sensory, and textural properties. The product required only 3 minutes of cooking and showed a 101.5% increase in mass after cooking, while the loss of solids into the cooking water

was relatively low at 0.6%. Sensory evaluation indicated a high level of consumer acceptance, with the pasta receiving an overall liking score of 7.2 out of 9. In addition, 42% of the consumers expressed an intention to purchase the product. The pasta was characterized by a light yellowish colour and provided relatively high amounts of dietary fibre (9.37 g/100 g) and protein (10.41 g/100 g). From a textural perspective, the product exhibited adequate firmness, measured at 43.6 N, together with relatively low stickiness of 3.2 N, indicating desirable eating and handling characteristics [74].

7. Challenges of Developing Gluten-Free Bakery Products

From a nutritional perspective, incorporating pulses and pseudocereals into gluten-free bakery products is strongly recommended rather than relying exclusively on gluten-free cereals and starches such as rice, maize, and sorghum. Currently, a wide variety of gluten-free bakery products are formulated using gluten-free cereals, including rice, maize, sorghum, and millet; legumes and pulses such as soybean, chickpea, lupin, lentils, and peas; and pseudocereals such as buckwheat, amaranth, and quinoa. In addition to these gluten-free flours, starches—particularly maize and rice starch—are frequently incorporated into gluten-free bakery formulations to improve their processing and product characteristics.

In conventional wheat-based bakery products, gluten plays a central role in the formation and stabilization of the dough structure. When wheat flour is mixed with water, gluten proteins develop into a viscoelastic network that provides strength and elasticity to the dough. This network is also capable of retaining carbon dioxide produced during yeast fermentation or chemical leavening, thereby supporting the expansion and structure of the baked product. In gluten-free formulations, the absence of wheat gluten makes it difficult to develop a similar structural network and may result in a weak, fluid, or batter-like consistency.

Consequently, one of the major challenges in producing gluten-free bakery products is the lack of functional gluten, which can negatively affect the rheological properties of the dough or batter. This structural limitation may ultimately lead to products with undesirable texture, volume, appearance, and overall quality compared with conventional wheat-based products. Furthermore, many gluten-free bakery products tend to contain relatively high levels of carbohydrates and calories, which can be a concern for consumers who are increasingly conscious of the nutritional and health aspects of the foods they consume.

Therefore, beyond simply eliminating gluten, there is a need to improve the nutritional composition, functional properties, technological performance, sensory characteristics, and overall acceptability of gluten-free bakery products. Developing formulations that combine gluten-free cereals, pulses, legumes, pseudocereals, and appropriate starches may provide

opportunities to enhance both the nutritional value and quality of these products while better satisfying the changing needs and expectations of consumers [78].

7.1. Technological Limitation

Gluten is essential for giving wheat-based dough and batter their unique rheological properties and for developing the final product's structure. Without it, gluten-free doughs and batters become non-elastic and poorly cohesive, struggle to rise during leavening, and are challenging to handle during processing [49]. A major obstacle in producing gluten-free bakery items is replacing wheat gluten with alternative ingredients that replicate its functional properties. To enhance the texture and overall quality of these products, researchers and bakers employ several techniques, including flour modification and the addition of enzymes, protein isolates, and hydrocolloids. Among these, hydrocolloids are frequently used to serve as binders and structural improvers in gluten-free formulations [40]. In addition to hydrocolloids, various proteins including soy protein isolate, whey protein, egg white, and pea protein isolate are used to enhance the quality of gluten-free baked goods. Specifically, soy protein isolate has been proven to improve the structural texture of both rice starch cakes and rice flour cookies [64]. The structure of millet muffins was enhanced by adding transglutaminase and chickpea protein isolate [79]. Rice flour modification, such as heat treatment [80] and extrusion [81] improves cake batter and qualities, partially attributed to the pre-gelatinization of starch through heat treatment and extrusion.

7.2. Nutritional Quality

Several gluten-free grains are available, including the pseudocereals amaranth, quinoa, and buckwheat, which are recognized for their excellent nutritional composition [82]. Celiac disease sufferers can safely consume gluten-free baked goods, but their nutritional value may be compromised by the use of highly refined flours and starches, which are high in starch carbohydrates but poor in protein quantity and quality, as well as low in fiber [83]. The protein content of legumes, pulses, and pseudocereals is on par with or more than that of wheat flour, and they are comparatively more nutritious than gluten-free cereal flours and starches (such as rice, maize, and sorghum). Because pulses are high in fiber, proteins, minerals, and antioxidant bioactive substances, they give the gluten-free baked good extra nutritious values [84]. For use in baking, blends of gluten-free cereal and pulse flours offer higher-quality proteins with complementing amino acid profiles. Compared to gluten-free cereal flours, some pseudocereal flours have higher concentrations of nutrients like proteins, dietary fibers, micronutrients, and polyphenols. More minerals can be found in gluten-free items made from buckwheat, millet, chickpeas, oats, amaranth, and quinoa than in those manufactured from rice, maize, and potato starch [85].

7.3. Sensory Properties

Sensory acceptability continues to be one of the major challenges in the development and commercialization of gluten-free bakery products. Compared with conventional wheat-based baked goods, gluten-free products can differ considerably in several sensory characteristics, including appearance, colour, texture, aroma, and flavour. These differences may negatively influence consumer perception and willingness to accept the products.

Gluten-free baked products often develop a darker colour, which may result from the combination of different alternative flours and other ingredients used in their formulations. They may also have a lower or denser volume and a firmer or less tender texture, particularly in products such as cakes and muffins, because of the absence of gluten and the resulting differences in batter structure and gas retention.

Flavor is another important factor affecting the acceptability of gluten-free products. The sensory profile can vary substantially depending on the type and proportion of alternative flours and other ingredients incorporated into the formulation. For example, the use of quinoa flour may reduce consumer acceptance because it can contribute a noticeable bitter taste. On the other hand, the incorporation of suitable protein sources can improve the overall palatability of gluten-free baked products by contributing to better texture and, consequently, enhancing consumer acceptance. Therefore, careful selection and combination of alternative ingredients are essential for developing gluten-free bakery products with desirable appearance, texture, aroma, flavor, and overall sensory quality.

8. Conclusion

The increasing demand for gluten-free products is largely driven by two major factors. First, many consumers choose gluten-free foods to eliminate allergenic proteins from their diets or to address food sensitivities. Second, the growing prevalence of celiac disease has increased the need for gluten-free diets as the primary treatment for individuals affected by this autoimmune disorder. As a result, the market for gluten-free bakery and cereal products has expanded significantly in recent years.

The absence of gluten is the main characteristic that distinguishes gluten-free products from conventional wheat-based products. Gluten plays a fundamental role in providing the viscoelastic properties required for dough development and without it, gluten-free doughs and batters often have weaker structure, reduced elasticity, and inferior textural characteristics. Consequently, gluten-free baked products frequently differ from wheat-based products in terms of volume, softness, chewiness, and overall eating quality.

In wheat-based bakery products, gluten performs several essential technological functions. It binds water, forms and stabilizes the dough structure, acts as an emulsifying agent, retains gas produced during yeast fermentation or chemical

leavening, and contributes to the characteristic chewy texture of the finished product. To compensate for the absence of gluten, gluten-free formulations often rely on a combination of enzymes, hydrocolloids, alternative gluten-free proteins, and nutrient-rich flours such as amaranth and buckwheat. These ingredients work together to mimic some of the functional properties of gluten and improve the structure and quality of gluten-free products.

The quality of gluten-free bread and other baked products can be substantially improved through the use of macromolecules, including proteins, hydrocolloids, and starches, as well as food additives and processing aids. These functional ingredients enhance water retention, improve dough rheology, increase gas-holding capacity, strengthen product structure, and contribute to better texture and shelf life.

Most gluten-free bakery products are produced from naturally gluten-free cereals, legumes, pulses, and pseudocereals. Common gluten-free cereals include rice, maize, sorghum, and millet, while frequently used legumes and pulses include soybean, chickpea, lupin, lentils, and peas. Pseudocereals such as buckwheat, amaranth, and quinoa are also widely incorporated because of their superior nutritional composition and functional properties.

A wide variety of gluten-free foods, including bread, cakes, crackers, cookies, and pasta, are manufactured using gluten-free grains as substitutes for wheat, rye, and barley. Rice, teff, sorghum, millet, and Pseudocereals are among the most commonly used grains in gluten-free baking. In addition, certain legumes and starchy tuber crops are utilized because they provide the starch necessary for developing the structure of baked products. To further improve the quality and functionality of gluten-free products, manufacturers commonly incorporate hydrocolloids and enzymes as gluten substitutes, helping to enhance dough stability, texture, volume, and the overall sensory characteristics of the finished products.

Abbreviations

GF	Gluten-Free
IGA	Immunoglobulin
FDA	Food and Drug Authority
CMC	Carboxymethyl Cellulose
HPC	Hydroxypropyl Cellulose
HPMC	Hydroxypropyl Methylcellulose
MC	Methyl Cellulose
DP	Polymerization Degree
WF	Wheat Flour

Acknowledgments

The authors are grateful to Manufacturing Industry Development Institute (MIDI), Ethiopian Food and Beverage Industry Research and Development Center (FBIRDC) for facilitating the review time as part of main work.

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Conflicts of Interest

The authors declare no conflicts of interest.

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