Review article

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Nutrient-dense ingredients and processing innovations for gluten-free foods in celiac disease: improving nutritional quality, functionality, and safety

Abstract

Celiac disease requires lifelong strict exclusion of gluten, yet many commercial gluten-free products remain nutritionally imbalanced and technologically inferior to wheat-based foods, limiting dietary adherence and long-term health outcomes. This review critically examines recent advances in ingredient selection and processing technologies aimed at improving the nutritional quality, sensory properties, and safety of gluten-free foods for individuals with celiac disease. Particular attention is given to nutrient-dense pseudocereals, legumes, and sustainable by-products as sources of protein, dietary fiber, minerals, and bioactive compounds. The review also evaluates functional ingredients, including hydrocolloids, modified starches, and protein isolates, that are used to mimic the viscoelastic properties normally provided by gluten. In addition, we discuss process innovations such as sourdough fermentation, hydrothermal treatment, extrusion, and high-shear processing, which can improve texture, flavor development, shelf life, and nutrient availability. Remaining challenges include limited clinical validation, incomplete understanding of long-term metabolic effects, and the need for scalable formulations that combine safety, nutritional adequacy, and consumer acceptance.

Keywords: celiac disease, gluten-free diet, food reformulation, nutritional quality, sensory acceptability, processing technologies

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Introduction

Celiac disease is a chronic immune-mediated enteropathy triggered by exposure to gluten proteins found in wheat, barley, and rye.[1] In genetically predisposed individuals, especially those carrying HLA-DQ2 or HLA-DQ8 haplotypes, gluten-derived peptides initiate an inflammatory response that damages the small intestinal mucosa and impairs nutrient absorption.[2] The disease may present with gastrointestinal symptoms, such as diarrhea, abdominal pain, and weight loss, or with extra-intestinal manifestations, including iron-deficiency anemia, osteoporosis, neurological complaints, and dermatitis herpetiformis. In all forms, the only established treatment is lifelong adherence to a strict gluten-free diet.[3]

Although effective in preventing intestinal injury, the gluten-free diet remains difficult to implement optimally. Many commercial gluten-free products rely heavily on refined starches and simple carbohydrate matrices that provide limited protein, dietary fiber, vitamins, and minerals, while also displaying inferior texture, volume, and palatability compared with wheat-based products.[4] In addition, cross-contact during processing, inconsistent labeling, and the higher cost of specialty products continue to complicate safe and sustained dietary adherence. These limitations have increased interest in food reformulation strategies that can improve both the nutritional profile and the technological performance of gluten-free foods.[3,4]

Recent progress in food science has made it possible to rethink gluten-free product development from a more integrated perspective. Nutrient-dense ingredients such as pseudocereals, legumes, and selected agro-industrial by-products can enhance protein quality, mineral content, and dietary fiber. At the same time, hydrocolloids, functional proteins, enzymes, and advanced processing technologies can partially recreate the structure and viscoelasticity normally contributed by gluten. However, the success of these approaches depends not only on formulation performance, but also on analytical validation, regulatory compliance, and consumer acceptability.[5,6]

This review synthesizes recent advances in ingredient selection and processing innovations for gluten-free foods intended for individuals with celiac disease. It focuses on three interconnected dimensions: nutritional enhancement, functional and sensory improvement, and safety assurance. Where possible, it also highlights current knowledge gaps and translational challenges that must be addressed to support the development of gluten-free foods that are both clinically appropriate and technologically competitive.

Pathophysiology of gluten-induced intestinal injury

Celiac disease is an immune-mediated disorder triggered by gluten exposure in genetically susceptible individuals. In the small intestine, incompletely digested gluten peptides, particularly gliadin-derived fragments, resist gastrointestinal proteolysis and persist long enough to interact with the intestinal mucosa. After crossing the epithelial barrier, these peptides are deamidated by tissue transglutaminase, which increases their affinity for HLA-DQ2 or HLA-DQ8 molecules and promotes presentation to gluten-specific T cells.[7]

This multi-step pathogenic sequence, from peptide survival to immune activation, is schematically illustrated in Figure 1. This immune recognition initiates a cascade involving both innate and adaptive immune responses. Activated T cells release pro-inflammatory cytokines that amplify mucosal inflammation, leading to villous atrophy, crypt hyperplasia, and increased intraepithelial lymphocytosis. These characteristic histological lesions (Figure 1) are directly responsible for impaired absorptive capacity and reduced epithelial function.[8] The pathogenesis of celiac disease is therefore not limited to simple food intolerance, but reflects a highly specific autoimmune-like response driven by antigen presentation, lymphocyte activation, and epithelial injury. The clinical expression of the disease varies widely, ranging from asymptomatic forms to severe malabsorption syndromes, depending on genetic susceptibility, gluten exposure, and disease duration. Understanding these mechanisms is essential for designing gluten-free foods that not only exclude the triggering proteins, but also support intestinal recovery and long-term nutritional well-being.[9,10]

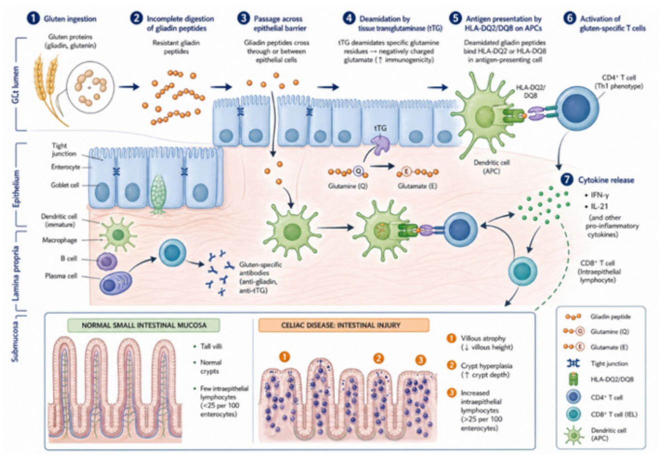

Figure 1 Cellular and molecular mechanisms of gluten-induced intestinal injury, highlighting antigen presentation, mucosal inflammation, and epithelial damage in celiac disease.

Intestinal homeostasis and epithelial integrity

The intestinal mucosa plays a central role in nutrient absorption, barrier defense, and immune regulation. In celiac disease, inflammation-induced structural damage reduces villous surface area and disrupts the normal organization of the epithelial layer, thereby impairing the uptake of macronutrients and micronutrients. As the disease progresses, absorptive efficiency declines and the intestine becomes less capable of maintaining homeostasis under physiological dietary conditions.[11]

Barrier dysfunction is another critical feature of active celiac disease. Tight-junction disruption increases intestinal permeability, allowing luminal antigens and inflammatory mediators to interact more readily with the mucosal immune system. This process contributes to a self-perpetuating cycle of inflammation, epithelial damage, and impaired barrier repair. The structural and functional differences between an intact mucosa and this compromised state are contrasted in Figure 2. In this context, epithelial integrity is not only a structural issue, but also a functional determinant of disease severity and recovery.[12,13] Although a gluten-free diet supports mucosal healing, recovery may be slow and incomplete in some patients (Figure 2), particularly when accidental gluten exposure persists or adherence is imperfect. The extent of injury depends on the amount and duration of gluten intake as well as individual sensitivity and disease activity at diagnosis. For this reason, the development of gluten-free foods should be guided not only by safety requirements, but also by their ability to support epithelial recovery, minimize nutritional deficiencies, and maintain long-term dietary suitability.[14,15]

Limitations of current gluten-free regimens

When appropriately followed, a gluten-free diet leads to symptom improvement, mucosal recovery in many patients, and a reduced risk of long-term complications. However, translating this therapeutic principle into a diet that is simultaneously safe, nutritionally balanced, affordable, and palatable remains a major challenge. In practice, many commercially available gluten-free products are based on refined starches and simple carbohydrate-rich formulations designed to replace the structural properties of gluten rather than to deliver optimal nutrition.[16,17] The multi-faceted bottlenecks of these current dietary options are structured and summarized in Figure 3.

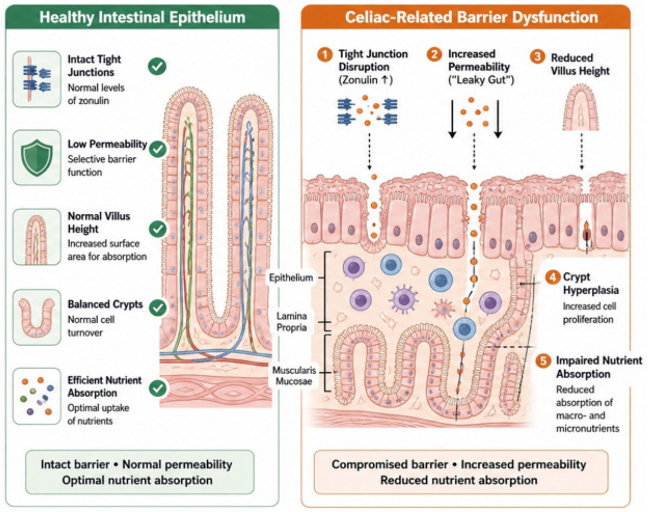

Figure 2 Comparative representation of intestinal epithelial status, showing healthy homeostasis (yellow) versus celiac-induced tight-junction disruption and mucosal damage (orange).

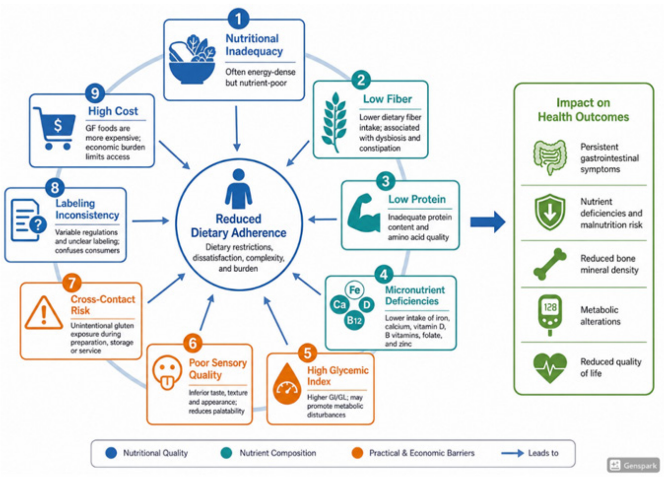

Figure 3 Interconnected challenges of commercial gluten-free products, outlining nutritional deficiencies, technological and sensory shortcomings, and socioeconomic barriers.

As a result, gluten-free products are often lower in protein, dietary fiber, iron, folate, calcium, zinc, and several B vitamins than their gluten-containing counterparts. Some products also show higher glycemic indices and, in certain cases, increased fat and sugar content, which may reduce their overall nutritional quality. These specific nutritional gaps (Figure 3) are particularly important for children, adolescents, and patients with restricted food choices, in whom dietary inadequacy may have greater clinical consequences.[18,19]

In addition to nutritional limitations, sensory quality remains an important barrier to adherence. Many gluten-free baked products have inferior crumb structure, reduced volume, poor sliceability, and limited shelf stability compared with wheat-based foods. These technological shortcomings (Figure 3) may reduce consumer satisfaction and lower long-term compliance, especially when gluten-free products are perceived as inferior substitutes rather than acceptable foods in their own right.[20]

Practical constraints further complicate dietary management. Cross-contact during production, inconsistent labeling practices, and the higher cost of specialty products all increase the burden of maintaining a strict gluten-free diet. For these reasons, improving gluten-free food quality requires not only elimination of gluten, but also deliberate reformulation to restore nutritional value, technological functionality, and consumer acceptability.[20,21]

Ingredient-driven interventions: nutrient-dense raw materials

Ingredient-driven reformulation offers one of the most direct strategies for improving the nutritional profile of gluten-free foods. Nutrient-dense raw materials such as pseudocereals, legumes, and selected agro-industrial by-products can enrich gluten-free formulations with protein, dietary fiber, minerals, and bioactive compounds while helping to correct the imbalanced composition of starch-based products.[22,23] The distinct nutritional advantages and technical trade-offs associated with each of these raw material classes are systematically categorized in Table 1.

Table 1 Main classes of nutrient-dense raw materials for gluten-free reformulation, highlighting their key nutritional contributions and technological challenges

Ingredient class	Examples	Main nutritional/ functional value	Main advantage in gluten-free foods	Main limitation
Pseudocereals	Quinoa, amaranth, buckwheat	High-quality protein, lysine, minerals, fiber, bioactives	Improves nutrient density and glycemic profile	Formulation and flavor optimization needed
Legumes	Pea, chickpea, lentil	Protein, fiber, water binding, satiety	Supports structure and nutritional enrichment	Beany flavor, dense texture if overused
Fibers / by-products	Fruit fibers, bran fractions, defatted oilseed cakes	Fiber, minerals, phytochemicals	Sustainability and circular economy value	Functional variability, standardization needed
Functional hydrocolloids	Xanthan, guar, HPMC	Viscosity, gas retention, crumb softness	Improves dough/batter stability	Excess may impair mouthfeel
Functional proteins	Soy, egg, whey, pulse proteins	Matrix formation, protein enrichment	Supports network development	Allergen and sensory constraints

Pseudocereals, including quinoa, amaranth, and buckwheat, are of particular interest because they provide high-quality protein and a favorable amino acid profile, especially with respect to lysine, which is limited in many cereal-based gluten-free formulations. In addition, these grains contribute minerals, polyphenols, and dietary fiber, thereby improving both nutritional density and functional performance. Their inclusion (Table 1) may also help reduce rapid starch digestion and moderate postprandial glycemic responses.[24,25]

Legumes such as chickpea, lentil, and pea are another valuable ingredient class in gluten-free product development. Legume flours and protein isolates can significantly improve protein content, enhance water-binding capacity, and contribute to dough or batter structure (Table 1).

They may also support a lower glycemic response and improve satiety. However, their use must be carefully optimized because excessive incorporation can introduce beany flavors, dense textures, or reduced loaf volume if not balanced with complementary structure-forming ingredients.[26,27]

Beyond conventional plant sources, novel milling fractions and agro-industrial by-products offer additional opportunities for sustainable reformulation. Fruit fibers, bran fractions, and defatted oilseed cakes can increase dietary fiber, minerals, and selected phytochemicals, while also supporting circular economy approaches in food innovation. These materials (Table 1) may improve water retention and crumb structure, but their composition, particle size, and functional behavior must be standardized to ensure consistent product quality.[22–27]

On the whole, ingredient-driven interventions are most effective when they are used to create balanced formulations rather than simply to replace wheat flour. The best outcomes are achieved when nutritional enrichment is combined with careful control of hydration, texture, and flavor properties. For this reason, ingredient selection should be viewed as the first step in a broader formulation strategy that is complemented by hydrocolloids, proteins, enzymes, and processing innovations.

Functional formulations: polymeric blends and enzymatic systems

Because gluten is responsible for the unique viscoelastic network of wheat dough, gluten-free formulations require carefully designed substitutes to approximate its structure and functionality. In this context, hydrocolloids, modified starches, functional proteins, and enzymes are widely used to improve gas retention, dough cohesion, batter stability, and final product texture.[28]

Hydrocolloids such as xanthan gum, guar gum, and hydroxypropyl methylcellulose (HPMC) are among the most frequently used structuring agents in gluten-free baking. These polymers increase viscosity, improve water retention, stabilize gas cells during proofing and baking, and reduce crumb crumbliness after cooling. Their effectiveness depends on concentration, hydration conditions, flour composition, and the specific product type, meaning that formulation must be optimized for each application rather than applied generically.[29–30]

Modified starches also play an important role by increasing paste viscosity, improving expansion during baking, and slowing staling. When combined with hydrocolloids, these ingredients can partially recreate the functional properties of gluten by improving the balance between gas entrapment and crumb setting. However, excessive reliance on starch can still produce nutritionally poor products, which reinforces the need to combine technological functionality with nutritional improvement.[31–33]

Enzymatic systems provide another route for enhancing gluten-free dough quality. Microbial transglutaminase can cross-link proteins such as soy, egg, or dairy proteins, thereby strengthening the matrix and improving structural stability. Other enzymes, including alpha-amylases and glucose oxidase, may improve loaf volume, softness, and crumb resilience by modifying starch behavior and oxidation state. These effects are highly formulation-dependent and require careful control to avoid negative outcomes such as excessive stickiness, over-tightening of the crumb, or reduced process tolerance.[31–33]

Ultimately, polymeric blends and enzymatic systems are most effective when used as complementary tools within a balanced formulation strategy. Their role is not to fully reproduce gluten, which remains technically difficult, but to create a sufficiently stable and palatable structure for specific gluten-free applications such as bread, cake, pasta, or snack products.

Process innovations: advanced industrial processing technologies

In addition to ingredient selection, processing conditions strongly influence the quality of gluten-free foods. Advanced technologies such as sourdough fermentation, hydrothermal treatment, extrusion, and high-shear processing can modify starch structure, protein interactions, flavor development, and shelf stability, thereby improving the performance of gluten-free products.[34] The mechanisms, specific physical transformations, and industrial applications of these operations are systematically summarized in Table 2.

Table 2 Advanced industrial processing technologies for gluten-free products, detailing their structural impacts, functional effects, and food design applications

Processing technology	Main effect	Evidence strength	Industrial relevance
Sourdough fermentation	Improves flavor, mineral bioavailability, shelf life	Moderate	Medium
Hydrothermal treatment	Modifies starch crystallinity, improves water retention	Moderate	Medium
Extrusion	Texturization, expansion, ready-to-eat structures	High	High
High-shear/ microfluidization	Enhances protein unfolding and matrix formation	Moderate	Medium
Enzymatic systems	Improves cohesion, loaf volume, crumb softness	High	High

Sourdough fermentation is particularly attractive because selected lactic acid bacteria can acidify the dough, enhance flavor complexity, and improve the functional behavior of the matrix. Fermentation may also reduce anti-nutritional factors such as phytic acid and increase mineral bioavailability, which is especially relevant for gluten-free products based on pseudocereals, legumes, and alternative grains. In some formulations, sourdough can also improve texture and extend shelf life through its effects on water retention and microbial stability (Table 2).[35]

Hydrothermal treatments, including heat-moisture treatment and annealing, alter starch crystallinity and gelatinization behavior. These structural modifications (Table 2) may improve water-holding capacity, batter stability, and resistance to mechanical stress during processing. Such treatments are useful for tailoring the functional properties of gluten-free starches, particularly when the goal is to enhance baking performance without introducing synthetic additives.[36]

Extrusion is another important technology for gluten-free product development. By combining heat, pressure, and shear, extrusion can gelatinize starch, denature proteins, and generate expanded or textured products with improved structure (Table 2). It is especially useful for producing pasta analogues, snacks, and ready-to-eat products based on legumes, pseudocereals, or mixed plant proteins. However, the high intensity of extrusion requires careful optimization to avoid excessive nutrient losses or undesirable textural changes.[37]

High-shear mixing and microfluidization offer additional means of reorganizing protein networks and improving ingredient dispersion. These mechanical technologies (Table 2) can promote protein unfolding, enhance matrix formation, and improve the uniformity of gluten-free doughs or batters. Their industrial value lies in their ability to strengthen functional interactions without necessarily requiring major changes in ingredient composition.[38]

Taken together, these process innovations broaden the formulation toolbox for gluten-free food design. Their value is greatest when they are integrated with appropriate ingredient selection and product-specific optimization, rather than applied as isolated technological fixes.

Analytical characterization and food safety frameworks

For people with celiac disease, gluten-free product development must be guided by rigorous safety control at every stage of formulation and manufacturing. Preventing cross-contact with gluten-containing materials is essential, and all processing steps should be compatible with validated analytical methods capable of detecting residual gluten at very low levels. This is particularly important because even small amounts of gluten may be sufficient to trigger intestinal injury in susceptible individuals.[39]

Current regulatory frameworks generally consider products containing less than 20 parts per million gluten to be gluten-free, although compliance must always be interpreted in the context of the specific analytical method used and the risk of contamination during production. Immunochemical methods, especially R5-based ELISA assays, remain widely used for routine screening, while liquid chromatography–mass spectrometry approaches offer higher specificity for confirming gluten-derived peptides in complex food matrices. Because no single method is universally perfect, robust quality assurance should combine analytical testing with preventive manufacturing controls.[40] To visualize how these screening protocols align with product development steps, a conceptual roadmap for gluten-free food design is proposed in Figure 4.

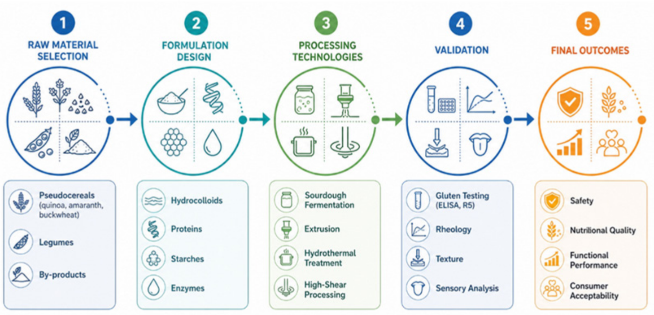

Figure 4 Conceptual roadmap for gluten-free food design, integrating analytical validation, regulatory compliance, quality control, and consumer acceptability.

Beyond gluten detection, food quality assessment is also necessary to evaluate technological performance and consumer acceptance.

Rheological measurements, including oscillatory testing, provide information on viscoelastic behavior and help predict dough handling, gas retention, and baking performance. Texture profile analysis can quantify hardness, springiness, cohesiveness, and chewiness, while sensory evaluation is essential for determining whether improved formulation translates into acceptable eating quality. These analytical tools (Figure 4) are indispensable for comparing product prototypes and guiding iterative development.[40–42]

A comprehensive food safety framework should therefore integrate ingredient control, validated testing, hygienic design, and traceability across the production chain. For gluten-free foods, safety is not limited to the absence of gluten in the final product, it also depends on raw material sourcing, processing environment, packaging, storage, and labeling accuracy. Effective gluten-free product development must therefore combine analytical precision with strict operational controls (Figure 4).[40–42]

Regulatory landscapes and future directions in gluten-free food innovation

The development of improved gluten-free foods must be aligned with both regulatory expectations and real-world clinical needs. Regulatory standards provide the minimum conditions for gluten safety, but they do not guarantee nutritional adequacy, desirable sensory quality, or long-term health benefits. For this reason, future product innovation should move beyond compliance-based reformulation toward a more integrated translational framework.

A major priority is the development of gluten-free foods that are not only safe, but also nutritionally superior to current commercial products. This will require formulations with higher protein quality, greater fiber content, improved micronutrient density, and lower glycemic impact. At the same time, products must remain technologically stable, affordable, and acceptable to consumers, because poor sensory quality remains a major barrier to long-term adherence. In this respect, the most successful innovations will likely be those that balance nutrition, functionality, and palatability rather than maximizing only one attribute.

Future research should also include more clinically relevant outcomes. In addition to texture and shelf life, studies should evaluate effects on nutrient status, satiety, glycemic response, gastrointestinal tolerance, and potentially the gut microbiota. Human intervention studies are particularly needed because many promising laboratory formulations have not yet been validated in real dietary settings. Without such evidence, translation from experimental prototype to practical product will remain limited.

Progress in this field will depend on collaborative work among food scientists, clinicians, nutritionists, regulatory experts, and industry partners. Standardized methods for formulation testing, gluten quantification, and sensory evaluation should be combined with clear product development goals and realistic manufacturing strategies. In the long term, the objective should be to create gluten-free foods that are safe for celiac patients while also supporting nutritional adequacy, digestive health, and consumer satisfaction.

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Conflicts of interest

The authors declare that they have no competing interests.

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