Indian Journal of
Nutrition

Open Science Publications

Volume 12, Issue 1 - 2025

www.opensciencepublications.com

A Comprehensive Review of Gluten - Free Cupcake Formulations and Their Nutritional Properties

Review Article

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Article Information: **Submission:** 30/12/2024; **Accepted:** 25/01/2025; **Published:** 29/01/2025

Abstract

Gluten-free baking presents significant challenges in replicating the texture and quality of traditional wheat based products, particularly in cupcakes. The absence of gluten reduces dough elasticity and cohesion, often resulting in batters rather than doughs. To address this, bakers incorporate various ingredients, such as hydrocolloids (e.g., xanthan gum and cactus mucilage), which mimic gluten's properties and improve the texture, structure, and stability of gluten-free baked goods. The addition of pseudocereals, legumes, and dairy proteins further enhances the nutritional profile and texture of gluten-free cupcakes, improving their volume and crumb texture. Nutritional deficiencies in gluten-free products, such as lower levels of B vitamins, iron, and fibre, are a concern and may be mitigated by incorporating ingredients like quinoa, amaranth, or legumes. Despite these efforts, gluten-free products often have higher glycemic indices and may be high in fats and sodium, which can affect their nutritional value. Commercial and homemade gluten-free cupcakes each face unique challenges. In commercial production, consistency in texture, flavor, and shelf life is vital, requiring precise formulations and stabilizers, while homemade versions struggle with achieving the right texture and preventing cross-contamination. Advanced processing techniques, such as sourdough fermentation and the use of functional additives like egg whites and microbial proteases, offer potential solutions to enhance both the sensory and nutritional quality of gluten-free cupcakes.This review synthesizes current strategies for improving GF cupcake quality, focusing on ingredient innovation, processing advancements, and nutritional enhancement to meet both consumer demands and the needs of individuals with celiac disease and gluten sensitivities.

Keywords: Gluten Free Diet; Celiac Disease; Glycemic Index; Hydrocolloids; Sourdough Fermentation; High Hydrostatic Pressure Processing (HHP)

Introduction

Understanding Gluten-Free Cupcakes

Consumer demands in food production have undergone significant changes. There is a growing belief among consumers that food plays a direct role in promoting health. [1] Today, food is no longer solely viewed as a means to satisfy hunger and provide essential nutrients but also as a way to prevent nutrition-related illnesses and enhance both physical and mental well-being. [2, 3]

Wheat accounts for 20% of the world's calorie intake, ranking among the most important crops globally. Its adaptability allows it to be used in a wide range of foods, including bread, pasta, cereals, and baked goods, establishing it as a dietary staple in temperate regions. [4] Wheat has long been recognized as a nutritious source of proteins, vitamins, and minerals, but concerns have emerged about one of its components, gluten. The use of gluten can be traced back to 6th-century Chinese cuisine, where it gained popularity among Buddhists as a meat substitute. Gluten is mentioned in Qimin Yaoshu, an agricultural encyclopedia by Jia Sixie written in 544 CE, which describes its use in noodles called bótuō. In Western literature, references to gluten appeared much later; Bartolomeo Beccari's

ISSN: 2395-2326

1745 Italian treatise on wheat, De Frumento, detailed the process of extracting gluten from wheat flour.[5]

Structure of Gluten

Gluten is composed of water-insoluble prolamin proteins, which are a complex group of alcohol-soluble lectins. These prolamins serve as the primary seed proteins in cereals, making up approximately 80% of the storage proteins in the starch endosperm of mature cereal grains. [6] Notably, they have not been identified in other parts of the grain. [7] The primary gluten prolamins, known as gliadin and glutenin, are mainly found in wheat. However, prolamins are present in other cereal species under different names, such as hordeins in barley, secalins in rye, avenins in oats, and in other closely related grains, each exhibiting distinct molecular characteristics. [8] Gliadins consist of four main alcohol-soluble monomers that together enable gluten to stretch and provide intermolecular binding sites. The α-helices and β-sheets in α/β- and γ-gliadins facilitate hydrogen and disulfide bonding, while ω-gliadins are made up of β-turns and lack both α-helices and β-sheets. [9] When flour and water are combined, a thiol group from glutenin reacts with the disulfide bonds in gliadin, leading to the formation of intermolecular disulfide bonds. [10] The high concentration of glutamine amino acids leads to the formation of numerous inter-chain hydrogen bonds, which together contribute to the strength of gluten. [9, 10] Additionally, the elevated proline content in gluten alters its protein structure, enhancing its elasticity. [9]

Celiac Disease (CD)

Celiac disease (CD), also known as gluten-sensitive enteropathy, is a common disorder of the digestive system. In affected individuals, the immune system attacks the small intestine tissue, particularly the villi responsible for nutrient absorption. [11] Chronic mucosal damage and inflammation can result in the malabsorption of essential nutrients like calcium, vitamin D [12], iron [13], vitamin B12, folic acid, and zinc. [14] This deficiency may lead to serious health issues such as osteoporosis, anaemia, and stunted growth.[15] The clinical presentation of celiac disease (CD) can differ by age. In paediatric patients, the classic symptoms include malnutrition, failure to thrive, abdominal pain, and distension. In contrast, adults typically experience gastrointestinal symptoms, though they are generally less severe,[16] with most patients suffering from severe diarrhoea. [17]

Gluten ataxia is an immune-mediated disorder in which gluten consumption triggers the immune system to attack nervous system tissue, particularly the cerebellum. Transglutaminase 6 (TG6) autoantibodies are more prevalent in individuals with gluten ataxia and have proven to be a reliable diagnostic marker for the condition, as highlighted by Hadjivassiliou and colleagues. [18] Although the gluten-free diet (GFD) has demonstrated effectiveness in managing gluten ataxia and celiac disease (CD), its purported benefits for other health issues remain largely uncertain. [5]

In recent years, however, a gluten free diet has also become one of the most popular dietary choices among the general public and individuals managing various health conditions. These include non-celiac gluten sensitivity (NCGS), irritable bowel syndrome (IBS), autism, as well as neurological, psychiatric, and rheumatologic disorders. Additionally, some adopt this diet to enhance athletic performance. [19]

Gluten – Free Products

A gluten-free product is defined as containing less than 20 parts per million (ppm) of gluten, accounting for potential contamination during the manufacturing process. [20] The demand for alternative food options is growing rapidly. In 2019, the global market for ketogenic diets was valued at $9.57 billion, and it is projected to grow at a compound annual rate of 5.5% through 2027. [21] Gluten-free products are typically made using pseudo-cereal flours and are often less nutritionally dense compared to their gluten-containing counterparts. They also face various technical challenges, such as undesirable texture, low specific volume, quick staling, poor colour, and suboptimal flavor. Gluten-free dough tends to have lower strength and elasticity while being highly adhesive, which impairs its ability to trap gas. These factors contribute to issues like brittle texture, reduced specific volume, poor appearance, and shorter shelf life. [22]

Gluten-free bakery products often feel unfamiliar to consumers who are accustomed to traditional wheat or wheat-rye based products. Gluten-free bakery products typically have a less elastic crumb that hardens more quickly and crumbles easily. Their taste also varies, largely depending on the specific ingredients used in their preparation. [23]

Essential Ingredients in Gluten-Free Cupcakes

The development of gluten-free (GF) bakery products has involved the use of various ingredients and technologies, including: (a) gluten-free flours; (b) starches; (c) dairy products; (d) protein supplementation; (e) gums and hydrocolloids; (f) functional ingredients. [24]

These alternative ingredients can be derived from cereal and non-cereal sources [25], fruit or vegetable fibres [26, 27], flax and chia seeds [28, 29], psyllium [30], modified starches, and proteins from various sources.[31]

Gluten-Free Flours

Corn (*Zea mays L. ssp. mays*) and cornstarch have been used in gluten-free products, often combined with xanthan gum as the networking component. The resulting bread exhibits a good specific volume but tends to have a coarse crumb structure and lacks flavor.[32] Rice (*Oryza sativa*) flour is considered highly suitable for preparing gluten-free (GF) products due to its bland taste, colorlessness, easy digestibility, and hypoallergenic properties.[33] Additionally, it is low in sodium, fat, and fibre.[34][35] However, for baking applications, the proteins in rice lack the elastic and plastic properties of wheat gluten, which are essential for retaining gas produced during fermentation. Sorghum (*Sorghum vulgare*) is often recommended as a safe food for celiac patients because it is more closely related to maize than to wheat, rye, and barley.[36] Starch plays a pivotal role in gluten-free sorghum-based bread. The addition of starches that gelatinize more readily helps to develop a cohesive crumb network that traps gas bubbles, preventing the loss of carbon dioxide and crust collapse. Additionally, the extra starch dilutes the particles of endosperm and bran in sorghum flour, which would otherwise

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disrupt the liquid films around the gas cells and affect the uniformity of the starch gel. [37] Whole oat flours with coarse particles, minimal starch damage, and low protein content produced bread with good quality, a pleasing volume, and a soft crumb structure.[38]

Pseudocereals

Pseudocereals, unlike monocotyledonous cereals, are dicotyledonous, but their starch-rich seeds can be used similarly to cereals. These pseudocereals are being explored as alternatives to gluten-containing grains in the gluten-free diet due to their nutritional benefits for individuals with celiac disease (CD). [39]

Quinoa

Quinoa (*Chenopodium quinoa*Willd) is a seed crop that originated in the Andes. However, gluten-free (GF) products were improved by replacing 50% of the potato starch with quinoa in a formulation that also included rice flour. This substitution significantly increased the protein and fibre content, helping to meet nutritional recommendations for celiac patients. Additionally, the presence of vitamins and other bioactive compounds, such as phytosterols, further enhanced the nutritional quality of GF products containing quinoa. Nonetheless, more studies are required to explore this promising gluten-free alternative. [40]

Dairy Products

Dairy, egg, soy, and maize have traditionally been used in baking, making them logical alternatives to replace gluten in gluten-free foods in order to enhance both their nutritional and functional properties. [23] In baked products, dairy ingredients help form networks that enhance flavor and crust colour, improve texture, reduce staling, and increase water absorption, thereby improving the handling properties of batters.[41] Despite the functional benefits of using dairy in gluten-free formulations, this protein source has a notable limitation. Damage to the intestinal villi caused by celiac disease can lead to lactose intolerance, potentially restricting the acceptance of gluten-free products containing dairy ingredients.[42] The holding capacity of gluten-free (GF) products improves as proteins form a network analogous to that in wheat bread. This enhances the resulting product by reducing baking losses, increasing crumb moisture, and promoting fineness, lightness, and homogeneity.[43]

Dietary Fiber

The addition of fibre, by absorbing water, enhances the quality of bread. In addition to its positive health effects, fibre improves texture, specific volume, apparent viscosity, consistency, sensory qualities, and shelf life. This is because fibre has the ability to bind water, form gels, and thicken the dough. [24] The key parameters that influence the effect of fibre on bread quality include fibre length, the degree of polymerization, the ratio of soluble to insoluble fibre, and how the fibre interacts with other ingredients. [44,45,46]

Starch

Starches are extensively utilized in the food industry for their gelling, thickening, moisture retention, emulsifying, film-forming, and texturizing properties. In dough, starches play a crucial role in absorbing water and enhancing the texture, appearance, and overall acceptability of baked products. Structurally, starches can function as inert fillers within the continuous dough matrix or form part of a bicontinuous network of protein and starch. During the baking process, starch granules undergo gelatinization, swelling, and partial solubilization while retaining their granular structure.[47] Starch derived from sources such as corn, cassava, sweet potato, potato, sorghum, barley, and rice is commonly utilized in gluten-free products. Further studies are necessary to gain a deeper understanding of the impact of various starch types and their functional properties in gluten-free products.[23]

Gums and Hydrocolloids

The replacement of gluten in gluten-free products poses significant challenges, as gluten-free batters tend to have a liquid consistency due to the lack of a sufficient gluten network. Therefore, polymeric substances that impart viscoelastic properties are necessary for the development of gluten-free breads to enhance their structure, mouthfeel, acceptability, and shelf life. Hydrocolloids or gums are hydrophilic, long-chain, high molecular weight polysaccharides that are extracted from plant, seaweed, and microbial sources, as well as gums derived from plant exudates and modified biopolymers prepared through chemical treatment of cellulose. [23] HPMC (Hydroxypropyl Methylcellulose) and xanthan gum are the most commonly used hydrocolloids in gluten-free breads because they effectively replace gluten, enhancing the texture, structure, and stability of the product, regardless of the specific formula used.[48]

BakingTechniques for Perfect Gluten-Free Cupcakes

Gluten free baking requires alternative technologies, such as fermentation, enzymatic processing, and high hydrostatic pressure (HHP) processing.

Gluten-free dough is a complex semi-liquid system composed of polysaccharides, structure-forming components, viscosity-increasing substances, and dough-stabilizing agents. It is typically characterized by high density and low elasticity. Compared to conventional wheat dough, gluten-free dough contains more water, with the amount depending on the type of raw materials used, their water absorption capacity, and their granulation. Additionally, kneading time and speed play a crucial role, as prolonged kneading can increase the specific volume of the final product. [47]

Complete gelatinization of starch greatly affects the quality of the bread. Starch gelatinization requires sufficient water, which is particularly important as gluten-free doughs often resemble batters. Additionally, the presence of gelatinized starch during the initial stages of bread-making can significantly enhance dough consistency. [48]

Impact of Ingredients on the Texture of Gluten-Free Cupcake

Gluten-free baking presents a significant problem for all bakers and cereal researchers. The quality of the finished gluten-free products, the production process, and the dough's rheology are all significantly impacted by the lack of gluten in the dough. doughs without gluten are significantly less elastic and cohesive than those made with wheat. Actually, these gluten-free doughs are frequently referred to as batters rather than dough.[49]

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When making leavened products with gluten-free flours, the main method is to add polymeric ingredients, which mirror features of gluten by producing a volume that resembles that of wheat.[50] A key element in controlling the quality characteristics of the finished bread products is hydrocolloids. Hydrocolloids are frequently used in gluten-free recipes because they enhance dough quality, delay starch retrogradation, simulate some of the rheological characteristics of gluten, and enhance bread's texture, appearance, and stability.[51] According to multiple investigations, xanthan gum (XG) and cactus mucilage powder (CMP) were the hydrocolloids that demonstrated the suitable quality of loaf making. Microorganism Xanthomonas campestris secretes XG, an extracellular heteropolysaccharide with a molecular weight of around 1000 kDa (kilodaltons) [52]. CMP and xanthan gum work well with a variety of food ingredients, such as starch, which enhances the rheology, texture, baking properties, eating quality, and appearance of gluten-free baked goods [53]. Hydrocolloids, microbial intervention, transglutaminase enzymes, gluten-free flours, gluten-free starches, dairy products, and proteins have all been used to create gluten-free goods. [54] Pseudocereals, which include nuts, legumes, and seeds (such as sorghum, chickpeas, millet, quinoa, amaranth, linseeds and flaxseeds), can be used in place of gluten. The legume chickpea (Cicer arietinum) is a member of the Fabaceae family. In addition to minerals, β-carotenes, and unsaturated fatty acids, it provides a significant source of protein. When added to gluten-free baked goods, chickpea protein can enhance their blending qualities and increase their volume.[55]

Nutritional Analysis of Gluten Free Products

Macro and Micro nutrients

To improve the structural acceptability of gluten-free products, a variety of flours, starches, proteins, enzymes, and hydrocolloids have been utilized to replicate the viscoelastic qualities of gluten.[56] Consequently, the various combinations of these substances result in a significant variation in the nutritional makeup of gluten-free foods compared to their gluten-containing counterparts, which in turn impacts the nutritional value of these goods.[57] Gluten Free cereals and products derived from them have lower levels of iron, fibre, folate, thiamine, riboflavin, and niacin than their gluten-containing counterparts, which could have an effect on the nutritional value of adequacy of the Gluten Free Diet [58] The key ingredients of gluten free products, starches and low-protein flours (such maize and rice), also seemed to be poor sources of folate, with just 6 µg folate/100 g fresh weight, while a typical wheat flour with an 8.5% protein content has 21 µg folate/100 g [59]. Many GF products, particularly those in the baking industry, have a high sodium level, which helps to stabilize their structure and improve their flavor and taste, particularly in those where the tasteless starches are the primary ingredient [60].

Glycemic Index of Gluten Free Products

The GI is a crucial metric for assessing the nutritional value of food since elevated or upper-limit moderate GI is linked to the rising rates of cardiovascular disease, diabetes, and obesity. For this reason, dietary guidelines recommend a low-GI (<55) diet in order to prevent chronic diseases. [61]Removing gluten may theoretically worsen the glycemic response of foods high in carbohydrates because the stronger network of gluten retains the starch, preventing it from expanding and being hydrolysed by the digestive enzymes. First noted in a study, a gluten-free bread had a noticeably higher GI value than a conventional white bread [62]. Addition of fibre and sourdough fermentation are known to lower the GI of foods that contain leavened starch [63].

Challenges in Baking Gluten Free Cupcakes

Research convey that using various gluten-free ingredients, such as rice, maize, potato, or quinoa flour, can replicate the visco-elastic qualities of gluten, preserve gas, and enhance the preservation of final goods' structure, mouth feel, and shelf life [64]. Gluten-free flours often absorb more liquid, leading to dry cupcakes, therefore adding more water can make the cupcakes soft and spongy [65]. Gluten-free batters often rise unevenly or collapse during cooling because they lack gluten's elasticity. Use a combination of baking powder and baking soda for better leavening. Adding flavouring agents like cocoa powder, vanilla essence can put away the off flavors that usually accompany gluten free flours like quinoa flour, sorghum etc. Cereal technologists have developed various strategies to address challenges in producing gluten-free breads while meeting the expectations of celiac patients [66]. Particle size distribution method was used to make gluten free cupcakes with rice flour to achieve the optimum sensory attributes [67].

In order to enhance the nutritional, sensory, and physiochemical qualities of gluten-free products, it may be advantageous to incorporate functional components like egg whites, sweet potatoes, or other substances [68]. For a significant section of the global population, gluten-containing items are also a staple diet. Therefore, creating gluten-free products for people with celiac disease is not only urgently needed, but also a challenging task for food scientists. Due to social constraints, cross-contamination, and the protein's widespread presence, a total eradication of gluten is not feasible. Because of the poor dietary compliance, alternative approaches to treating celiac disorders must be used [69]. Additives and nutritive ingredients, such as whole grains like amaranth, quinoa, millet, and teff, enhance the nutritional value. Hydrocolloids improve visco-elastic properties, and milk proteins create a gluten-like matrix for better crumb texture and delayed staling. Microbial proteases and trans-glutaminase enhance the quality and network formation in gluten-free flours. Advanced processing techniques, including high pressure, extrusion, and sourdough fermentation, further improve product quality. Gluten-free foods also lack pyrazines that cause aroma. This was addressed by adding aroma precursors of the Maillard process to the dough before baking, which are proline and glucose [70].

Commercial vs Homemade gluten free cupcakes

In 1976, the Food and Agricultural Organization (FAO) and the World Health Organization (WHO) Codex Alimentarius Commission adopted the Codex Standard for gluten-free foods. So-called gluten-free foods are defined as follows in 1981 and 2000 draft revised standards: (a) made entirely of ingredients that do not contain any prolamins from wheat or all Triticum species, such as spelt, Kamut or durum wheat, rye, barley, oats, or their crossbred varieties

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[71] In contrast to other items where gluten is crucial, cupcakes with and without gluten have fewer significant nutritional variations. This has to do with how much more homogeneous gluten-containing formulations are than gluten-free ones [72].

The formulas of gluten-free items typically use more egg and thickening ingredients [73]. Compared to many vegetables, Quinoa is a more complete protein because it contains a lot of the important amino acid lysine. Because it doesn't contain gluten, both persons with celiac disease and those who are allergic to wheat can eat it. The seeds' oil fraction is very nutritious and of excellent grade. Along with fibre, vitamin E, copper, phosphorus, potassium, zinc, and several B vitamins, it is also high in iron and magnesium. The saponins found in the outer seed layer of quinoa are toxic and bitter, so it must be removed before consumption or processing in order to make culinary products. One defensive characteristic of the plant is its saponin concentration [74].

Sorghum is regarded as a marginal crop despite its lower cost and ease of production because, in comparison to wheat and maize, it is not as widely consumed worldwide. For instance, it has been said that the food industry is ignoring a sustainable, affordable, and healthy source of sorghum that could benefit both the industry and consumers. Due to its environmental sustainability and the growing demand for functional and healthful foods, sorghum has recently presented new potential for use as a raw material for human food. Using sorghum in baked goods that are already commonly consumed and readily incorporated into diets is one strategy to boost sorghum intake and reach a large portion of the population [75]. Celiac disease affects about 1% of the global population and is growing. The only treatment is a strict gluten-free diet. While corn and rice are commonly used in gluten-free (GF) products, alternative flours from pseudo-cereals (quinoa, buckwheat, amaranth), legumes (soybean, lentil, chickpea), seeds (flax, chia, pumpkin), nuts (almonds, hazelnuts), and tubers (tapioca, potato) are gaining attention. These alternatives are more expensive and less accessible than corn and rice. Developing GF products is challenging due to nutrient deficiencies in celiac patients and the structural role gluten plays in baked goods. GF products created from commercial starches and non-gluten grains are believed to have lower levels of DF, B vitamins, and iron than traditional gluten-containing foods.

The strict GF diet has consequently raised persistent concerns about the eating habits and food preferences of celiacs [76]. Without gluten, dough lacks structure, leading to defects. Sourdough fermentation, though not widely used industrially, improves nutritional value, shelf life, texture, and sensory quality of GF bread [77]. Commercial and homemade gluten-free cupcakes face distinct challenges. Commercially, maintaining consistency in texture, flavor, and shelf life across batches is crucial. Gluten replacements often require precise formulations and stabilizers, like hydrocolloids, to mimic the structure gluten provides, while ensuring mass production is cost-effective. Additionally, sourcing high-quality, allergen-free ingredients at scale and meeting labelling regulations add complexity. For homemade gluten-free cupcakes, challenges include achieving the right texture without advanced equipment or specialized additives, as gluten-free flours often result in denser or crumbly baked goods. Balancing flavor and moisture while avoiding cross-contamination with gluten-containing ingredients in home kitchens is also a significant concern [78].

Results and Discussion

The development of gluten-free (GF) products has significantly progressed, particularly through the incorporation of various alternative grains and ingredients. Rice, quinoa, amaranth, and chickpea flours have been widely studied for their functional properties in GF baking, offering potential to improve both texture and nutritional profiles of GF products [54, 72]. The use of high-protein flours, such as brown rice and chickpea, has been found to enhance the protein content of GF products, compensating for the typical low protein content of many GF foods [44, 54]. Additionally, hydrocolloids such as xanthan gum, guar gum, and psyllium have been crucial in addressing the lack of gluten, improving dough structure, moisture retention, and texture in GF breads [48, 51, 52]. Moreover, the addition of dietary fibres, like inulin, has been shown to improve the texture and nutritional benefits of GF breads while also contributing to better digestive health [45, 46]. Studies also highlight the importance of fibre in lowering the glycemic index (GI)

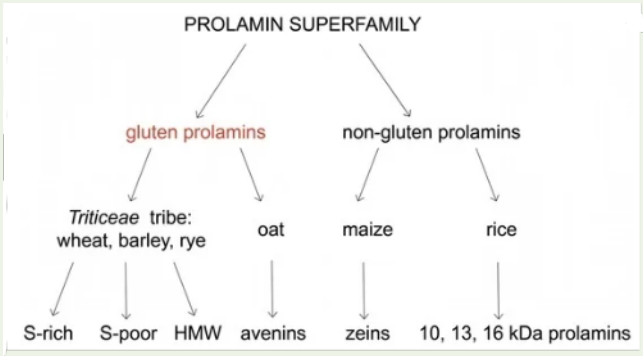
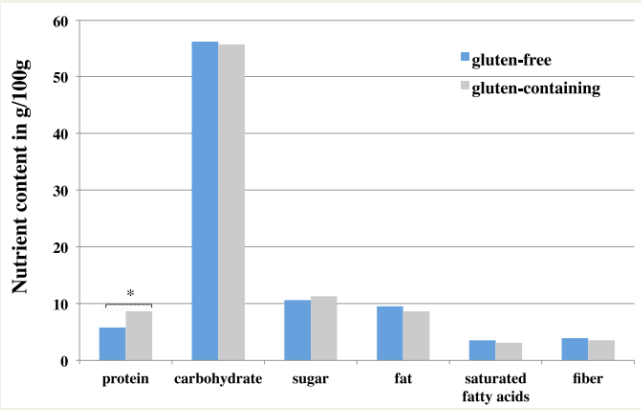


Figure 1: Balakireva AV, Zamyatnin Jr, A. A. (2016). Properties of gluten intolerance: gluten structure, evolution, pathogenicity and detoxification capabilities. Nutrients 8: 644.



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Major Drawback in Gluten Free Products	Gluten Free Products	Techniques for improving GF products' nutritional value
high content of total and saturated fats	bread, Cupcakes, dough / pastry / pizza and pasta categories	to avoid starch as a major ingredient; sourdough fermentation
high content of sodium	Cakes, cupcakes, pastas and bakery products;20 breads and pastas2	to avoid using starch as a primary component; fermentation of sourdough
low content of B vitamins (e.g., thiamine and niacin)	flours, breads, pastas, bakery products (cupcakes, cakes) and breakfast cereals; breads; and pasta	to incorporate pseudocereals (such amaranth, quinoa, and buckwheat64) and legumes (like lupine)
low content of total folate	GF ingredients (e.g., rice starch), flours and breads; flours, breads, pastas, bakery products (cake, cupcakes) and breakfast cereals.	to use quinoa and amaranth instead of starch as a main element, particularly in type of wholemeal
low content of calcium and iron	breads; cupcakes, cakes breads and pastas	to add teff, quinoa and amaranth
presence of mycotoxins (e.g., fumonisins)	corn-based foods, including flours, breads, pastas, and baked goods; flours and extruded products goods as well as cereal for breakfast	sourdough fermentation
high glycemic index	Bread, cake, cupcakes, puffs and pastas	viscous fibre (e.g., inulin-type fructans); sourdough fermentation; to include legumes

of GF products, which can be particularly beneficial for individuals with diabetes [61, 63].

However, challenges remain in replicating the texture and structure of traditional gluten-containing products. While alternative ingredients have provided viable solutions, achieving the same sensory quality in GF products is difficult. The use of rice flour, though common, often results in inferior texture and crumb structure compared to wheat-based breads [43, 56]. The combination of flours and the use of enzymes or protein isolates, such as those from soy or chickpea, have been found to improve both the functional and sensory properties of GF breads [56, 55, 57]. Furthermore, improving the glycemic response of GF breads through the strategic selection of ingredients, like amaranth and quinoa, has been a focus of recent studies [63, 64]. The integration of these ingredients into GF bakery products also presents a significant opportunity to combat common nutritional deficiencies in the GF diet, such as low iron, fibre, and folate intake [60, 59]. Ultimately, continued research into ingredient synergies and processing methods will help overcome these barriers, providing consumers with better-quality and more nutritious GF products [47, 58, 60]

Conclusion

The gluten-free (GF) bakery industry has witnessed significant advancements in the development of products that cater to the growing demand for gluten-free alternatives. Through the application of diverse ingredients such as alternative flours, dietary fibres, hydrocolloids, and fermentation agents, it has become possible to improve the nutritional and sensory qualities of gluten-free breads and pastries [42, 43, 49]. However, while these innovations have brought about notable improvements in texture, taste, and nutritional balance, challenges remain. Achieving the ideal combination of ingredients that mimic the characteristics of wheat-based products, particularly in terms of elasticity, crumb structure, and shelf life, is still an ongoing area of research [40, 48, 51].

Further research is essential to address the gaps in our understanding of the interactions between ingredients and processing methods, as well as to enhance the bioavailability of essential nutrients like iron, calcium, and fibre[58, 61] Additionally, consumer acceptance plays a vital role in the success of gluten-free products, as taste and texture remain primary factors influencing choice [77, 78]. As the GF market continues to expand, it is crucial that innovations in ingredient formulation and processing not only enhance product quality but also ensure that these foods provide a well-rounded, nutritionally complete alternative to traditional gluten-containing products [60, 76].

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