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Formulation and preservation innovations in gluten-free muffins: A comprehensive review

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Abstract
The need for gluten-free baked goods has grown fast due to rising problems of Celiac Disease, non-celiac gluten sensitivity, and increasing demand for healthy alternatives. Muffins are popular due to their convenience, taste, variety of flavours and ability to be boosted with extra nutrients. But skipping gluten causes issues like poor shape, texture, and moisture retention, as well as going stale faster. Because gluten helps to form a continuous, viscoelastic protein network in dough, which provides better structure and texture and helps to extend shelf life. New studies look at using wholesome grain substitutes like millets, rice, oats, quinoa and pseudocereals. The researchers also focus on using fruit-based flours, like unripe banana flour, pumpkin seed flour, black carrot flour, and beetroot, which enhance nutritional value while maintaining acceptable sensory characteristics. At the same time, growing awareness regarding clean-label products has driven the demand for natural preservatives like plant extracts, herbal blends, and natural active ingredients in place of synthetic additives. This review takes a close look at the formulation challenges, physiochemical and sensory properties of gluten-free muffins, and the potential of natural preservatives in extending shelf life and maintaining product quality. Focus shifts on millet-based formulations and the role of natural extracts as antioxidants and antimicrobials. This paper concludes by highlighting future research gaps in optimising natural preservative dosages and developing sustainable gluten-free formulations.

Keywords: Gluten free, celiac disease, natural preservatives, shelf life, etc

1. Introduction
The demand for gluten-free products has been increasing over the past few years as people are concerned about their health and lifestyle preferences. A major reason for this shift is the growing identification of gluten-related disorders, which are now considered remarkable global health issues. Gluten, an insoluble protein composite mainly of glutenin and gliadin found in wheat, barley and rye, has a complex structure that is not easily soluble in water or solvents, is responsible for the viscoelastic properties but also acts as a threat for immune disorders and inflammatory responses in some individuals. Gluten-free product innovation has become a major research area within food science, which focuses on improving sensory, nutritional, and shelf-life aspects (Caponio *et al*., 2024) [9]. Celiac disease is an autoimmune disorder in which, when a person consumes gluten-containing foods, their immune system reacts abnormally and damages the lining of the small intestine and leads to inflammation. It affects about 1% of the global population and requires a lifetime strict gluten-free diet. Non-celiac gluten sensitivity, although poorly understood, involves gastrointestinal and extraintestinal symptoms that improve with gluten elimination and also causes gut issues. On the other hand, some people have a true allergy to wheat due to Immunoglobulin E (IgE) antibodies, which means they should avoid it altogether. These conditions raise the demand for gluten-free alternatives in the market (Sahu *et al*., 2024; Singla *et al*., 2024; Størdal & Kurppa, 2025) [42, 48, 52].
Muffins, a widely consumed bakery product, serve as a convenient model system for gluten-free product development due to their simple construction, short baking time, consumer familiarity, and variety of flavours. Lack of gluten affects texture, mouthfeel, volume, and moisture retention, creating challenges for consumer acceptance. Most standard recipes use lots of processed starches like rice, corn, or tapioca that don't add much nutrition and spike

blood sugar sharply. To fix this, researchers are now testing richer, better-performing flours from sources like millet, oats, fake grains, and beans to enhance both the functionality and nutritional value of gluten-free muffins. Millet-based muffins pack more minerals plus antioxidants; oat versions bring beta-glucans that can help lower cholesterol, while legume flours boost protein levels. Additionally, xanthan gum along with plant fibres acts as a thickening agent and also helps with the structure of gluten-free muffins. In an experiment the authors used black carrot fibre extract with xanthan gum in rice-based gluten-free muffins; the results showed better thickness, rise, and extra fibre (Singh *et al*., 2016) [45]. Beyond formulation challenges, shelf-life preservation is still a big challenge. Muffins contain a high amount of water, fats, and nutrients, which promotes the growth of microorganisms and oxidative rancidity and affects the storage stability. Synthetic preservatives such as calcium propionate or benzoates work fine, but people now often doubt them, worry about side effects and want chemical-free products, favouring natural, less-processed options instead. The clean label supports the idea of using plant-based natural preservatives - like essential oils, polyphenols, seed juices, leftover fruit bits, and natural defenders - to extend shelf life. Many experiments showed that the addition of natural preservatives not only affects microorganisms, but also improves taste, flavour, appeal and internal protection in muffins (Gularte *et al*., 2012) [23].

This review combines recent advancements in gluten-free muffin development, focusing on formulation strategies, physicochemical and sensory evaluations, and the integration of natural preservatives. By comparing multiple studies, it aims to provide a comprehensive understanding of how natural ingredients can simultaneously improve product quality, nutritional value, and preservation.

2. Gluten-Related Disorders and the Need for Gluten-Free Products

2.1 Celiac Disease

Celiac disease is an autoimmune disorder that mostly affects individuals with a high-risk genotype. Instead of just passing through, parts of gluten like gliadin spark inflammation that flattens tiny gut ridges, messes up nutrient uptake, and brings ongoing belly troubles (Sahu *et al*., 2024) [42]. It not only affects the digestive health - they end up dealing with low iron, weak bones, itchy skin rashes, trouble having kids, nerve issues, or stunted growth in young ones. When a person with an autoimmune disorder eats gluten, their immune system sees it as a harmful threat and damages the small intestine's lining. The immune system attacks the villi, which are responsible for absorbing nutrients in the small intestine. This situation leads to a decrease in nutrient absorption. The only effective treatment is to completely and permanently eliminate gluten from the diet. This treatment requirement increases the demand for safe, high-quality gluten-free bakery products (Ashwath *et al*., 2025; Caponio *et al*., 2024) [3, 9].

2.2 Non-Celiac Gluten Sensitivity (NCGS)

NCGS is a condition wherein a person falls ill after consuming gluten but does not have either celiac disease or a wheat allergy. Common symptoms include bloating of the abdomen, cramping, pressure in the head, headache, and joint or muscle pain. Scientists don't know exactly why this occurs, but some theories include the immune system reacting or reactions to substances such as Amylase-Trypsin Inhibitors (ATIs) and some types of carbs called fermentable oligosaccharides, disaccharides, monosaccharides, and polyols (FODMAPs) contained in wheat. Many sufferers avoid gluten intentionally, so there is continued growth of demand for gluten-free bread products and other gluten-free baked goods (Czaja-Bulsa, 2015; Singla *et al*., 2024) [14, 48].

2.3 Wheat Allergy

Wheat allergy is an Immunoglobulin E (IgE)-mediated hypersensitivity reaction to wheat proteins, typically presenting with urticaria, anaphylaxis, or exercise-induced allergic reactions. In contrast to Celiac Disease, where only the small intestine is affected, there is an immediate systemic reaction to wheat allergy, and strict avoidance of wheat is necessary. When made correctly, gluten-free muffins can also be safe options (Czaja-Bulsa, 2015; Singla *et al*., 2024) [14, 48].

2.4 Expanded Consumer Demand beyond Medical Need

Interestingly, individuals with gluten-related medical conditions no longer consume gluten-free products exclusively. Many health-conscious consumers perceive gluten-free foods as healthier, less processed, or easier to digest. Despite the lack of complete scientific support, this perception has significantly expanded the gluten-free market. The challenge remains, however, that gluten-free does not mean nutritionally superior. Therefore, fortification with natural preservatives, fibres, proteins, and antioxidants becomes important to ensure that not only are gluten-free muffins safe, but they are also health-promoting.

3. Challenges in Gluten-Free Muffin Formulation

Formulating gluten-free (GF) muffins presents significant engineering and biochemical challenges, as shown in figure 1, because gluten is the primary structural protein responsible for the viscoelastic network in traditional wheat-based batters. One of the most crucial issues is the absence of the gluten matrix, which is responsible for gas retention, elasticity, and structure upon baking. In addition, the unique viscoelasticity of gluten traps air bubbles and makes wheat-based muffins soft, with spongy crumb structures. This is opposite to the gluten-free batters that tend to collapse during baking, leading to much denser textures and reduced volume. The lack of a cohesive dough structure also complicates handling and shaping processes (Susman *et al*., 2020) [53]. The researchers have tried supplementing these deficiencies with hydrocolloids like xanthan gum, guar gum, and hydroxypropyl methylcellulose (HPMC). Each of these ingredients attempts to emulate gluten's viscoelasticity through facilitating the binding of water and stabilising the air cells in the batter. However, optimisation of hydrocolloids is not very easy, as their excessive inclusion often results in either rubbery texture development or the development of off-flavours. The complex interaction between starch gelatinisation, protein denaturation, and moisture distribution further complicates quality outcomes for gluten-free muffins (Shaabani *et al*., 2018) [44]. Another persistent problem is texture deterioration. Gluten-free products show increased hardness and rapid staling due to the high rates of amylopectin retrogradation in alternative flours. Moreover, the absence of gluten negatively affects fat distribution and air incorporation, yielding dry or crumbly muffins. Scientists reported that the replacement of a part of starch-based flours with whole-grain or pseudocereal flours enhances textural and nutritional balance. However, the use of high-fibre flours may promote the darkening of the crumb and earthy flavours, which could influence consumer acceptability (Filipčev *et al*., 2021; Capriles & Areas, 2014) [17, 10].

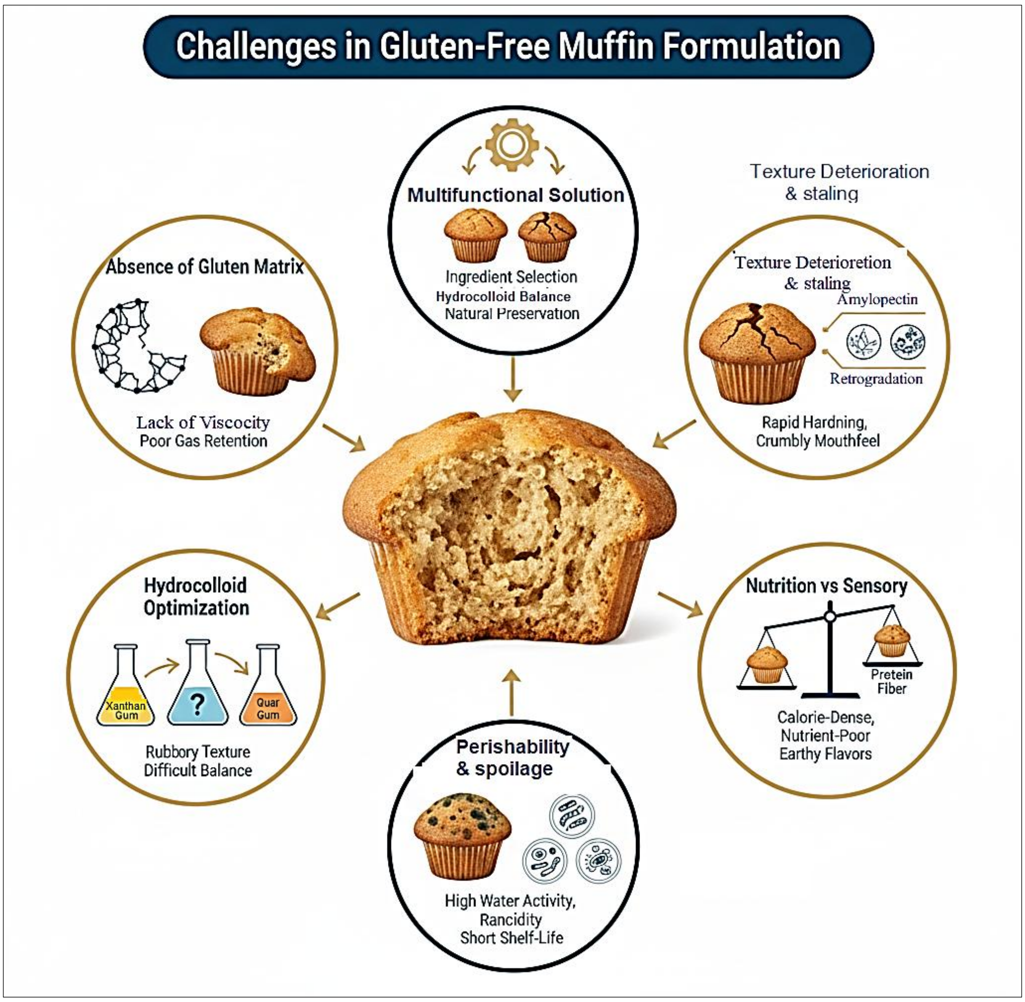

Fig 1: Various challenges in gluten free muffins

Another challenge is to balance nutrition with sensory attributes. Since most gluten-free formulations are designed to achieve acceptable texture, nutritional adequacy is often an afterthought. A large number of commercial GF muffins are calorie-dense but protein, mineral and vitamin-deficient (Talens *et al*., 2017) [55]. Lastly, from a preservation point of view, gluten-free muffins are very perishable. Their higher water activity and lack of strong protein matrices promote microbial spoilage and oxidative rancidity. Therefore, the optimal formulation definitely involves a multidisciplinary approach: ingredient selection, hydrocolloid balance, and natural preservation strategies.

4. Alternative Flours in Gluten-Free Muffins

The variety and combination of gluten-free flours, as written in Table 1, determine the success of gluten-free muffins (as shown in Figure 2). Wheat flour not only provides gluten but also imparts flavour, colour, and texture; hence, its substitution also needs functional ingredients that can mimic these functions. Research work is increasingly being reported on the utilisation of millets, rice, sorghum, legumes, and pseudocereals as successful substitutes due to their nutritional and technological attributes.

4.1 Millet-Based Muffins

Foxtail, pearl, and finger millets have emerged as promising gluten-free grains, and they are rich in fibre, essential amino acids, minerals, and natural antioxidants. Millet flour makes a muffin that is denser than the rice flour muffins due to the coarser texture and lower starch gelatinisation capacity. Millet flours have gained particular attention because of their high dietary fibre, bioactive compounds, and slow digestible carbohydrates. Various studies that developed gluten-free muffins using millet-based blends demonstrated improved mineral content, better antioxidant capacity, and more stable crumb textures compared to rice-only controls. Moreover, the natural phenolic richness of millet contributes to oxidative stability, acting indirectly as a weak natural preservative by slowing down lipid rancidity. Several formulations show that muffins made from millet blends have desirable sensory characteristics along with an improved nutritional density. Moreover, millet flours enhance the antioxidant capacity of muffins due to phenolic compounds, which also impart natural colour and flavour (Goswami *et al*. 2015; Abedin *et al*., 2022; Bhasin *et al*. 2024) [21, 60, 61]. According to a study by Paneria & Agarwal (2023), entitled Development of Gluten-Free Muffins Based on millets, three different millet-based gluten-free muffins were developed: Amaranth Millet, Proso Millet, and Barnyard Millet, while keeping the other ingredients constant. The results showed that amaranth-based muffins had the highest moisture content of 23.2%, along with calcium at 166 mg/100 g, while barnyard millet muffins showed the maximum ash of 2.66% and crude fibre of 3.33%. Proso millet muffins had the maximum iron content and were reported as most acceptable among the sensory panel members.

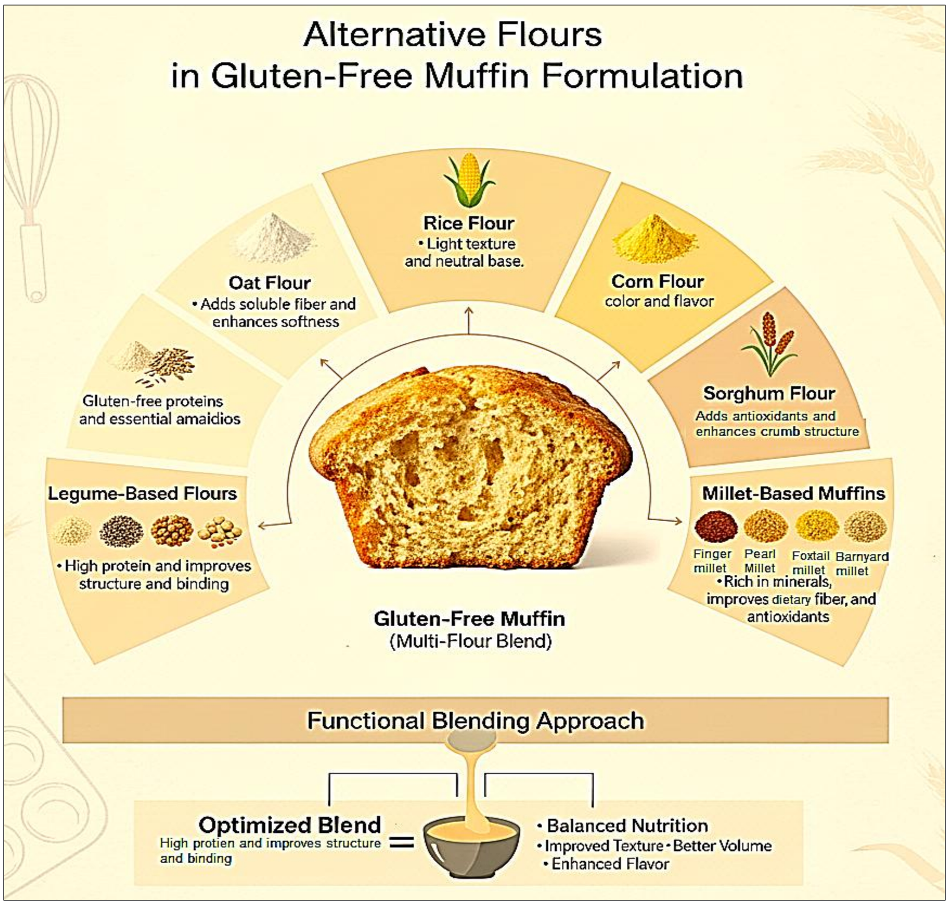

Fig 2: Alternative flours in gluten free muffins formulation

4.2 Legume and Pseudocereal Blends

Legume flours especially chickpea and lentil flour have a higher content of proteins and participate in Maillard browning upon baking. However, their characteristic earthy flavour needs to be balanced by sweeter or more aromatic ingredients. Most of the researchers have used legume flours in partial substitutions (10-25%) in order not to compromise flavour while improving amino acid balance (Felisiak *et al.*, 2024) [16]. Pseudocereals, such as amaranth, quinoa, and buckwheat, along with flours from legumes like chickpea, lentil, and pea, are being used in making gluten-free muffins more frequently for protein fortification and enhanced essential amino acid balance. Essentially, these flours have higher lysine content naturally, which complements the amino acid profile of cereals (Antoniewska *et al.*, 2018) [1].

Table 1: Different Gluten-Free Flours Used in Muffin Formulation

Sl.no.	Flour Type	Key Properties	Reference
1	Rice Flour	It has low sodium, protein and fat content and mild flavour and light colour, Easily digestible	Arifin et.al., 2024 [2]
2	Pumpkin Flour	Nutrient-dense flour containing bioactive compounds such as carotenoids, omega-3 fatty acids and essential vitamins (A, C, E).	Arifin et.al., 2024 [2]
3	Unripe Banana Flour	Rich source of resistant starch, provides essential minerals and vitamins,	Arifin et.al., 2024 [2]
4	Barnyard millet	Rich in dietary fiber with both soluble and insoluble fractions. Contains easily digestible protein and slowly digestible carbohydrates. Good source of minerals	Goswami et.al., 2015 [21]
5	Finger Millet	Flour containing good levels of protein, calcium, iron, chromium, magnesium and antioxidants. Easily digestible and low in allergenic nature. High fiber content contributes to nutritional quality but gives a coarse texture.	Nidhi Budhalakoti et.al., 2014 [33]
6	Foxtail Millet	It has good amounts of protein, dietary fiber, minerals and antioxidant compounds.	Barbhai,et.al., 2020 [6]
7	Pearl Millet	Contains slowly digestible starch and natural enzyme inhibitors, supporting better glycaemic response. Exhibits favourable physicochemical and techno-functional properties	Singh, et.al., 2024 [47]
8	Chickpea Flour	Contains slowly metabolized carbohydrates and beneficial unsaturated fatty acids. High lysine content improves protein quality when blended with cereal flours	Cravo et.al., 2023 [12]
9	Oat Flour	Nutritionally rich cereal flour containing high levels of soluble dietary fiber and essential minerals, and have bioactive compounds such as vitamin E, phenolic acids and phytic acid	Prasad et.al., 2023 [39]
10	Corn Flour	Nutritious vegetable rich in vitamins, dietary fiber and potassium, with nutritional value comparable to common vegetables. Imparts a mild, distinctive flavour and is widely used in various culinary applications.	Kaur et.al., 2021 [25]

4.3 Oats, Rice, Corn, and Sorghum Flours

Another treasured ingredient in oat flour is the presence of β-glucans, which are water-absorbing soluble fibres capable of creating rich, creamy, and cohesive textures. Many studies show that with the addition of oat flour with flaxseed and pumpkin seed, improvements not only occurred in nutritional value but also in moisture retention, softness, and shelf life. Seeds provided natural antioxidants and natural oils, which both helped reduce the staling process during storage. Significantly, the flaxseed provides lignans as natural oxidative stabilisers (Soong *et al*., 2014; Xu *et al*., 2025) [50, 58]. Rice flour is commonly used as a base flour in gluten-free muffins because it has a balanced flavour and possesses small particles. However, rice flour alone produces a dry and crumbly texture in muffins due to its low protein and fibre content. Therefore, it is generally used in combination with other gluten-free flours, like oat, corn, or sorghum flours, which have more thickness and taste (Sahu *et al*., 2024) [42]. Sorghum flour contains tannins and phenolic acids, which helps to improve antioxidant potential. Corn flour helps to improve crumb structure and moisture retention, but excessive use may slightly reduce muffin volume. These flours, when combined, provide better control over texture, moisture, and sensory balance. The general feeling within the field is that no gluten-free flour can replace wheat flour's structural and organoleptic properties; a well-thought-out combination of flours will be necessary, assisted by hydrocolloids, fibres, and natural preservatives, to produce high-quality gluten-free muffins.

5. Functional Ingredients: Hydrocolloids, Fibers & Natural Enhancers

Without a gluten matrix, gluten-free systems must have their structure artificially developed. Therefore, hydrocolloids have recently become central to gluten-free technology. Table 2 and Figure 3 show the functional characterisation and application potential of key ingredients in gluten-free muffin formulation. Xanthan gum, one of the most effective hydrocolloids for gluten-free bakery products, showed an improvement in water binding, batter viscosity, and air cell stabilisation, thus reducing the crumbliness of the products. In research, black carrot fibre rice muffins showed how xanthan gum increased the specific volume, improved crumb uniformity, and compensated for firmness caused by high dietary fibre addition. Black carrot fibre concentrate, or BCF, was also a functional ingredient that increased the total dietary fibre content and contributed natural antioxidants due to the high amount of anthocyanins it possessed. It was observed that BCF had a much higher degree of water and oil absorption capacity in comparison to rice flour and was therefore highly compatible with gluten-free batter systems. BCF by itself, however, reduced the volume of the muffin due to its coarse particles. The combination with xanthan gum restored and even enhanced the total quality, thereby proving the power of synergistic interaction among ingredients.

Table 2: Functional Characterization and Application Potential of Key Ingredients in Gluten-Free Muffin Formulation

Sl.no.	Functional Ingredients	Key Properties	Reference
1	Xanthan gum	Widely used as a food thickener and stabilizer. Exhibits high water-holding capacity, leading to increased batter viscosity and improved rheological properties. Enhances structure, stability	Singh et.al., 2016 [45]
2	Black Carrot Fibre	Fibre-rich by-product obtained from black carrot pomace, retaining significant bioactive components. Exhibits good stability under processing conditions and serves as a natural, health-promoting ingredient suitable for enriching eggless gluten-free muffins.	Singh et.al., 2016 [45]
3	β-glucan	It has strong water-binding ability, capable of forming hydrogels. Enhances viscosity and matrix stability in bakery systems, delays staling and moisture loss, and acts as a structure-forming component	Kurek, et.al., 2021 [28]
4	Pumpkin seed flour	Nutrient-rich, Provides valuable bioactive compounds such as carotenoids, tocopherols and phytosterols, along with dietary fiber and iron. Rich in essential amino acids,	Białek, et.al., 2016 [7]
5	Guar Gum	Helps in retaining moisture during storage, reduces crumb dehydration and delays staling. Contributes to improved freshness and extended shelf life of baked products when used as an anti-stalling agent.	Guarda, et.al., 2004 [22]
6	Flaxseed	Nutrient-dense oilseed rich in lipids, protein and dietary fiber, with a higher proportion of insoluble fiber and a notable soluble fraction. Excellent source of omega-3 polyunsaturated fatty acids, particularly alpha-linolenic acid (ALA), along with lignans and other phytochemicals.	Rabail et.al., 2023 [40]

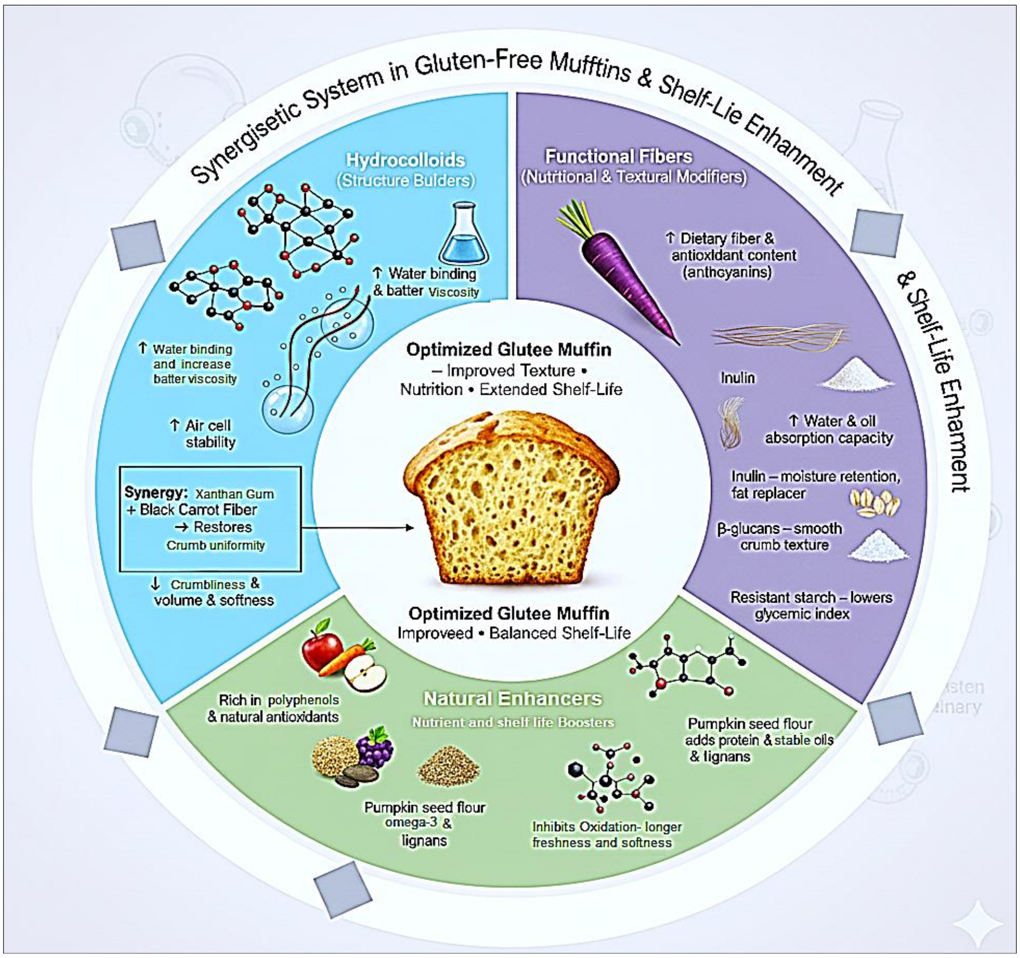

Fig 3: Functional ingredients in gluten free muffins

According to a study by Singh *et al*. (2016) [45], the role of black carrot dietary fibre concentrate as an active ingredient in the preparation of eggless gluten-free rice muffins. Refined muffins prepared from rice flour without the dietary fibre were taken as the control samples. Three different proportions of black carrot dietary fibre were used, which were 3% (BCF-3), 6% (BCF-6), and 9% (BCF-9), compared to flour. Xanthan gum on a 0.5% level had been incorporated along with other ingredients in selected samples for better batter and overall quality. Enhancement of functional, physicochemical, and quality properties due to increased proportions of dietary fibres had been studied. In modern gluten-free systems, soluble fibres like inulin, β-glucans, and resistant starches are widely researched. Inulin improves the moisture retention and can partly replace fat. Viscosity is conferred by β-glucans, especially oats, which also contributes to a smoother crumb structure. Resistant starch helps lower the glycaemic index of muffins, appealing to health-conscious consumers (Xu *et al*. 2025) [58].

Natural enhancers like fruit pomaces, seed powders, and vegetable fibres provide both nutrition and shelf stability. Studies have shown that pomaces from apples, grapes, and carrots are rich not only in dietary fibre but also in polyphenols, which can serve as natural preservatives because they inhibit lipid oxidation (Majerska *et al*., 2019) [31]. Pumpkin seed flour, used in this oat muffin study, provided proteins, minerals, and highly stable natural lipids. The softness was retained throughout storage days due to the release of natural oils during baking. Flaxseed also introduced omega-3 fatty acids and lignans, enriching antioxidant activity and supporting freshness in this product. Taken together, these active ingredients play dual roles in structuring and extending shelf life. Recent gluten-free muffin product development has increasingly focused on such multi-functioning components rather than isolated additives.

6. Batter Behavior, Rheology & Pre-Baking Quality

The behaviour of muffin batter during mixing and baking determines the structural development, gas-holding capacity, and final textural quality of the product. In wheat-based muffins, gluten proteins like gliadin and glutenin are the dominant agents in batter preparation. During mixing these gluten proteins develop a continuous viscoelastic gluten network that traps and stabilises air bubbles during thermal processing. This network provides desirable batter viscosity, optimal flow properties, and uniform bubble dispersion for a well-risen, soft crumb structure upon baking. Generally, wheat batter demonstrates pseudoplastic flow - the viscosity decreases with shear - which allows easy pumping, mixing, and aeration. Gluten ensures elastic recovery, enhancing gas retention before baking and structural stability at oven spring (Urade *et al*., 2018) [57]. In contrast, gluten-free muffin batters prepared from rice flour, millet flour, or other gluten-free flours have highly different rheological characteristics because of the absence of gluten-forming proteins. Gluten-free batters are often denser, less cohesive, and less elastic; therefore, they poorly stabilise gas cells and show less expansion. Rice flour, for example, is rich in starch but low in binding proteins, making the batter exhibit weaker viscoelasticity and greater batter spread. Millet-based batter contains large amounts of dietary fibre and complex carbohydrates; these require more water. The extra water absorbed increases batter viscosity. The network developed in millet-based muffins is more starch-based than protein-based, thus giving more brittleness and a tendency to collapse during baking. The result of such baking is smaller air cells, a lower specific volume, and a tendency toward crumbliness in the finished muffins (Bahraminejad *et al*., 2024) [4].

Rheologically, gluten-free batters often appear as highly viscous and less shear-thinning systems their viscosity does not decrease effectively under mixing, which complicates the process of aeration and bubble incorporation. The starch granules swell in gluten-free systems and thus compete for water, impacting batter consistency and increasing the dependency on mechanical mixing conditions and the hydrocolloid addition typically found in industrial formulations. This lack of an elastic protein network means a lower storage modulus (G') and less energy required for deformation than wheat-based batters, which indicates a fragile structure with less resilience. Quality indicators before baking, like batter density, flowability, viscosity, foam stability, and gas retention, will also be quite different: under the same mixing conditions, wheat batter maintains uniform distribution of entrapped air, whereas gluten-free batter is at risk of phase separation, sedimentation of solids, and hence irregular rise (Culetu *et al*., 2021) [13]. The pre-baking performance has an immediate reflection in both the appearance and texture of the final muffin. Generally, wheat muffins have a smoother batter surface, a more stable foam structure, and an even oven spring. Gluten-free batters, especially those rice- or millet-based, result in coarser batter matrices, which generally assure a denser, gritty or dry crumb unless structural modifiers, such as hydrocolloids, starch blends, or protein fortification, are included. Besides these challenges, gluten-free cereals possess nutritional benefits along with technological adaptability, and optimising rheology by reducing flour particle size, balancing starch and protein, and adjusting water can lead to a considerable improvement in quality before baking and, more generally, in the acceptability of the product.

7. Physical, Chemical, and Sensory Properties

Gluten-free muffins are characterised mainly based on their physical, chemical, and sensory attributes. Gluten, an important structure-forming protein in wheat-based conventional muffins, means its absence totally changes the batter's behaviour and the quality of the final product. The gluten-free batter system, therefore, relies heavily on starch gelatinisation, hydrocolloid interactions, and the functional behaviour of alternative flours to trap air, retain gases, and stabilise the internal crumb structure during baking. These complex interactions finally affect the volume, texture, colour, moisture retention, and flavour profile of the muffin.

7.1 Physical Properties

Physical quality attributes, such as specific volume, density, crumb structure, and moisture distribution, are significantly affected by the type and composition of gluten-free flours used. For example, alternative grains such as millet and legume flours tend to absorb more water due to their higher fibre content, leading to thicker batter consistency. This increased viscosity would frequently prevent excessive spreading during baking and accounts for a more compact but cohesive crumb. Although the denser crumb slightly reduces muffin height, it may improve softness and avoid the dryness often seen in rice-based formulations (Petrović *et al*., 2025) [38]. Textural analysis of muffins made from millet, sorghum, or composite flour blends often indicates only slightly higher values for hardness compared to refined rice flour muffins. These muffins usually show better cohesiveness and springiness due to the enhanced starch-fibre interactions. Hydrocolloids such as xanthan gum enhance these properties further due to the gel-like network thus produced to simulate some of gluten's viscoelastic functionality. Muffins enriched with dietary fibres, such as black carrot fibre, oat β-glucan, or inulin, exhibit higher water-binding capacity, therefore slower staling kinetics, and longer softness during storage (Tahmouzi *et al*., 2026) [54].

7.2 Chemical Properties

In gluten-free muffins, chemical composition such as protein, fibre content, phenolic compounds, and natural antioxidants plays a crucial role in the retention of moisture, providing stability to lipid oxidation, and browning reactions. Bioactive compounds, like phenolic acids, flavonoids, and tannins, are naturally present in sorghum, buckwheat, millet, and legume flours. These compounds help to maintain the chemical stability of muffins during storage (Gulsunoglu-Konuskan *et al*., 2025) [24]. Chemical characteristics also affect the browning rate of the Maillard reaction amino acid-reducing sugar complex responsible for changes in colour but also the flavour and aroma. Muffins made with natural sweeteners like honey are applied to have a deeper browning and richer caramelised flavour because of their higher mineral content and reduced sugar content compared to the more refined white sugars (Cannas *et al*., 2024) [8].

7.3 Colour and Appearance

Colour is one of the first sensory clues that consumers notice, and gluten-free muffins tend to have different colours based on their flour mixtures. Millet, sorghum, buckwheat, and pseudo-cereal flours naturally tend to have light cream to golden brown and reddish-brown colours. These are derived from natural pigments like anthocyanins, carotenoids, and tannins, along with the Maillard reaction upon baking (Djordjević *et al*., 2024) [15].

Whole grains, or fruit and vegetable-derived ingredients, receive positive responses from the consumers due to their natural colour. The addition of functional fibres also helps to improve the colour and appearance of the muffin. For example, muffins enriched with black carrot fibre give a subtle purple or brownish tone due to anthocyanin pigments. This natural colour enhances consumer acceptance, as it shows the presence of nutrient-rich, natural colour extracted from plant compounds instead of using artificial colours (Kavak *et al*., 2025) [26]. Surface gloss and uniform crumb appearance are also influenced by fat distribution and batter aeration; hydrocolloids and natural emulsifiers help create smoother, more appealing surfaces.

7.4 Sensory Properties

Sensory attributes, such as aroma, taste, mouthfeel, aftertaste, and others, are very important for consumer satisfaction. The ingredients, their composition, and moisture content play a very important role in determining the sensory characteristics of gluten-free muffins. Millet-based muffins tend to bring out a light nutty flavour, while sorghum will generally give out earthy overtones, though these can be pleasant when mixed with sweet or citrus ingredients. Muffins made with seed flours such as pumpkin, flax, and sunflower seeds or natural sweeteners usually have higher acceptance values due to their higher moisture content, stronger flavour, and improved mouthfeel. Consumers generally prefer muffins that maintain their softness and taste for a long time. Therefore, it is important to keep in mind that there is not too much dryness in muffins during storage.

8. Role of Natural Preservatives in Gluten-Free Muffin Development

In modern gluten-free bakery development, natural preservatives have taken over due to increasing consumer demand for clean-label foods and growing concerns about the safety of chemical additives. Unlike artificial preservatives, which primarily ensure antimicrobial action, natural preservatives are recognised for their multifunctionality: extending shelf life, enhancing flavour, and providing antioxidants even nutritional benefits. Natural preservatives are ideal for gluten-free muffins; they help to increase shelf life because gluten-free muffins have a low shelf life due to the absence of gluten and also have weak structural integrity (Chauhan & Rao, 2024) [11].

Table 3: Natural Preservatives are used in gluten-free muffins

Sl.no.	Natural preservatives	Key properties	Reference
1	Pomegranate Peel	Containing high level of polyphenols, tannins and flavonoids. Exhibits strong antimicrobial and antioxidant activity due to the presence of ellagitannins, inhibit spoilage microorganisms. Acts as a natural preservative, improves shelf life, enhances oxidative stability	Giri, et.al., 2024 [18]
2	Rosemary Extracts	Aromatic herb rich in phenolic compounds with strong antioxidant activity. Helps in controlling oxidative stress and is suitable for use as a natural preservative in food products as an alternative to synthetic additives.	Pedrosa et.al., 2021 [36]
3	Lemon Balm	Exhibits antioxidant properties and is valued for its potential role in improving food safety and stability when used as a natural additive.	Pedrosa et.al., 2021 [36]
4	Oregano	Phenolic-rich herb with notable antioxidant capacity. Contributes to oxidative stability of food systems and shows potential as a natural preservative	Pedrosa et.al., 2021 [36]
5	Clove	Exhibiting strong antioxidant and antimicrobial activity. Effective against a wide range of bacteria and microorganisms and helps reduce lipid oxidation, thereby slowing food deterioration. Acts as a natural preservative by inhibiting microbial growth and improving storage stability of food products.	Soumya *et al*. 2017 [51]
6	Cinnamon	It has compounds such as cinnamaldehyde, eugenol and caryophyllene, which contribute to its preservative action. Shows strong bacteriostatic and antifungal effects, inhibits yeast growth and aflatoxin production, and functions as an effective natural antioxidant and antimicrobial agent in food preservation.	Soumya *et al*. 2017 [51]
7	Lemon Grass	Strong antifungal activity, effective in retarding mould growth, fungicidal properties, control spoilage microorganisms,	Soumya *et al*. 2017 [51]
8	Orange Peel	Exhibits strong antioxidant potential and nutritional value, supports sustainable waste utilization,	Caponio et.al., 2024 [9]
9	Banana Peel	Exhibits antioxidant, antimicrobial, anti-inflammatory, and potential anticancer activities; improves batter rheology, texture, moisture, colour; acts as natural preservative and reduces agro-waste.	Kumar et.al., 2025 [27]
10	Thyme	Rich in essential oils, mainly thymol and carvacrol; exhibits strong antimicrobial (against Aspergillus, Penicillium, Ulocladium, Cladosporium, Trichoderma, Rhizopus, Chaetomium) and antifungal activity; has antioxidant properties	Gonçalves et.al., 2017 [20]

Herbs, spices, and essential oils, such as clove, cinnamon, rosemary, oregano, thyme, and citrus peel, contain various bioactive compounds, including eugenol, thymol, carvacrol, rosmarinic acid, and limonene. These compounds act as antimicrobial, antioxidant and antifungal compounds, which helps to reduce the growth of microorganisms. Various studies, as listed in table 3, have compared natural preservatives with synthetic preservatives. In these studies natural preservatives showed good results; they were effective in delaying mould growth and lipid oxidation and improving sensory quality. For example, muffins treated with clove extract had a longer mould-free shelf life, a richer aroma, and lower peroxide values than muffins that received calcium propionate or sorbates (Teshome *et al*., 2022) [56]. Natural plant-extracted preservatives, such as seed extract, green tea extract, pomegranate peel, and fruit pomace, are rich in polyphenols and act as free radical scavengers. The addition of these polyphenol-rich extracts to gluten-free muffins slows down the rate of fat oxidation, which is highly significant for diets rich in seeds, nuts, or whole grains with natural oils. The anthocyanin extract from black carrot fibre, used in one of your cited studies, has been recognised for its pronounced antioxidant activity, which has significant implications for the use of natural preservation in gluten-free muffins. Black carrot pomace shows a retention of nutrients despite juice processing, making it a significant addition as a potential antioxidant, not merely as a fibre supplement (Zhang *et al*., 2022; Singh *et al*., 2023) [59, 46].

Seed-based natural preservatives are also on the rise. Pumpkin seed flour and flaxseed powder, used in the preparation of oat muffins, are rich in lignans, as well as natural oils that are stable against oxidation. The natural oils, when combined with muffins, prevent them from becoming hard. The muffins prepared with seed flours retained softness even after a couple of days because the natural oils worked as humectants, retarding the development of hardness (Sonawane & Arya 2018) [49]. Among a great many natural preservatives, citrus peel extracts are becoming critical. They contain a positive percentage of flavonoids and essential oils responsible for the inhibition of microbial growth and peculiar fruity aroma. When these types of extracts are added at low concentrations, they cannot overpower the flavour of the muffin but will give a fresh aroma profile that is highly valued in sensory evaluation. In addition, extracts from lemon or orange peels reduce water activity naturally, which will have an additional positive effect on microbial resistance.

Natural sweeteners like jaggery and honey, besides providing sweetness, also contribute mild preservative action due to their mineral content, antioxidant properties, and relatively lower water activity compared to refined sugars. In the oat muffin research, the use of jaggery provided a richer flavour, increased moisture retention, and delayed staling more effectively than white sugar, which did not contribute any antioxidant compounds. What sets natural preservatives apart from their synthetic counterparts is how they are in synergy with the general nutritional and sensory profile of gluten-free muffins. Instead of providing their function in an additive manner, they form part of a more complex matrix of functional ingredients that support flavour, texture, moisture retention, and consumer-perceived healthiness. This is particularly the case for gluten-free products, where natural ingredients balance out structural weaknesses and lower nutritional density. They not only provide function in an additive manner, but they also support flavour, texture, moisture retention and consumer-perceived healthiness. This factor is especially important in gluten-free products, where natural ingredients compensate for structural weaknesses and lower nutritional density.

A comparative study by Soumya *et al*. (2017) [51] assessing the impact of natural preservatives on muffin quality involved the use of lemongrass, clove, and cinnamon powders in separate as well as combined forms. The preservative-treated muffins showed significantly low microbial levels compared to control muffins. In all treatment options, it has been found that mixtures of clove and cinnamon, as well as lemongrass, were found most potent in preventing microbial development, thereby increasing the shelf life of muffins up to 21 days.

9. Shelf Life, Microbial Stability, and Storage Characteristics

Gluten-free muffins limit the storage stability because the absence of gluten leads to higher water mobility, easy staling, and a loss of structural toughness. Moisture migration, lipid oxidation, and microbial growth can hence be initiated a lot earlier than in wheat-based muffins, which would strongly shorten the shelf life in the absence of preservatives.

9.1 Moisture Retention and Water Activity

Water activity is important in controlling microbial growth. Foods containing a higher level of dietary fibre, such as muffins enriched with black carrot fibre, will generally show reduced water activity due to the fibres binding free water. This trend was certainly evident in the study on black carrot fibre (BCF), where the muffins containing added BCF exhibited lower aw than that of the control group, hence being more stable to microbial attack. Xanthan gum enhanced this effect by increasing the water binding and reducing water mobility (J. P. Singh *et al*., 2016) [45].

The oat-based muffins with the addition of jaggery and seeds showed better moisture retention over several days of storage, since jaggery exerted humectant properties, while flaxseed and pumpkin seed oils reduced moisture loss. This ensured slower firming, a reduction in crumbliness, and an improved mouthfeel (Lamdande *et al*., 2018; S. Singh & Gaur, 2024) [29, 47].

9.2 Lipid Oxidation

Lipid oxidation is also another stability issue associated with gluten-free baked products because of the abundance of whole grain flours and seeds, contributing to high amounts of unsaturated lipids (Petcu *et al*., 2023) [37]. Natural antioxidant sources, such as black carrot fibres, citrus extracts, cinnamon, rosemary, and flaxseed, inhibit peroxide and secondary oxidation compound formation (Lante & Momayezhaghighi, 2025; Moczkowska *et al*., 2020) [30, 32]. The comparative study on batter revealed that natural preservatives were far more effective in reducing peroxide values than synthetic preservatives. The reason behind this finding is that polyphenolic compounds can hamper the formation of free radicals before the onset of oxidation, whereas synthetic preservatives can hamper the growth of microbes but cannot hamper the oxidation process (Rathee *et al*., 2023) [41].

9.3 Mould Growth and Microbial Spoilage

Gluten-free muffins are more susceptible to mould development due to their high moisture content as well as the lack of gluten inhibition. The essential oils from cloves, cinnamon, thyme, and oregano also demonstrated strong inhibitions against mould growth. The addition of these extracts to gluten-free muffin mixtures prolonged mould-free shelf life by several days (Bakkali *et al*., 2008) [5]. Muffins treated with natural preservatives were free of mould. The synthetic preservatives also increased the time before moulds appeared, but with better qualities offered by the natural preservatives without the unpleasant chemical flavour (Sayas-Barberá *et al*., 2023) [43].

9.4 Staling and Texture Alteration

Staling can be defined from the viewpoints of texture change, water distribution, and retrogradation of starch. The addition of fibres, inulin, oat beta-glucans, and BCF delays the retrogradation process of starch by retaining water and inhibiting the process of starch crystallisation. The addition of natural oils derived from seeds helps in the combined effects of fibres, thereby retaining the softness. Muffins prepared using BCF and xanthan gum were softer and more elastic in texture compared to the firm and crumbly rice muffins. The issue of shelf life in gluten-free muffins is one that involves multiple dimensions and can be effectively remedied by using natural preservatives, functional fibres, and structured flour blends. Together, the three components prevent the growth of microorganisms, reduce oxidation, preserve the moisture level, and combat staling.

10. Consumer Acceptability, Market Demand & Clean Label

The gluten-free market had transformed from a speciality to a mainstream market. This had happened not just because of medical requirements but because of the rising wellness trend. Customers are increasingly looking at products that do not contain additives, such as synthetic substances, colouring agents, or preservatives. Gluten-free muffins with natural preservatives perfectly fit the requirements. Consumer research has demonstrated that consumers associate natural preservative agents and products that use them with improved health, quality, and confidence in the food items. The muffins that contain plant extracts, fruit fibres, or seed preservative agents perform better than the chemical preservatives in taste and sensory analysis. Another key aspect of consumer acceptance is the appearance. Muffins that are fortified with either the fibre extracted from the black carrot or the whole grains tend to be brighter in appearance and have shades of brown, purple, and reddish colours. Instead of being viewed as flaws, these characteristics have been regarded as positive attributes. The ingredient that contains higher levels of anthocyanins, the black carrot fibre, provides dual benefits. The gluten-free muffin market is also foreseen to continue growing, especially in areas with a greater level of awareness about celiac disease and gluten intolerance. Furthermore, the trend for plant-based eating, sustainability, and natural preservatives will drive the acceptability of muffins made with natural preservatives, fibres, and ingredients.

11. Future Prospects and Research

Although great strides have been made, certain areas of research require further exploration. A prominent area of research relates to the optimal dosage of natural preservatives. Although natural preservatives are quite effective, high concentrations could result in overpowering flavour and batter rheology. Researchers should conduct research centred around specific levels for particular muffin matrices. Another area that has come forth is the synergistic combination of several natural preservatives. The idea of synergistic preservative combinations may result in higher preservation capabilities when citrus peel extract is combined with rosemary oil, or combinations like the use of black carrot fibres together with seed antioxidants being more effective compared to the use of one preservative. There would also be a requirement to understand the interactions between natural preservatives, hydrocolloids, and gluten-free flours. For instance, polyphenols could interact with protein and/or starch in a manner that affects gel formation. Such interactions could affect the final textures and volumes of the muffins.

12. Conclusion

The development of gluten-free muffins is a priority in fulfilling the nutritional requirements of patients suffering from coeliac disease, non-celiac gluten intolerance, and wheat allergy, as well as the increasing demands from health-orientated consumers. But the problem of handling gliadin-free batter characteristics, texture, moisture content, and shelf-life stability is a serious concern. But the hurdles can be easily overcome by combining different gliadin-free flours, such as millet, oats, and legume flours, along with different functional additives like fibre supplements, gums, etc. The addition of natural preservatives will further improve the quality of gluten-free muffins, as it will increase microbial shelf stability and prevent oxidative decomposition through the addition of preservatives that contain synthetic compounds. Natural preservatives from plants, vegetables, fruits, and seeds and antioxidants from natural sources will prolong the shelf life of gluten-free muffins and function as further advantages in improving the nutritional quality and consumer acceptance of the products. Therefore, naturally preserved gluten-free muffins will be produced with acceptable quality in terms of physical, chemical, and sensory characteristics to serve as good-quality baked products that are safe and free from impurities.

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