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Advancing gluten-free noodles development through sustainable and nutritional interventions

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ABSTRACT

The gluten-free noodle (GFN) market is expanding due to gluten-related diseases, dietary preferences, and the increasing number of health-conscious consumers. However, the production of GFN of comparable quality to traditional wheat-based noodles in terms of texture, cooking quality, and sensory acceptability remains a challenge. Herein, a systematic overview of sustainable approaches to improved quality and consumer acceptance of GFN is highlighted based on the incorporation of functional ingredients such as bioactive compounds, dietary fibres, hydrocolloids, and starch blends that synergistically enhance cooking quality, nutritional contents, shelf life, and sensory attributes. This approach emphasizing the synergetic effect offers an alternative to processing methods that could lead to degradation of thermolabile compounds. Careful considerations on the effect of ingredient proportions, particle size, and moisture content on enhancing the shelf life and product stability of GFN are highlighted. Regulatory compliance and transparent labeling critical for minimizing misconceptions and fostering product integrity among consumers are delved into. Further studies should focus on the optimization of sensory attributes, extending shelf life, addressing global regulatory discrepancies, and tailoring products to diverse consumer preferences. By integrating these sustainable approaches, GFN can offer nutritious and healthy foods aligning with the Sustainable Development Goals.

1. Introduction

The demand for gluten-free foods has risen in recent times, fuelled by the rising occurrence of gluten-related conditions, such as wheat allergy, non-celiac gluten sensitivity, and celiac disease, along with an expanding interest in gluten-free diets for perceived health advantages (Liu et al., 2020). Two factors are primarily responsible for the rising incidence of these disorders: first, modern wheat cultivar species have higher gluten contents; second, people prefer industrially processed foods like noodles, bread, pasta, pizza, etc., which contain a lot of refined or essential wheat gluten (Giannou & Tzia, 2016; Gong et al., 2024; Lux et al., 2025). Among these items, GFN have become a key substitute for consumers aiming to preserve dietary diversity while ensuring that health remains intact. Nevertheless, creating GFN involves distinct difficulties, especially regarding texture, flavour, nutritional quality, and market acceptance (Brand-Miller, 2007; Gao et al., 2017; Lux et al., 2025).

Gluten, a structural protein in barley, rye, and wheat, is fundamental to conventional noodles ' elasticity, texture, firmness, and cohesiveness (Liang et al., 2022; Lux et al., 2025). The absence of gluten frequently leads to lower sensory and textural qualities. For instance, GFN which are produced from processed starches, including rice or corn, are deficient in essential nutrients such as dietary fibre, protein, and micronutrients (Yao et al., 2020). Therefore, there is an increasing demand to improve the nutritional quality and overall performance of GFN to satisfy consumer expectations. Shifting from gluten-containing to gluten-free foods is not merely a trend but a critical health necessity for millions worldwide (Hong et al., 2021a). For those with celiac disease or gluten intolerance, adherence strictly to a gluten-free diet is proffer as an effective solution, as even small amounts of gluten can be detrimental to the intestine and reduce nutrient absorption (Xhaferaj et al., 2020). Similarly, removal of gluten is often accompanied by a reduction in

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bloating, brain fog, and fatigue in non-celiac gluten sensitivity (Aljada et al., 2021). Besides health obligations, health-conscious people prefer GFN for possible benefits such as improved digestion, reduced inflammation, and weight management. This shift underscores the importance of developing high-quality GFN that meet dietary requirements, with improved nutritional value and sensory attributes. GFN are brittle, sticky, with low cooking and nutritional attributes since they are produced from refined starches with low dietary fibre, protein, and vital micronutrients (Obadi et al., 2022; Wang et al., 2018). The recent innovations in GFN have created pathways for addressing issues of the absence of gluten and low nutritional components. One of the effective approaches is through the incorporation of ingredients including bioactive compounds, pseudo-cereals, and dietary fibres (Fu, 2008; Kraithong et al., 2023; Wang et al., 2018). Other techniques such as the incorporation of hydrocolloids, protein structuring, and starch blends, have reportedly enhanced the sensory and nutritional attributes of GFN (Nitta et al., 2018; Ren et al., 2020; Yi et al., 2015). Despite these innovations, GFN often receive criticism for their low-quality texture, bland taste, and nutrients compared to wheat-based varieties. These could affect consumers' acquiescence, even when health reasons make it necessary. Therefore, a need to delve into the approaches to improving the overall quality of GFN is necessary. Moreover, the study highlights the current gaps in the nutritional, sensory, and shelf-life attributes in GFN, thus promoting good health and well-being, responsible production and consumption, aligning with the objectives of the Sustainable Development Goals.

2. Search strategy

To conduct an in-depth analysis of this study, a systematic review of journals, scientific books, and databases such as ScienceDirect and Google Scholar (2015–2025) was conducted. Keywords such as "gluten-free noodles," "novel ingredients," "texture improvement," and "nutritional enhancement" were used. Articles were critically screened to retrieve relevant information on GFN, problems encountered, enhancements, and impacts of different composite formulations on GFN's nutritional, sensory, and cooking qualities.

3. Gluten-free foods: a potential substitute for gluten-containing foods

The elimination of gluten in the diet remains the cornerstone of effective management of celiac disease and non-gluten tolerance (Liu et al., 2018). As gluten-intolerant individuals increases, so does the demand for gluten-free products; consequently, gluten-free grains have become increasingly popular as an essential material in the food industry. With a rise in gluten-related disorders, a heightened rate in gluten-free product development, replicating the texture, flavour, and functionality of gluten-containing foods, is observed. The demand for quinoa, oats, buckwheat, sorghum, millet, corn, and rice as raw materials in food industries has increased due to their nutritional compositions (Fig. 1) (Woomer & Adedeji, 2021).

4. Drawbacks associated with GFN

The absence of gluten in GFN creates a considerable formulation challenge in that gluten contributes to cohesion, structure, and extensibility in conventional wheat-based noodles. It contributes viscoelasticity that influences extensibility, elasticity, and structure of dough during processing and cooking. In the absence of this protein network structure, GFN are mechanically weak with propensities towards poor dough handling, crumbly texture, and decreased cooking quality. GFN is reported to rupture easily due to the lack of a continuous protein network, hence compromising its structural stability and cooking consistency (Hager et al., 2012; Matos & Rosell, 2012; Naqash et al., 2017). Cooking results in excessive leaching of starch in GFN, producing clumping, softening, and unsatisfactory sensory qualities affecting consumer acceptability (Matos & Rosell, 2012; Naqash et al., 2017)

GFN are often deficient in nutrients such as dietary fibre, protein, and micronutrients like zinc, iron, and vitamins because of the limited nutritional significance of typical gluten-free flour (rice, corn, cassava), thus leading to nutritionally inferior products. To enhance the nutritional content, nutrient-rich ingredients like pseudo-cereals and legume flours were incorporated; however, achieving a balance between augmenting nutrition and preserving sensory qualities is a serious challenge (Matos & Rosell, 2011; Miranda et al., 2014; Pellegrini & Agostoni, 2015). In the absence of a gluten structural network, the compositional strength or structural scaffold in the GFN is weak, resulting in poor moisture control and large porosity, which constitutes a medium that promotes microbial proliferation due to moisture migration and the weakening of the natural barrier to contaminants. Hence, GFN are susceptible to staleness and microbial deterioration, so the need arises for novel formulation approaches to enhance their sensory and shelf life (Suliburska et al., 2013; Thompson, 2000).

5. Improving the quality of GFN

The innovations in GFN are restructuring the global market for gluten-free products by solving long-standing issues of texture, nutritional value, and shelf life. By means of novel ingredients and formulation strategies, researchers are creating GFN that closely match the quality of their wheat counterparts with more nutritious content.

5.1. Ingredients innovations

Enhancing the texture and nutritional properties of GFN through

	Wheat	Rice	Corn	Oats	Sorghum	Buckwheat
STARCH (g/100g DW)	68.98	74.40	4.30	60.00	71.95	54.50 – 57.40
PROTEIN (g/100g DW)	10.30	7.04	9.42	18.40	11.36	13.20
LIPID (g/100g DW)	1.34	1.03	4.74	4.70	4.70	3.40
FIBRE (g/100g DW)	0.26	0.10	2.70		2.76	17.802.10
ASH (g/100g DW)	2.42	0.42	1.96	2.00	3.17	2.10
POLYPHENOL (mg GAE/g DW)	0.54	0.56	2.86	0.64	8.61	2.76 – 5.32
AMYLOSE (%)	25.10	20.60	22.10	23.00	23.70-27.60	33.56

Fig. 1. Amylose content and proximate composition of gluten-free grains compared to wheat (Adapted from Ge et al. (2023); Hou et al. (2024); Kong et al. (2024); Obadi and Xu (2021)).

ingredients fortification is an important area of innovation. This section outlines current methods of creating improved sensory, shelf life, and nutritional qualities of GFN through functional ingredients:

5.1.1. Hydrocolloids

Hydrocolloids such as konjac glucomannan (KGn), guar gum (GG), and xanthan gum (XG) are polysaccharide chains with authenticated functional behaviour in food networks (Yemenicioğlu et al., 2019). Their extensive hydroxyl (–OH) group concentration or polyelectrolyte concentration allows them to dissolve in aqueous solutions, which leads to their optimum reactivity in water-based networks (Goff & Guo, 2019). These polymers are useful as thickening agents and modifiers of rheological and textural properties (Table S1) (Liao et al., 2021). In aqueous systems, hydrocolloids function as a thickening or gelling agent in noodles. These properties are dependent on the concentration and have varying implications on the quality of GFN. At low concentrations, they functioned as a thickener by increasing the dough matrix's viscosity, thus enhancing water binding, starch leaching upon cooking, texture, and cohesiveness of the product. Conversely, under high concentration or in hydrocolloids with high gelling properties, a three-dimensional network is formed analogous to gluten viscoelasticity. This network formed improves structural strength, elasticity and firmness while the cooking loss of noodles is reduced. At extremely high concentrations, over-gelling results in restricted water diffusion, causing a hard texture which deteriorates the sensory quality of GFN. Therefore, the regulation of thickening and gelation effects, dependent on the hydrocolloid nature and concentration applied, is critical in attaining the optimum textural and functional quality of GFN (Fig. 2) (Kraithong et al., 2023; Saha & Bhattacharya, 2010; Yang et al., 2022).

5.1.1.1. Thickening mechanisms. In GFN, hydrocolloids thicken through immobilization of water molecules, reduction of molecular mobility, and alteration of rheological properties. Their thickening effect is controlled by concentration, molecular structure, pH, and temperature (Saha & Bhattacharya, 2010). At dilute concentrations ($C < C^*$), hydrocolloids exhibit Newtonian flow behaviour, flowing freely with no intermolecular collision and imparting low viscosity as a consequence of minimal entanglement (Goff & Guo, 2019). As concentration surpasses the critical overlap concentration (C*), polymer chains begin to interact and entangle, forming disordered coils, thus entering the semi-dilute regime. This transition increases the viscosity due to molecular crowding and side-chain interactions being increased. Low concentration of hydrocolloids (C*) such as XG, GG, and locust bean gum are good thickeners due to their high molecular weight and branched structures which allow them to form extensive three-dimensional networks in aqueous systems (Fig. 3) (Himashree et al., 2022). These polymers display non-Newtonian flow behaviour such as pseudoplasticity, thixotropy, shear-thickening, and rheopexy, enabling them to withstand shear forces without disrupting their network integrity. At the second critical concentration (C**), the system is in a concentrated regime with increased macromolecular aggregation and a marginal increase in viscosity (Rayner et al., 2015).

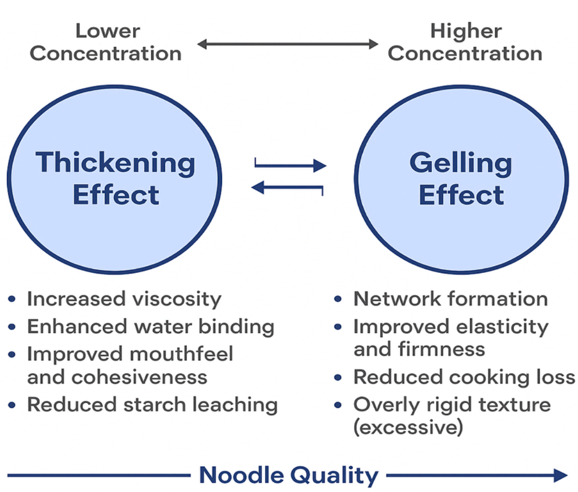

Fig. 2. Mechanistic pathways of hydrocolloid functionality: thickening vs. gelling effects in GFN.

5.1.1.2. Gelling mechanisms. Hydrocolloids are functional biopolymers used extensively in food systems to create gel structures with enhanced texture, stability, and water-holding capacity. Gelling is done by the formation of an aqueous medium-immobilizing three-dimensional network polymer. The most important step is the formation of junction zones, which are cross-linked regions between two or more polymer chains that stabilize the gel matrix (Fig. 4) (Wüstenberg, 2014). Their formation and strength are controlled by varied intermolecular interactions such as hydrogen bonding driven by hydroxyl groups along polysaccharide backbones, ionic interactions between charged functional groups, particularly in hydrocolloids like alginate and carrageenan, covalent cross-linking, which creates permanent gel networks, through reactive solvents or cross-linkers, hydrophobic interactions, and Van der Waals forces which facilitates gelling of materials through the promotion of non-covalent interactions, especially within amphiphilic materials. Phase-separated gel matrices are products of complex coacervation from electrostatic attraction of oppositely charged polymers (Saha & Bhattacharya, 2010). Temperature influences gelation, chain unfolding, and reassociation resulting in heat-set gels, while helix formation on cooling produces cold-set gels. These interactions all govern the viscoelastic and mechanical properties of the hydrocolloid gel, required to control functionality in GFN (Saha & Bhattacharya, 2010).

5.1.1.3. Functional applications of hydrocolloids in GFN. Hydrocolloids play a critical part in noodle production, improving stability, structure, texture, and product quality. Several hydrocolloids of plant, animal, and microbial-based origin have been reported to enhance the sensory, stability, and shelf-life of GFN with a focus on replicating the product quality of gluten noodles (Hong et al., 2021b; Huang et al., 2022; Liang et al., 2022; Liu et al., 2022). They reduce the post-prandial glucose by regulating the starch hydrolysis in GFN, which is essential in foods administered to diabetic patients. As presented in Table 1, at low concentrations, hydrocolloids exhibited comparable roles in both wheat-based and gluten-free systems to improve the quality of noodles which are essential in consumer acceptance of GFN. They enhance the viscosity of dough, water-binding capacity, texture (such as elasticity and structure), and reducing noodle breakage through stabilization of water and retardation of staleness. Their multi-functionality requires

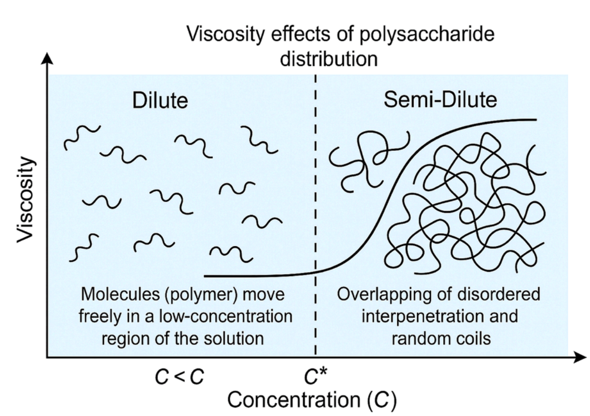

Fig. 3. Polysaccharide concentration-dependent viscosity behaviour and thickening mechanism of hydrocolloids in aqueous systems (Adapted from Goff and Guo (2019); Himashree et al. (2022); Rayner et al. (2015)).

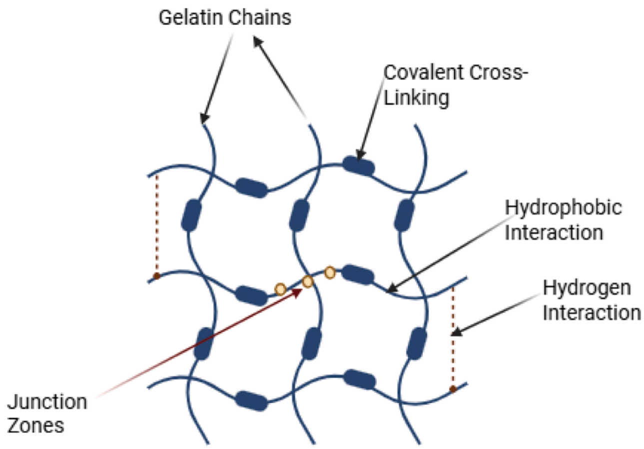

Fig. 4. Mechanistic illustration of hydrocolloid gelling: formation of junction zones via intermolecular interactions (Adapted from Saha and Bhattacharya (2010)).

their incorporation into ensuring product quality, sensory properties, and storage stability in different flour matrices (Hu et al., 2024; Li et al., 2024b; Obadi et al., 2022). XG significantly impacted the structural and nutrient attributes of rice-based GFN fortified with native autoclaved resistant starch. As the concentrations of XG increase (0.625–5 %), the resistant starch (RS: 44.06 % to 18.40 %) and total starch contents (92.82 % to 60.41 %) decrease due to the interference of XG with starch retrogradation and amylose-amylose junction formation. Also, the glycemic index reduced from 61.15 to 50.15 by forming viscous matrices that inhibit enzymatic access and slow down digestion (Raungrusmee et al., 2020). Similarly, XG forms electrostatic bonds with protein particles, thus enhancing the viscoelasticity through the formation of hydrated gel networks (Zhang et al., 2023). In a similar study, XG (0.2–1.0 %) significantly enhanced the storage (G′) and loss modulus (G″) of maize composite dough indicating an improved structural strength and elasticity. When compared with sodium carboxymethyl cellulose and sodium alginate, XG showed an insignificant effect on the loss factor, highlighting its rheological performance in improving dough stability without over-stiffening (Lazaridou & Biliaderis, 2007).

The quality of sweet potato dough was enhanced using GG (0.5–1.0 %) through the formation of a viscous gel network during starch gelatinisation leading to enhanced peak, breakdown, and ultimate viscosities (Rolandelli et al., 2024). Through water binding and bridging with starch granules, GG reduces starch swelling and retrogradation through hydrogen bonding and Van der Waals forces. Thus, in the production of sweet potato dough, GG increase the water retention capacity, inhibits amylose leaching, and enhances the texture (Lee et al., 2002). In a similar study, GG (0.1, 0.3, and 0.5 %) significantly increased flexibility (7.11–7.13 mm), breaking strength (62.20–66.65 g), expansion index (190.40 to 191.69 %), water absorptivity (178.17 to 194.70 %), and cooking loss (5.81 to 5.92 %), while a reduction was observed in the splitting rate (25.00–20.00 %) of fermented hollow dried noodles as the concentrations of GG increases (Hu et al., 2024). These findings collectively define the complementary but divergent functions of XG and GG in gluten-free systems: XG primarily controls rheological and nutritional properties by hydration and protein interactions, while GG enhances pasting and textural properties by water-competitive and stabilizing effects.

5.1.1.4. Limitations of hydrocolloids in GFN. The comparative overview of significant limitations of common hydrocolloids in GFN highlights that XG, GG, and KGn vary regarding cost factors, processing limitations, consumer acceptance, and regulatory limitations. Approved in almost all countries, XG is comparatively costly and degrades in high-heat or acidic conditions, with some consumer resistance due to its synthetic attributes (Rather et al., 2015). GG is relatively cost-effective but is susceptible to lumping, off-flavours, with its usage subject to pre-approval by

Table 1
Applications of hydrocolloids in noodle production.

Hydrocolloids	Objective	Target	Findings	References
XG and dodecyl gallate [Rice noodles]	To produce rice noodles with desirable digestibility and sensory qualities	Sensory/ Texture	Hardness (486.15–567.71 g), springiness (1.03–1.06), cohesiveness (0.45–0.47), gumminess (207.06–217.83), chewiness (214.75–230.94), and flavour (21.00–25.00) The cooking qualities increase as the concentrations of XG (2.5–5.0 g/kg) and dodecyl gallate (5.0–10 g/kg) increase.	(Huang et al., 2022)
Sodium Alginate [buckwheat flour]	Effects on the structure, cooking quality, and in vitro starch digestibility	Stability/ Texture	Cooking loss (8.64–10.03 %) for 1 and 2 % of sodium alginate. Optimal cooking time (4.67–3.83 min) Both properties decreased as the concentration of SA (0.5, 1.0, and 2.0 %) increased.	(Xu et al., 2023)
Hydroxypropyl corn starch, GG, and compound phosphates [Rice flour]	To improve the freeze-thaw frozen storage quality of noodles	Texture	Water absorption (14.00–35.00 %), cooking loss (0.1–2.2 %), and broken rate (18.00–53.00 %). All cooking qualities increase as the concentration of GG (RS + 0.37 %), hydroxypropyl corn starch (RS + 7.91 %), and compound phosphates (RS + 0.23 %) increases.	(Han et al., 2024)
Gelatin [Potato flour]	To reduce the cooking time	Cooking time	Hardness (78.78–176.56 g) and springiness (0.83–0.94 %). Rehydration time (11.75–5.33 min), and cooking loss (4.25–5.43 %) The texture increases as gelatin increases (0–80 %). Rehydration time decreased while cooking loss increased.	(Li et al., 2024a)
Curdlan [Rice noodle]	Improve the quality of sterilized fresh rice noodles (high-temperature sterilization)	Stability	Hardness (1207.62–1419.67), adhesiveness (48.76–37.70 gs^{-1}), springiness (0.92–0.93), cohesiveness (0.75–0.81), and chewiness (1080.16–1088.41). Rehydration time (120.33–88.00 s), water absorption rate (16.53–19.31 %), and cooking loss (4.25–5.43 %). As curdlan increases from 0 % to 0.13 %, rehydration time decreases while cooking loss and water absorption rate increase.	(Gao et al., 2024)
GG, sodium alginate, and sodium carboxymethylcellulose*	Effects on the dough rheology, microstructure, physicochemical properties, and quality of fermented noodles	Rheology and stability	Cooking time (8.19–8.32 min), cooking loss (6.50–6.36 %), water absorption (195.04–192.48), and splitting rate (35.00–32.50) Cooking loss and splitting rate of cooked noodles are reduced.	(Hu et al., 2024)

* Wheat flour.

regulatory bodies through validated daily intake levels, and labeling (Rather et al., 2015; Singh et al., 2021). KGn, a cost-reflective hydrocolloids are only suitable for high-end products, with potential textural issues, limited Western market exposure, and strict regulatory limitations due to safety factors (Borompichaichartkul et al., 2020). These factors or constraints should be considered in selecting hydrocolloids in GFN production.

5.1.2. Starch blends

Starch blends in the production of GFN have been reported to exhibit the structural and viscoelastic roles typically provided by gluten. In the absence of gluten's extensibility and matrix-filling effects, starches (in their blend or modified form) play fundamental roles in enhancing the texture, firmness, elasticity, and cooking stability of GFN (Zhu, 2017). The bifunctional roles of starch blends involve enhancing the structural and nutritional characteristics of GFNs. This is largely based on the amylose-to-amylopectin ratios, granular structure, and resistant polysaccharide content (Srikaeo et al., 2011). In a recent study, the substitution of rice flour with canna, green banana flour (20 %), and modified corn starch enhanced resistant starch content to 2.5 %, 3.6 %, and 8.8 %, respectively, compared to 1.0 % in controls. The trends are attributed to enhanced retrogradation resistance and compact crystalline structures, which slow down glycemic response and enzymatic hydrolysis (Srikaeo et al., 2011). The supplementation of rice noodles with cassava pulp (15 %) and pomelo peel (5 %) increased the total dietary fibre to 14.4 % (from 3.0 % in controls). The high contents of insoluble and soluble fibres in rice noodles formulated (pectin, cellulose, hemicellulose) offered physiological, water-holding, and bulk-forming effects without detrimental effects to textural properties (Wandee et al., 2014)

Blending starches of varying granule size and composition was reported to enhance the quality of potato noodles. The blend of potato starch with quinoa and oat starch increased gel tensile strength and elasticity, although it decreased paste viscosity. These trends could be linked to the higher amylose content and interchain entanglement of oat and quinoa starches, forming stronger gel networks by retrogradation and molecular interaction (Ma et al., 2024). In a similar study, the incorporation of cassava starch (25 %) into the formulation of potato noodles significantly enhanced the textural properties and swelling capacity. Cassava starch with high branched amylopectin and low lipid content initiates an improved water absorption and gelatinization with improved dough cohesiveness and elasticity (Zhang et al., 2025a). According to Zhang et al., the sweet potato starch reduced enthalpy changes and crystalline order with increased crystalline layer thickness, edibility, gel springiness (0.86 to 0.92), and tensile strength (63.93 to 170.38 kPa) increased with an ordered network structure in the noodles. This signifies partial disruption and reorganization of starch chains. enhancing gel springiness, and reducing gel springiness (63.93 % to 170.38 %). crystalline layer thickness, edibility, gel springiness (0.86 to 0.92), and tensile strength (63.93 % to 170.38 %) increased with an ordered network structure in the noodles (Zhang et al., 2025b). These findings emphasise that optimised starch blends, achieved through physicochemical compatibility and specific molecular interactions, are critical for maximising the sensory and nutritional quality of GFN.

5.1.3. Prebiotics and probiotics in GFN production

The use of prebiotics and probiotics in GFN presents a novel solution for improving both nutritional quality and functionality. Prebiotics such as inulin, oligofructose, resistant starch, galactooligosaccharides, and fructooligosaccharides promote a healthy gut through their mechanism of action in gut microbiota modulation, improved calcium absorption, and application as fermentable dietary fibres (Marco et al., 2021). Their physiological role is due to high hydrophilicity and specific glycosidic linkages that resist upper gastrointestinal digestion. In GFN, they enhance water-binding capacity due to their hydrophilic nature resulting in improved dough viscoelasticity, elasticity, and moisture retention, although it suppresses starch retrogradation by binding to amylose and amylopectin chains, leading to enhanced shelf stability and lower staling. Due to high fibre contents in prebiotics and probiotics, they destabilize gluten networks or disrupt protein–polysaccharide interactions in gluten-free systems, resulting in crumbliness or coarseness (Kumar et al., 2015).

Probiotics such as *Lactobacillus spp* such as *Lactobacillus acidophilus, Lactobacillus plantarum, Bifidobacterium bifidum, Bifidobacterium longum*, and *Saccharomyces boulardii* are reported for maintaining gastrointestinal health as well as modulating inflammatory reactions (Terpou et al., 2019; Dudek-Wicher et al., 2020; Mishra et al., 2022). However, their application in GFN could be affected by their sensitivity to heat and mechanical stress. For effective preservation, freeze- or spray-drying coupled with encapsulation in biopolymers (alginate or starch) is employed (Hernández-Pinto et al., 2024). Probiotics in GFN prevent degradation during cooking (Dudek-Wicher et al., 2021).

5.1.4. Fibres

The incorporation of dietary fibres into GFN offers multi-functional benefits including improved nutritional value, texture quality, and sensory properties. Given the inherent deficiencies of GFN such as undesirable cooking quality, elasticity, and texture, the quality of products could be enhanced using fibre. However, the choice of fibre is significant due to its distinctive features and functional impacts that need to be optimized for optimal noodle quality (Table 2). Soluble fibres increased the specific volume and product density, with lower luminosity and surface hardness while insoluble fibres enhance the texture and lower product brittleness. Cereal-derived β-glucans improve the structural functionality, lower the postprandial glucose, insulin response and serum LDL-cholesterol (Ronda et al., 2013). Incorporating these fibres improves the functionality and nutritional quality of GFN, highlighting their consumer-centred and health-promoting properties.

The incorporation of ingredients such as chia seeds, flaxseed, oat bran, and psyllium husk in gluten-free formulations has been an effective strategy for enhancing their nutritional quality and textural stability. They contain soluble and insoluble dietary fibres, which enhance the water-binding capacity, elasticity, and matrix cohesiveness through the formation of hydrogen bonding and an entanglement network (Brennan et al., 2004). Fruit and vegetable isolates from banana, citrus peels, beetroot, spinach, and carrot are natural fibres in GFN that enhance colour, taste, and thermal stability during cooking. Aside from structural enhancements, they lower glycemic index, triggered by decreased starch digestibility due to interference with enzyme hydrolysis and the formation of less accessible starch structures (Dziki et al., 2014). The increase in resistant starch from green bananas or modified corn enhances fermentable fibre content and the production of short-chain fatty acids and gut microbial balance (Birt et al., 2013). Similarly, inulin, an oligosaccharide prebiotic, has been reported to reduce glycemic index and lipids, thus improving gastrointestinal health (Aravind et al., 2012; Morreale et al., 2019). In a recent study, the cellular hydrolysis of extruded okara fibre caused a modification in the proportionality of soluble to insoluble fibre influencing the quality of GFN. Increasing the fibre proportions reduced water mobility and competitive hydration, facilitating better network development. As more hydrogen bonding and protein interaction, especially between gliadin and glutenin are formed, a robust, solid microstructure is produced, contributing to the production of noodles with improved textural and cooking characteristics. Thus, okara noodles extruded using 4.0 % cellulase had a low estimated glycemic index (eGI < 55), which was equivalent in quality to wheat-based noodles (Fig. S1) (Xie et al., 2025).

The enzymatic treatment of dietary (insoluble) fibre into soluble dietary fibre has been reported to improve the textural and rheological properties of high-fibre flour matrices. Such modifications enhance water-binding and network-forming capacity which contribute to dough viscoelasticity (Arslan et al., 2019). The synergistic impacts of psyllium powder (PP), psyllium husk powder (PHP), and rice flour enriched with resistant starch (RS) on noodle quality and starch digestibility of GFN

Table 2
Applications of fibres in GFN.

Fibre	Sources	Chemical structure	Applications	Shortcomings	References
Resistant starch	Potato starch, high-amylose corn starch, and starches from pseudocereals and legumes.	Consists of amylopectin and amylose molecules with a crystalline structure	Enhance the texture making GFN less sticky and firmer Promote the growth of bacteria responsible for gut health (prebiotics) Control the glycemic response of GFN	Require specific processing methods, like extrusion. Overuse of resistant starch might lead to a dry or flaky noodle consistency.	(Zhang et al., 2022)
Soluble fibres	GG (from guar beans), pectin (from fruits), and Inulin (from chicory root)	Polysaccharides with various branching structures.	Enhance water absorption, preventing noodles from drying out or becoming tough after boiling (GG). Improve the dough's binding capacity, leading to a more uniform and firm texture	Overuse of soluble fibres can adversely impact the flavour and texture of noodles, resulting in a slimy or excessively soft consistency.	(Marco & Rosell, 2008)
Dietary Fibre (Pseudocereals and legumes)	Buckwheat, quinoa, and chickpea flour	Polysaccharides (pectin, hemicellulose, and cellulose)	Provide minerals, vitamins, and protein while also improving the texture. Enhance the sensory attributes, taste, and mouthfeel of GFN (quinoa and buckwheat).	Impart an unpleasant flavour (bitter) which could influence the taste. High amounts can produce dry and dense noodles.	(Sofi et al., 2022)

were studied. From observation, rice noodles with a high amount of RS have inferior starch digestibility and poor sensory qualities; however, incorporation of PHP and PP substantially improved textural attributes including chewiness, reduced breakage and cooking loss. The glycemic index (86.69) of native high-RS rice noodles was significantly reduced in the presence of PP and PHP. The predicted GIs of 5PHP-2PP-RN and 5PHP-RN were lowered to 65.77 and 66.74, respectively, which signifies a significant reduction in the postprandial glucose response. These modifications are attributed to the increased water retention, gel-forming ability, and suppression of starch hydrolysis by psyllium-derived soluble fibres (Gong et al., 2024). This study demonstrates the possibility of combining fibre-modified rice flour and precision psyllium enrichment to produce structurally robust, low-glycemic index (GI) rice noodles of improved nutritional and cooking performance.

Collectively, these findings demonstrate that dietary fibre is not merely a nutritional supplement in gluten-free systems but, more importantly, has a pivotal role in starch–fibre–protein interaction modulation. These interactions are at the core of enhancing dough structure, reducing starch digestibility, and improving functional and sensory quality in GFN.

5.1.5. Protein fortification

Enrichment with plant proteins in GFN improves their textural, water-holding capacity, thermostability, nutritional, and cooking qualities. Protein substitutes for the absence of gluten with the improvement in the structural cohesiveness, water-holding, and viscoelastic properties of the dough matrix. In GFN, flours such as chickpea, soybean, and pea (legumes) are extensively used due to high amounts of essential amino acids and functional proteins, assisting in enhancing the elasticity, chewiness, and hardness in dough (Marco & Rosell, 2008). Denaturation of protein in legumes upon thermal processing promotes protein–starch and protein–protein interactions through hydrogen bonding, electrostatic forces, and disulfide bridge formation that create a supporting protein matrix in the absence of gluten. These interactions reduce cooking loss and increase the uniform gel network development responsible for enhancing the integrity and mouthfeel of noodles (Marco & Rosell, 2008).

In GFN formulations, soy, pea, and rice protein isolates are frequently incorporated to improve gel strength, water-holding capabilities, and thermostability. They enhance water absorbency, water retention, tensile strength, and lower stickiness. Quinoa and amaranth pseudo-cereals contain essential amino acids and bioactive compounds that are responsible for the nutritional content and texture (dough) with the development of amyloid-like fibrils and surface hydrophobicity, resulting in cohesive and elastic matrices (Alvarez-Jubete et al., 2010). The observed variations in the functionality of protein sources require a balanced formulation procedure between the protein type and content which are significant parameters in the enhancement of cooking quality and consumer acceptability (Table 3).

The protein isolates (2,4,6,8, and 10 %) obtained from two germinated chickpea cultivars (GNG 469 and GNG 1581) were incorporated into rice noodles. The rheology showed that protein-enriched rice dough exhibited pseudoplastic behaviour. As more protein isolate is added, the viscous moduli and elasticity of the dough increase; antioxidant activity increases from 22.6 to 31.3 %, cooking time from 13.4 to 15.1 min, and protein content increases from 7.52 to 19.3 %. A significant weight loss and cooking loss were observed in the rice noodles, decreased lightness (L), enhanced blueness (b*), greenness (a*), and consequently, darker noodles. Rheological properties demonstrated that the dough fortified with proteins exhibited pronounced pseudoplasticity with stepwise elevation in the viscous modulus (G'') and the elastic modulus (G') as a reflection of the enhancement in viscoelastic strength because of the enhanced protein–starch and protein–protein interaction. Chemically, the incorporation of chickpea isolate protein improved the structural networks through electrostatic, hydrophobic, and hydrogen bonding, which improved the viscosity and elasticity of the dough. The glycemic index reduced from 70.8 to 61.0, and the in vitro starch digestibility of the rice noodles significantly reduced as more chickpea protein isolate was added. There are variations in the polypeptides (10–250 kDa) with different intensities within the protein bands. Out of these protein isolates, chickpea isolates (6 %) obtained from the GNG 1581 cultivar exhibited significant acceptability based on the sensory evaluation (Fig. S2) (Sofi et al., 2020). However, at 10 % protein isolate, a decline in the overall acceptance, lightness, and elongated cooking time of the rice noodles was observed. Similar acceptability patterns from the sensory evaluations of noodles fortified with different legume enrichments were obtained by Sahay Meena (Sahay Meena, 2018).

According to Sofi et al., incorporating protein isolate (2,4,6,8, and 10 %) obtained from two germinated chickpea cultivars (GNG 469 and GNG 1581) were added to from rice flour for the production of GFN. The dynamic rheology showed that protein-enriched rice dough exhibited pseudoplastic behaviour. As more protein isolate is added, the viscous moduli and elasticity of the dough increase; also, the antioxidant activity (22.6 to 31.3 %), cooking time (13.4 to 15.1 min), and protein content (7.52 to 19.3 %) increase. However, there is significant weight and

Table 3
Applications of proteins in GFN.

Protein	Properties	Findings	Shortcomings	References
Chickpea Protein (GNG 1581 and GNG 469)	High in lysine, enhancing other plant-derived. Mild taste and excellent solubility.	Crude protein (7.52–10.5 g/100 g), crude fibre (1.3–4.4 g/100 g), amylose (21.2–25.9 g/100 g), antioxidant activity (22.8–34.5 g/100 g), total phenolic acids (117.7–203.04 mg GAE/100 g) and in vitro protein digestibility (78.7–84.9 %). All properties were increased as the concentration of chickpea increased.	Restricted heat tolerance, influencing processing parameters.	(Sofi et al., 2020)
Fish gelatin hydrolysates (1–5 %)		Thickness (1.16 mm), cooking loss (24 %), cooking weight (279 %), water absorption (179 %), and tensile strength (0.19 N). Antioxidative activities (IC_{50}): DPPH (0.57 g/mL), ABTS (0.87 g/mL), and FRAP (0.01 mmol FeSO4/g). Resulted in a slightly rougher surface with sensory properties [like slightly to moderately (6–7)].	Poor structural network	(Wangtueai et al., 2020)
Zein (5 % w/w)	High in non-polar amino acids making it insoluble in water. Soluble in ethanol (60–95 %)	Cooking time increases as rice-zein particle size decreases (7.53, 6.10, and 6.90 min, for 80–100, 100–140, and 140–250 μm, respectively) Water absorption (2.65 to 2.51), water solubility (1.82 to 1.25 %), and swelling power (2.70 to 2.55) increased as rice-zein particle size increased.	Low nutritional value	(Kim et al., 2019)
Sodium caseinate (SC) (10 and 20 %)	Water soluble	Cooking loss (10.38 ± 0.25 and 11.08 ± 1.71), yellowness (b*) (16.11 ± 0.29 and 15.79 ± 0.32), brightness (L*) (42.10 ± 0.49) (at 20 %), pasting properties, redness (a*) (2.81 ± 0.10 and 3.58 ± 0.16), all increased at 10 and 20 %, respectively, while water absorption (1.73 ± 0.19 and 1.47 ± 0.04) decreased. All sensory attributes increased except colour and adhesiveness.	Flavour interference and thermal instability	(Manoj Kumar et al., 2019)
Rapeseed protein 6 to 15 %)	High in protein and amino acids	Pasting temperature (75.0 to 75.2) and breakdown viscosity (75.3 to 78.3) increased. Peak viscosity (999.0 to 837.0), hot paste viscosity (923.0 to 759.0), and setback viscosity (333.0 to 294.0) decreased. Freezable water (0.342 and 0.357 g/g).	Bitter or pungent flavour	(Witczak et al., 2021)

cooking loss observed, decreased lightness (L), and enhanced blueness (b*), greenness (a*), and subsequently darker noodles. The glycemic index (70.8 to 61.0) and in vitro starch digestibility of the rice noodles significantly reduced as more chickpea protein isolate was added. There are variations in the polypeptides (10–250 kDa) with different intensities of the protein bands. Out of these protein isolates, chickpea isolates (6 %) obtained from the GNG 1581 cultivar exhibited excellent acceptability according to the sensory evaluation (S2) (Sofi et al., 2020). At 10 % protein isolate, a reduction in the total acceptance, lightness, and elongated cooking time of the rice noodles was observed. A similar trend in the total sensory acceptability of protein incorporation was reported by Sahay Meena (Sahay Meena, 2018).

5.1.6. *Incorporation of bioactive compounds*

The incorporation of bioactive compounds from plants such as vegetables, fruits, cereals, and medicinal shrubs is a pathway towards producing GFN with enhanced nutritional compositions. These ingredients are environmentally friendly, economical, and accessible, presenting a sustainable innovation in the food industry. In the food industry, bioactive compounds such as dietary fibres, carotenoids, flavonoids, and polyphenols, are extensively used in GFN due to their significant antioxidant, as anti-inflammatory, and cardioprotective effects (Li et al., 2022; Wang et al., 2021). These compounds enhance the nutritional value, alter the starch–protein matrix, and modify the rheological properties by structurally interacting with starch and proteins through hydrogen bonding, hydrophobicity, or π-π stacking, thereby changing the gelatinisation, pasting, and retrogradation characteristics (Li et al., 2022). However, factors such as heat degradation, low solubility, and gut instability undermine their viability. These have been minimized through encapsulation with carriers such as liposomes, chitosan, or maltodextrin serving as a shield against heat (or high temperature), improving dispersibility, and boosting bioavailability (Zhang et al., 2023). Moreover, pH and temperature control during dough mixing and cooking are key parameters responsible for the preservation of functional integrity of bioactive compounds and preventing nutrient loss (Zhang et al., 2023). Some of the commonly used bioactive compounds, functional roles, sources, and findings are detailed in Table 4. The effects of these bioactive compounds in GFN including texture, sensory, cooking, and nutritional attributes are extensively discussed.

5.1.6.5. Fruit and vegetables. The incorporation of phytochemical-enriched plant residues is an innovative approach to enhance the nutritional and functional properties of GFN. Phytochemicals like polyphenols, flavonoids, and phenolic acid interact with gluten-free dough macromolecules via hydrophobic interactions, π-π stacking, and hydrogen bonding, impacting water absorption, starch gelatinization, protein network formation, the nutritional quality, rheological, and textural properties of dough systems (Cato & Li, 2020; Pimentel-Moral et al., 2020). Red grape marc seed extract, a cost-effective additive containing anthocyanins and phenolic acids, has been shown to reduce glycemic index by modulating the digestibility of starch and suppressing retrogradation of starch by interfering with amylose recrystallization, thus enhancing the antioxidant properties through free radical scavenging activity (Cato & Li, 2020). Tomato rind containing high amounts of chlorophyll, lycopene, and β-carotene significantly contributes to the micronutrient profile and functional colour attributes of GFN (Pimentel-Moral et al., 2020). Banana and mango with high phenolic contents inhibit the enzymatic hydrolysis of carbohydrate, act as antifungal, antibacterial and antioxidant agents. Blueberry skin powder with anthocyanins enhances the colour (20 %) and flavour (25 %) in noodles due to the presence of flavonoids, as verified using sensory analysis. Blueberry skin powder stabilizes structure via intermolecular interaction, and improves antioxidant activity via the donation of hydrogen atoms to scavenge the free radicals (Majumder & Annegowda, 2021). Citrus flavonoids contain high flavonoids, incorporated into GFN disrupt the protein–water interaction, alter water uptake, and improve elasticity and cohesiveness of the matrix. The citrus introduced a citrusy aroma and a slight orange hue into the GFN based on the report of the trained panel revealing higher scores for colour and flavour (Reshmi et al., 2020). In a different study, the incorporation of apple pomace into GFN increases water absorption (15 %) and cohesiveness (10 %),

Table 4
Bioactive compounds potentially used in GFN.

Bioactive compounds	Sources	Role	Findings	References
Flavonoids and anthocyanins	Apple flour	Substituting 40–45 % of the flour	Enhance the antioxidant activity (>96 %)	(Xu et al., 2020)
Glycosides, saponins, tannins, flavonoids, alkaloids, and Phenolic compounds.	Banana	Substituting with corn flour (3–5 %)	The texture and colour characteristics of the noodles remain largely unchanged.	(Segura-Badilla et al., 2022)
Kaempferol-3-O-rutinoside, Quercetin-3-rutinoside Eriocitrin, flavonols, flavonoids, phenolics, and Caffeoyl N-Tryptophan	Orange	Dietary fibres and carotenoids	The integration led to a 4 % rise in the solid loss.	(Ademosun et al., 2021)
Rhamnose acid arabinose and galactose.	Cladodes extract (opuntia family)	Substituting water (34.3, 67.7, 100 %) with dough (15, 20, 25, 30 % (v/w))	Improved antioxidant activity (97 %) and sensory acceptability parameters reached 20 % (v/w) in dough replacement.	(Sciacca et al., 2021)
Total polyphenols	Grape	Incorporating 3.5, 5, and 8.5 % of antioxidants (polyphenols) in the dough	The total phenolics, monomeric anthocyanins, and antioxidant capacity increased. Reduction in appearance, flavour, aftertaste, and fragrance.	(Oliveira et al., 2022)
Chlorophyll, vitamins (C and E), phenolics, organic acids, flavonoids, lycopene, and beta-carotene	Tomato	Wheat flour is replaced by hydrocolloids (2 %) (XG, guar seed flour, and carboxymethylcellulose.	β-lycopene, lycopene, and carotenoid content increased. Reduction in the sensory scores for odour, elasticity, and firmness as compared to the control	(Silva et al., 2023)
Flavonoids, phenolic compounds, hydroxycinnamates, luteolin-7-O-rutinoside, and chlorogenic acid.	Artichoke Canning	Dough (35 %, v/w) is substituted with water by using ultrasounds for extraction. L/S = 3 (30:70, v/v) ethanol: water	Tested noodles exhibited significant antioxidant activity and phenolics than the control noodles. The cooking qualities and texture are similar to control.	(Amoriello et al., 2022)
Protocatechuic acids, 4-hydroxybenzoic acid, quercetin-3-O-rutinoside, and catechin.	Green hulls (pistachio)	Substitute for wheat flour	Reduce the glycemic index and increase in vitro starch digestibility compared to the control group	(Kaveh et al., 2018)
Quercetin	Chia flour	Substitute for wheat flour	Increase the omega-3 and fibre contents. Increase in the fatty acid ratio of omega-3 to omega-6 from 0 to 3.	(González et al., 2020)
Pectin, gums, and cellulose.	Peanut flour	Replacing 7.3 % of the dough	Improves the nutrient content.	(Bongjo et al., 2022)

through the physical reinforcement of the starch structure, resulting in firmer noodles (Xu et al., 2020).

5.1.6.6. Cereal grains. A significant by-product in grain milling, cereal bran is a valuable source containing dietary fibre, bioactive compounds and functional ingredients in formulating fortified GFN (Baniwal et al., 2021). Oat hulls with high levels of insoluble fibres such as hemicellulose, cellulose, and lignin contribute to water retention and modification of dough rheology leading to a softer and more elastic texture of noodles. The quantitative sensory evaluation shows elevated scores for aroma and colour characteristics, leading to increased consumer acceptance (Ahmad & Khan, 2020). According to Chauha et al., incorporating oat bran gives the noodles a hint of sweetness and an earthy flavour based on expert analysis. In oat bran, β-glucans, a soluble polysaccharide, contribute to viscosity, gel-forming capability to form a cohesive and elastic noodle network leading to improved taste (10 %), aroma (5 %) and colour, attributed to Maillard reaction precursors in the hulls of the oats (Chauhan et al., 2018). In rice bran cake, the γ-oryzanol and tocopherols improve the antioxidant activity. These molecules form part of the starch-protein complex, enhancing oxidative stability while also providing the noodles with vitamin E enrichment (Betrouche et al., 2022).

5.2. Formulation techniques

The growing need for nutritious and health-promoting foods has driven the innovation of GFN through functional ingredients to improve structure, nutrition, and taste. The structural elasticity, water-holding capacity, and textural integrity of wheat noodles depend on the gluten, but the absence in GFN compromises dough cohesiveness and texture acceptability (Obadi et al., 2022). To counter this, formulation strategies are now directed towards the use of non-gluten flours, hydrocolloids, proteins, fibres, probiotics, and bioactive compounds for reconstructing a gluten-like matrix (Mahanand et al., 2019; Zaman et al., 2024). These functional ingredients interact by hydrogen bonding, van der Waals forces, and hydrophobic interactions to form a structural network for capturing water and increasing dough strength. Also, they act as cross-linking agents, catalyzing peptide bond formation between proteins, which increases gel structure and elasticity (Wangtueai et al., 2020). In addition, additives rich in bioactive compounds enhance the antioxidant activity, reduce glycemic index and increase flavour, colour, and consumer acceptability (Cui et al., 2024; Vlaicu et al., 2023). Table 5 provides detailed information on the effects of formulation techniques on the nutritional, sensory, and cooking attributes of GFN.

The incorporation of zein, a prolamin protein obtained from corn (Zea mays) into rice flour with particle sizes ranging from 80 to 100, 100–140, and 140–250 μm showed that the rice-zein composites consisting of finer particles (80–100 μm) exhibited higher water hydration properties and pasting parameters, and this could be linked to the increased elasticity of the noodles and hydrophobic nature of zein resulting in limited water retention capability of the noodles. The surface area of the finer particles of rice flour is large assisting the interaction of water with the hydrophobic ions in zein, hence improving the hydration properties attributed to the flexibility and texture of GFN (Kim et al., 2019). The formulation of pregelatinized rice flour and germinated chickpea flour (cultivars GNG 1581 and GNG 469) in proportions of 100:0, 95:5, 90:10, 80:20, and 70:30 demonstrated an enhanced nutritional profile, better cooking characteristics, lower glycemic index, and favourable sensory qualities. The addition of germinated chickpea flour increased the storage moduli, moisture content (ranging from 1.66 to 2.44 g/g), and the elasticity of noodle dough, enhancing the flour's ability to absorb and retain moisture (Sofi et al., 2020).

In GFN, finely ground flours influence their structure, hydrophilic and hydrophobic interactions, essential for the noodles' texture,

Table 5
The effects of each formulations on the nutritional, sensory, and cooking attributes of GFN.

Formulations	Cooking properties	Sensory characteristics	Nutritional constituents	Implications	References
Rice-zein (80–100 μm 100–140 μm 140–250 μm)	Samples with particle size (100–140 μm) exhibited significantly lower CL. Specifically, the CL was distinctly lowered by about 34 %, compared to the 80–100 μm samples.	140–250 μm rice fraction consisted of large and lumpy particles while the 80–100 μm fraction contained some small and fractured particles. The content of damaged starch was determined to be 7.96, 6.10, and 3.00 % in AACC units for the 80–100, 100–140, and 140–250 μm rice fractions, respectively. The water hydration properties of the rice-zein composites increase with decreasing particle sizes.		The rice-zein composites consisting of finer particles showed greater water hydration properties and pasting parameters that contributed to the increased elastic characteristics.	(Kim et al., 2019)
Rice-buckwheat flour (BF) blends (0, 15, 30, 45, 60 g/100 g)		The value of peak viscosity increased with increasing substitution level of BF from 0 to 30 g/100 g.	More BF increases the Total dietary fibre, insoluble dietary fibre, and soluble dietary fibre both in flour blends and extruded noodles. TFC and TPC contents increased as the BF increased in the blends both before and after extrusion cooking	BF enrichment significantly affected the gel structure and nutritional composition	(Fu et al., 2020)
W-RN = traditional white rice noodles; DA-RN = rice noodles from dual enzyme rice noodles (DA-RF); 5PHP-RN = rice noodles made from 5 % PHP and 95 % DA-RF; 5PHP-2PP-RN = rice noodles made from 5 % PHP, 2 % PP and 93 % DA-RF	DA-RN increased in breakage rate and cooking loss. DA-RF decreased in water absorption rate. PHP and PP, a reduction in the breaking rate of 5PHP-RN was observed and 5PHP-2PP-RN decreased in breaking rate and an increase in water absorption rate compared to WRN.	The rice noodles samples were smooth and delicate. W-RN presented bright white. PHP and PP, 5PHP-RN, and 5PHP-2PP-RN appeared brown in varying degrees. 5PHP-2PP-RN has the darkest colour. SEM image of the cross-sections and post-crushing. DA-RN and 5PHP-RN (rough and with pores in the fragmented particles).	Image data points: samples showed overlapping regions, indicating that the W-RN, DA-RN, 5PHP-RN, and 5PHP-2PP-RN possessed similar volatile profiles. W-RN, the RDS was notably high at 67.78 %, whereas SDS and RS were lower at 16.72 % and 15.75 %, respectively.	Addition of PHP and PP to modified rice flour, increased cooking qualities, and sensory and nutritional attributes.	(Gong et al., 2024)
Pathumthani 80 rice (RD 31-NARS) (100 g), whole egg (30 g), salt (3 g), sodium bicarbonate (3 g), distilled water (45 mL). XG (XG) at different concentrations (0.625, 1.25, 2.5, and 5 %)	The increase in XG on RD 31-NARS GFN exhibited a non-significant ($p \geq 0.05$) increase in OCT and a decrease in CL.	The addition of inulin and defatted rice bran in the gluten-free noodle increased the firmness; tensile strength and elasticity decreased significantly RD 31-NARS GFN with XG (2.5 %) and inulin (5 %) and RD 31-NARS noodles with XG (2.5 %) and defatted rice bran (5 %) got high scores for colour, flavour, stickiness, and overall liking acceptability compared with GFN without inulin and rice bran	The RS content of native starch (8.44 %) was observed to increase significantly with autoclaving treatment in RD 31-NARS (64.95 %). Glycemic index (GI) of native starch (66.32 %) was significantly higher than that of RD 31- NARS (46.12 %). The increase in the concentration of XG (0.625–5 %) resulted in a decrease in resistant starch content, whereas, the glycemic index was increased.	The addition of defatted rice bran and inulin increased the firmness, cooking time, protein, fibre, and ash contents of GFN.	(Raungrusmee et al., 2020)
Pregelatinized rice flour and germinated chickpea flour (GNG 1581 and GNG 469 cultivars) in ratios of 100:0, 95:5, 90:10, 80:20, and 70:30. The ingredients (Rice flour; germinated chickpea flour; GG 0.5 g/100 g; salt 1 g/100 g) were mixed with water (33 mL/100 g)	Enrichment of noodles with different levels (5, 10, 20, and 30 g/100 g) of germinated chickpea flour (GNG 1581 and GNG 469) significantly ($p < 0.05$) improved the nutritional profile compared to control noodle The moisture content of noodles showed a significant increase with addition (5–30 g/100 g) of germinated chickpea flour. Cooking time significantly increased in noodles	Enriched noodle dough showed an increase in viscous behaviour with added germinated chickpea flour (5–30 g/100 g). Storage moduli represent the elasticity of noodle dough increased with germinated chickpea flour The elastic modulus of enriched noodle, dough blends was observed higher values than the viscous modulus (G' > G"), representing the elastic behaviour of noodle dough	The crude fat increased by substitution with 30 g/100 g of GNG with no significant difference shown by 5, 10, and 20 g/100 g levels of GNG flour addition The total carbohydrate content of noodles decreased significantly from 79.8 to 71.9 g/100 g with the addition of GNG flour (0–30 g/100 g). The protein content of noodles showed increase (7.53–10.56 g/100 g) with	Substitution of rice noodles with germinated chickpea flour showed improved nutritional profile, cooking properties, low glycemic index and good sensory attributes.	(Sofi et al., 2020)

(continued on next page)

Table 5 (*continued*)

Formulations	Cooking properties	Sensory characteristics	Nutritional constituents	Implications	References
	incorporated with germinated chickpea flour. Water absorption capacity ranged from 1.66 to 2.44 g/g	enriched with germinated chickpea flour. Enriched noodles showed a significant decrease in lightness (L*) and an increase in yellowness (a*) and redness (b*) with the increase in the addition of germinated chickpea flour from 5 to 30 g/100 g.	the incorporation of germinated chickpea flour. TPC of GNG flour increased with the addition of germinated chickpea flour levels.		

FM- Fish mince; IN – Instant noodles; RS- Resistant starch; Water absorption capacity (WAC), and oil absorption capacity (OAC); high-resistant starch (RS); soluble dietary fibre (SDF); psyllium husk powder (PHP); psyllium powder (PP); SP-Swelling Power; TPC- Total phenolic content, TFC- Total flavonoid content; GABA-γ-aminobutyric acid content.

stability, and quality (Tan et al., 2024; Zhang et al., 2021). To improve these properties, adequate mixing of flours or composites during formulation establishes a pseudo-structure like protein-starch interactions. The proteins found in flours like lentil, quinoa, and chickpeas combine with starches from potato, rice, banana, or tapioca flours, creating a structure that simulates gluten. This network enhances the elasticity, texture, and cooking characteristics of the dough. Certain flours, like rice, have high amylose content, which, when mixed with protein-rich flours or hydrocolloids, creates a more robust network (Gong et al., 2024; Islam et al., 2024). The relationships between hydrophobic and hydrophilic constituents are essential in the production of GFN, affecting stability, texture, and moisture retention. Flours containing a high level of starch are highly hydrophilic and absorb water during mixing and cooking. Nonetheless, certain gluten-free flours, like almond or coconut flour, have natural fats that create a lipid-protein network through hydrophobic interactions with protein structures, improving smoothness and flexibility (De et al., 2024; Gong et al., 2024). Achieving a balance between hydrophobic and hydrophilic components in the flour mixture guarantees that the dough develops a cohesive, non-sticky appearance, essential for moulding and slicing noodles (Z. Cao et al., 2021).

6. Recent insights into the factors that affect acceptance of GFN: from structural mechanisms to socioeconomic considerations

Consumer acceptance of GFN is shaped by a mix of structural, sensory, and socioeconomic variables. More recent studies have highlighted how these factors interact to modulate consumer acceptability and economic strength. The following sections describe highlights of the structural and socioeconomic determinants of consumer acceptance of GFN.

6.1. Structural mechanisms and consumer acceptance

The structural characteristics directly impact the sensory qualities of GFN, which greatly affect consumer acceptance:

6.1.1. Texture and cooking qualities

The textural quality and cooking qualities of GFN are primarily regulated through interactions of starch, proteins, hydrocolloids, and particle size of constituent flours. In the absence of gluten, substitutes including zein, starch, and hydrocolloids play significant roles in building up the matrix. In noodles, flour particle size significantly regulates starch damage, hydration characteristics, and surface topography, which further affect the resulting noodle quality and consumer acceptability. In GFN, flours with smaller particle sizes result in greater organoleptic starch damage due to greater mechanical shear and thermal contact during milling. According to Sapirstein et al., the starch damage levels of rice flours with particle sizes (80–100, 100–140, and 140–250 µm) were found to be 7.96, 6.10, and 3.00 % in AACC units (42.03, 25.68, and 3.62 % in Farrand units), with smaller particles showing greater activity and resulting in higher amounts of damaged starch (Sapirstein et al., 2013). Similar trends were reported by Torbica et al., wherein the finely milled fractions of rice had greater starch damage (15–25 % in Farrand units), which increased organoleptic water absorption and enzymatic susceptibility (Torbica et al., 2012).

The particle size of flours influences hydration in noodles as a result of the large surface area of fine particles, which enhances water penetration kinetics. The water absorption characteristics of rice-zein at temperatures (25 and 100 °C) were observed to improve with smaller particle sizes. This could be attributed to the high-water affinities of smaller particles and the time required for water permeation inside the flours (Hatcher et al., 2002; Jang et al., 2016). In a related study, particle sizes of rice flour influenced the texture and surface characteristics of rice noodles. Flour with finer particles produced noodles with more uniform surface textures, while coarser fractions produced granularity and particulate residue appearances as particle size increases when analyzed using SEM (Fig. S3) (Kim et al., 2019). The application of zein, a prolamin capable of generating viscoelastic networks outside its glass transition temperature, has created rice sheeted doughs shredded into elongated, thin noodle strands depending on the ability of zein to form a viscoelastic protein matrix above its glass transition temperature (Jeong et al., 2017a).

Particle size and distribution of flour play a crucial role in determining noodle cooking quality, pasting characteristics, and internal gluten structure of GFN. Cooking loss, a key quality indicator for noodles, is linked to the solubilization and leaching of solids upon boiling and is directly related to flour particle size. Smaller particles (80–100 µm), with higher surface area and starch damage, exhibit increased cooking loss than larger particles (Hatcher et al., 2002). This is because compromised granule supports high water uptake and solute dissolution. On the contrary, large rice-zein noodles particles (>140–250 µm) have greater surface roughness, which favours adhesion with water and swelling during cooking, thus also leading to more loss during cooking (Kim et al., 2019). The intermediate particle sizes, 100–140 µm, resulted in ideal cooking performance with improved hydration balance and structural integrity, thus providing better and cooking loss. Particle size also affects pasting behaviour with larger rice particles (140–250 µm) yielding significantly lower peak, final, trough, and breakdown viscosities, reflecting lower swelling and breakdown on heating. Finer particles exhibit increased gelatinization due to greater water absorption, resulting in more compact starch networks (Kim et al., 2012). These findings are in agreement with those of cornmeal and high-amylose rice, confirming that particle size controls viscosity and texture (Lee & Oh, 2013). Thus, particle size optimization is critical in the development of the functional and sensory properties of GFN formulations.

6.1.2. Proportions of ingredients

The physicochemical characteristics of the flour blend, starch gelatinization level, and interaction of functional additives could be linked directly to the structural, cooking, and nutritional properties of GFN. In a study, substitution of wheat flour by Tartary buckwheat and bran fractions alters the gel matrix by modifying starch–protein–fibre interactions. Stepwise substitution of wheat flour with 0–30 % bran (0, 6, 12, 18, 24, 30 %) had a significant effect on the noodle microstructure in extruded Tartary buckwheat noodles (Fig. S4) (Tian et al., 2024). At 0 % bran, the cross-section of formulated noodles revealed a dense and moderately tight gel matrix, indicating optimum starch gelatinization and cohesive gel development. The matrix was interrupted with increasing bran content, progressively adding coarse textures, larger voids, protrusions, and broken structures. These interruptions were most extreme at ≥18 % (18, 24, and 30 %) bran substitution, when the starch matrix was brittle and disintegrated, indicating compromised gel integrity. The impaired network formation is primarily caused by reduced gelatinizable starch content and disruption of high-fibre, high-protein bran with amylose–amylopectin interactions essential for cross-linking. Bran components could compete for water, restrict swelling capacity, and reduce continuous starch gel formation, thereby disrupting the structural integrity and functional properties of GFN (Tian et al., 2024).

The addition of functional flours and hydrocolloids has propelled the production of GFN with improved internal structure and cooking quality. Hydrocolloids such as XG, inulin, and KGn have been utilized as structuring agents and stabilizers to improve the gel matrix and enhance the quality of GFN. Inulin and XG were shown to produce a porous internal structure in raw noodles composed of potato- and maize–field bean. While enhancing moisture distribution and texture, such porosity in these structures has been associated with higher cooking loss due to starch breakdown within the hydrocolloid network, reducing starch leaching with improved water retention (Javaid et al., 2018). The microscopy of wheat noodle presents a dense protein network (Fig. S5a), whereas incorporation of XG and inulin generates vacant voids and an increased heterogeneity, mostly with the use of resistant rice starch as substitute compared to GFN made with resistant rice starch alone (Fig. S5b) (Raungrusmee et al., 2020). Inulin, as soluble fiber, influences gelation characteristics through the formation of water-binding networks that enhance porosity and affect starch–protein interaction (Figs. S5c–e). Similarly, KGn (3 %) has been found to align starch granules into film-like structures with enhanced continuity in the gluten network primarily through non-covalent forces and physical entanglement. The incorporation of KGn creates a finer, more balanced matrix, reduces starch swelling, prevents breakdown of structure, and improves textural integrity in high-viscosity dough systems (Fig. S6) (Z. Cao et al., 2021; Zhou et al., 2013). The quality of cooking in GFN is regulated mainly by the flour composition and functional additives. Protein enrichment enhances the strength of noodle matrix through stronger protein–starch interactions, reducing leaching of starch during cooking. This results in improved water absorption, texture, and cooking stability, thereby enhancing the quality of GFN in general (Meenu et al., 2022).

6.1.3. *Shelf life and swelling performance*

Packaging and shelf life are critical to ensuring the safety, quality, and marketability of GFN with a direct impact on consumer satisfaction and commercial viability. These properties are founded on numerous elements including vulnerability to oxidation, drying and treatment processes, milling processes, protein and moisture content, starch integrity, and microbial stability (Chiang & Yeh, 2002; Heo et al., 2013). Shelf-life of GFN is linked to the moisture content and distribution within the noodle matrix, thus, fresh noodles have a shelf life ranging from 7 to 14 days, whereas dried noodles with a moisture content of 10–12 % are shelf-stable for 6–12 months. Quality loss in GFN is prevented by good packaging by inhibiting moisture absorption, lipid oxidation, loss of nutrients, and breakdown of pigments. The structure of the starch also impacts noodle shelf life: high-amylose starches (corn, rice, cassava, lentils) contain low water absorption and moderate swelling, resulting in more rigid noodles with longer shelf life. High-amylopectin starches (waxy maize, potato, tapioca) contain higher water absorption capacity due to their branched nature, resulting in softer noodles with shorter shelf life (Singh et al., 2003). To counterbalance these challenges, hydrocolloids are incorporated to stabilize the starch matrix, modulate water uptake, and suppress swelling, thereby enhancing the functional and microbial shelf life of GFN (Lazaridou & Biliaderis, 2007).

Moisture content plays a significant role in determining the structure and quality of GFN. Reduced protein levels in formulations guarantee increased starch granule mobility within the matrix, enhanced water penetration, and promote starch swelling, a process crucial to noodle texture formation (Miah et al., 2023). The swelling index, a measure of water uptake by cooking starch and protein, is of significant relevance to noodle integrity as it maintains starch gelatinization and protein hydration, preventing noodle disintegration (Hadiyanto et al., 2019; Omeire et al., 2014). Higher swelling capacity is crucial in GFN, where resistant starch and amylose, which are usually dominant in gluten-free foods such as banana starch, increase water uptake and rehydration rates (Adebowale et al., 2012). Water also participates in controlling physicochemical interactions between hydrocolloids, protein, and starch to mimic gluten viscoelasticity. Starch granules swell, gelatinize, and absorb water when heated, forming a gel matrix that binds the noodle network [1] (Rao et al., 2024). Simultaneously, hydrocolloids swell to create thickened systems, enhancing dough stickiness and elasticity [II] (Ali et al., 2024). In gluten-free systems, vegetable proteins swell, unwind, and cross-link through hydrogen bonds or disulfide linkages, creating a protein–starch network that adds to mechanical toughness and provides gluten-like textural qualities [III] (Kovacs et al., 2004).

$$(C_6H_{10}O_5)_n + H_2O \xrightarrow{\text{Heat}} \text{Gelatinized starch} \quad \textbf{[1]}$$

$$\text{Hydrocolloid} + H_2O \longrightarrow \text{Hydrated hydrocolloid gel} \quad \textbf{II}$$

$$\text{Protein} + H_2O \xrightarrow[\text{Heat}]{\text{Mixing}} \text{Protein network } \textbf{(Disulphide bond)} \quad \textbf{III}$$

Low moisture results in starch partial gelatinization and protein unfolding, resulting in brittle, hard, and non-elastic noodles (Rosell, 2009). High moisture results in over-swelling of starch and uncontrolled hydrocolloid hydration, resulting in soft, sticky noodles with decreased shelf stability (Ali et al., 2024). Despite the absence of gluten, ideal moisture allows for requisite interactions among starch, protein, and hydrocolloids and hence becomes critical for desired texture, cooking efficiency, and shelf life in GFN.

6.2. *Socioeconomic considerations and consumer acceptance*

6.2.1. *Regulatory compliance and labelling*

Compliance with regulations in the preparation of GFN is fundamental to the product's safety, marketability, and consumer acceptability. According to FDA and EU Regulation (No. 828/2014), "gluten-free" foods must have no >20 ppm of gluten to meet Codex Alimentarius standards (Maskeliunas & Miyagishima, 2008; Traynor, 2006). Chemically, structural gluten duplication requires a strict proportion of ingredients: starch (30–70 % w/w), proteins (5–20 % w/w), hydrocolloids (0.2–2 % w/w), and dietary fibre (1–10 % w/w). The ingredients form a functional matrix by hydrogen bonding and physical entanglement and enhance water retention, elasticity, and cooking stability. Compliance with these compositional specifications indicates products are physicochemically standardized and consumer-acceptably textured noodles (Traynor, 2006).

Accurate labelling of GFN is important for patients with celiac disease or gluten intolerance, where trace levels of gluten could potentially induce harmful health effects and raise contamination risks. Authorities such as the UK Food Standards Agency emphasize purity in foods in the form of transparent labelling of the ingredients' identity, processing method, and origin (Primrose et al., 2010). According to Sielicka-Rozynska et al., about 52 % of the respondents perceived gluten-free marking on packaged foods as unsatisfactory, despite 89.3 % resorting to the crossed grain symbol and printed gluten-free labels. Further, 91.3 % always checked ingredient lists prior to purchasing (Sielicka-Różyńska et al., 2020). These findings highlight the importance of scientific accuracy, clear readability, and salient foregrounding of marking in providing consumer protection, assurance, and regulatory compliance for gluten-free food markets.

Front-of-package (FOP) nutrition labeling is gaining popularity across various nations in promoting healthier foods through effective and transparent nutritional information (Ares et al., 2023; Crosbie et al., 2023; Song et al., 2024). An economical public health intervention, FOP labeling increases consumer awareness by highlighting essential nutritional aspects. Among the newly emerging instruments is the warning label that identifies products high in nutrients linked with non-communicable diseases, specifically, sodium, sugars, total fat, and saturated fats (Ares et al., 2023; Crosbie et al., 2023). In GFN, consumers' decision-making is primarily based on in-pack claims such as "zero-gluten," "low fat," and "cholesterol-free," which contribute to the health halo effect, a mental bias through which one attribute leads to overemphasized general well-being (Andrews et al., 2000; Centurión et al., 2019; Choi & Reid, 2015; Hall et al., 2020).

Studies have shown that health claims have the ability to counteract warning label deterrence, and consumers are misinformed about the nutritional value of the product (Acton & Hammond, 2018; Duffy et al., 2021). Warning labels have been found to be able to moderate the impact of health claims on the perceived healthiness and buying intentions (Centurión et al., 2019). Given that claim effectiveness is claim type and food category dependent, a more profound analysis of their interaction is required in order to inform labelling policy (Oostenbach et al., 2019). Sielicka-Rozynska et al. (Sciacca et al., 2021) noted that 52 % of consumer participants, irrespective of gluten tolerance, believed that gluten-free products were inadequately labelled. However, 89.3 % utilized the crossed grain sign and verbal gluten-free declarations, and 91.3 % indeed read labels when shopping. These results validate the need for harmonized FOP labelling frameworks that effectively balance nutrition information, health claims, and consumer understanding, especially for gluten-free foods, enabling informed decisions and regulatory compliance.

6.2.2. *Consumer preferences*

Consumer demand for GFN is prompted by the simultaneous search for nutritional functionality and sensory acceptability, which has catalyzed extensive research to meet the long-standing formulation and acceptability problems of gluten-free foods (Aguiar et al., 2021; Alencar et al., 2021; Capriles et al., 2023; Tóth et al., 2022). Knowledge in this direction will prove fundamental in steering regulatory policy, enhancing product development, and enhancing the knowledge of results that can be expected from the gluten-sensitive consumer. According to Savarese et al., non-celiac consumers prioritize product attributes such as nutrition, ethics, and brand loyalty. Sociocultural and psychological factors do not appear to exert much influence on their consumption patterns (Savarese et al., 2021). The consumer trends emphasized that young adults prefer organically grown, minimally processed, and non-GMO gluten-free products (Fig. 5) (Christoph et al., 2018). Similarly, Prada et al. reflected that consumers of gluten-free products perceive the healthiness and lower calorie levels of gluten-free products (Prada et al., 2019). This report is consistent with Hartmann et al., where "free-from" labeling has a positive effect on perceived healthiness in four European nations. Sensory analysis remains an important ingredient in product acceptability (Hartmann et al., 2018). In a randomized trial of 28 children with diagnosed celiac

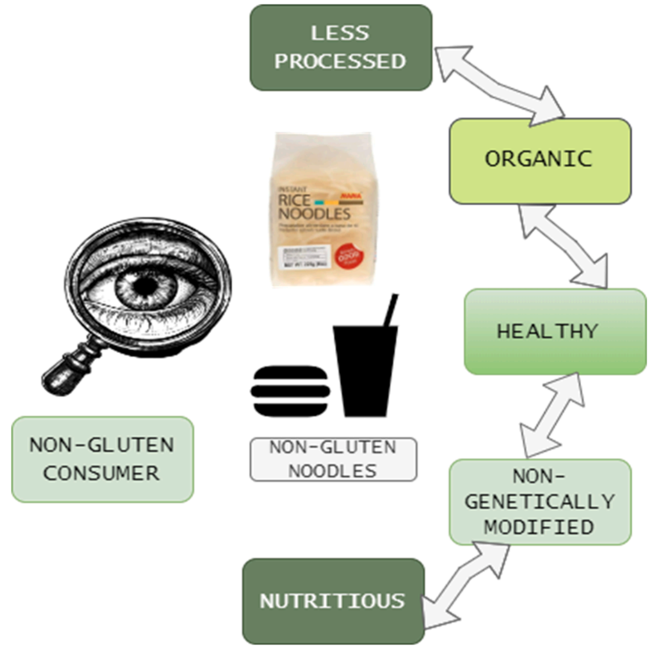

Fig. 5. Non-gluten consumers' perception of GFN.

disease, the participants rated the appearance and taste of gluten-free foods on a 5-point facial scale across four commercial brands within seven days. While visual presentation was generally positively perceived, visual presentation didn't affect the perception of flavour (Mazzeo et al., 2013).

These findings underscore the value of age-targeted, sensory evaluation of such groups, particularly in gluten disorder groups that are struggling to adapt to diet. Sensory optimization of the GFN for these groups has tremendous potential to enhance compliance, diet satisfaction, and long-term health outcomes. Overall, systematic knowledge of consumer attitudes, augmented by exhaustive systematic sensory and nutritional optimization, forms the foundation for the continued development of acceptable, high-quality GFN.

7. Findings

The production of GFN is a multi-faceted system whereby bioactive compounds, dietary fibre, hydrocolloids, and starch blends are mixed to enhance cooking functionality, nutritional value, sensory acceptability, and shelf life. The ingredients interact synergistically to enhance product functionality and preserve thermolabile materials. Optimisation of particle size, moisture, and ingredient proportion is required for achieving desirable textural characteristics and long-term stability. ingredient proportion is critical for generating desirable textural attributes and long-term stability. Consumers' demand especially from health-oriented and gluten-intolerant consumers calls for nutritionally enhanced, non-GMO, minimally processed, and ethically labeled products. Transparency of labelling and regulatory requirements remain cornerstones of market acceptability and product integrity in the new GFN industry (Aguiar et al., 2021; Alencar et al., 2021; Capriles et al., 2023; Christoph et al., 2018; Savarese et al., 2021; Tóth et al., 2022).

8. Prospects

The review highlights the innovations in the production of GFN through formulation using sustainable and nutritional interventions. The study systematically or strategically addresses the three-way interaction between formulation, nutritional fortification, and consumer-directed functionality for better quality, stability, and marketability worldwide. To create GFN with quality equivalent to, or superior to wheat-based, the following factors should be given specific consideration:

Improving Texture in Different Starch Matrices: The physicochemical and molecular interactions between all types of gluten-free starches with hydrocolloids need investigating to achieve the best viscoelastic properties and textural characteristics similar to gluten noodles.

Synergistic interactions between ingredients: Detailed ternary interactions between starch, hydrocolloids, and plant proteins based on rheological, thermal, and microscopic analysis should be studied to enhance structural cohesion, hydration dynamics, and gel network formation.

Enzymatic and Biotechnological Enhancement: Apply specific enzyme treatments (transglutaminase, amylase) to reform protein–starch network structures with a focus on building functional characteristics such as elasticity, water-holding, and cooking stability.

Nutrient Fortification and Functionalization: Explore low-cost, underutilized plant-based fortificants such as legumes and millet bran flours with high levels of dietary fibre, RS, and bioactive compounds to enrich the nutritional quality and prebiotic potential of GFN.

Bioavailability and Stability of Active Ingredients: Assess the heat treatment, structure of the matrix, impact on retention, release profile, and bioaccessibility of heat-sensitive micronutrients, including polyphenols and flavonoids.

Shelf-Life Stability in a Tropical Climate: The water activity, retrogradation characteristics, and microbial resistance of GFN need investigating in high-temperature, high-humidity storage with an emphasis on natural preservatives and packaging technologies.

9. Conclusion

The development of GFN calls for a multidisciplinary approach leveraging food chemistry, nutrition, and sustainable processing. In this review, fibres, hydrocolloids, starch blends, and bioactive compounds are recognized as potential ingredients for replicating gluten structure and textural functionality, with the nutritional content being enhanced. Strategic formulation including modulating interactions between starch, protein, and hydrocolloid is fundamental in obtaining viscoelastic properties equivalent to conventional noodles. Utilizing underutilized crops, plant-based, improves functionality, biodiversity, and sustainable production systems. Low-temperature treatment and controlled hydrations preserve thermolabile bioactive compounds and nutrients, resulting in enhanced health benefits. From a shelf-life perspective, advances in packaging, edible films, controlled atmospheres, and moisture restriction have enormous potential for preserving noodle quality under diverse environmental conditions. Also, strict regulatory controls and label transparency are required to ensure consumer acceptance with respect to gluten, nutrition, and ingredient origin. As worldwide demand for GFN increases, intensified research is required for optimizing texture, flavour, and nutritional density with the provision of an enlightenment programme for consumers, demystifying myths about GFN. With accurate formulation and sustainable production, the GFN industry has tremendous potential in providing evidence-based, consumer-driven, and environmentally sustainable products.

Ethical statement

This article is a review of existing literature. No new experiments involving human subjects were conducted by the authors. Sensory findings in Fig. S2 are adapted from Sofi et al. (2020) with due citation.

CRediT authorship contribution statement

Oluwole Solomon Oladeji: Writing – review & editing, Writing – original draft, Visualization, Resources, Investigation, Conceptualization. **Farhan Mohd Said:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Nur Fathin Shamirah Daud:** Visualization, Investigation. **Fatmawati Adam:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.afres.2025.101209.

Data availability

No data was used for the research described in the article.

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