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REVIEW PAPER

# Structure – function insights into hydrocolloid in cereal-based gluten-free noodles: from cooking behavior to consumer preference

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**Abstract**

The rapid expansion of the gluten-free (GF) market underscores an urgent need for GF noodles with good structural and sensory qualities. However, the absence of gluten continues to impose fundamental limitations on texture, cooking stability, and consumer acceptance. This review synthesizes recent advances in cereal-based GF noodles through an integrated structure–function–sensory framework. Emphasis on how hydrocolloid molecular characteristics (e.g., charge density, branching architecture, hydration behavior) govern starch–protein interactions, gelatinization dynamics, recrystallization, and network formation. Its mechanisms, including competitive hydration, hydrogen bonding, and cross-linking, are discussed as strategies to partially replicate gluten functionality and reduce cooking loss (CL) below 10%, in optimized systems. The incorporation of hydrocolloids has proven effective in strengthening the gel network, particularly in rice-based noodles, where the CL was reduced by 23.6%. Carboxymethyl cellulose (0.5–1.0% w/w) consistently reduces CL in rice-based systems due to enhanced hydrogen bonding with amylose that strengthens network cohesion. Xanthan gum and guar gum are highly effective at low concentrations (0.25–0.5% w/w) in starch-dominant formulations, while konjac flour markedly decreases CL at high inclusion levels. The review further introduces a Technology Readiness Level (TRL) perspective, identifying a persistent gap between laboratory-scale validation (TRL 4–6) and industrial deployment. Future progress requires predictive structure–function modelling, pilot-scale validation, techno-economic assessment, and regulatory alignment. Collectively, this work provides a mechanistically grounded roadmap for engineering scalable, consumer-accepted cereal-based GF noodles.

**Keywords** Gluten-free noodle · Cereals · Hydrocolloids · Cooking quality · Morphology · Thermal analysis

## Introduction

The global market for gluten-free (GF) products was valued at USD 7.07 billion in 2022 and is projected to expand at a compound annual growth rate (CAGR) of 9.8% from 2023 to 2030 (Fig. 1) [1]. This growth is primarily driven by increasing awareness and diagnosis of celiac disease (CD), resulting in a notable rise in the GF products [2].

Noodle is considered a staple food for the world's population. The markets are projected to grow at a CAGR of 5.47% over the next four years, with particularly high demand in the Asia-Pacific region, such as India, Malaysia, Indonesia, and China, while Europe is the largest market [3]. Traditionally, noodles are made using wheat flour, which is the major source of gluten and can cause health risks to individuals with CD or gluten intolerance. As a result, GF noodles have emerged as a promising alternative.

Various cereal-based flours and starches have been explored for GF noodles, such as rice [4], corn [5], sorghum [6], millet [7], and teff [8]. Each grain has unique nutritional and functional properties. For instance, long-grain rice, particularly the *indica* species, has a lower glycemic index (GI) compared to short-grain *japonica* species due to its higher

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**Fig. 1** Global market projection for gluten-free products based on industry reports

amylose content (19–23%) [9]. GI values describe the relation between carbohydrates and blood sugar or glucose levels.

Corn (*Zea mays*) is the third important cereal after rice and wheat [10], also associated with low GI due to its structural resistance to α-amylase enzymatic hydrolysis [5]. Millets are another example of cereal, which is considered suitable for individuals with CD and diabetes due to their naturally GF and low GI [11]. Sorghum grain (*Sorghum bicolor (L.) Moench*) is rich in starch and polyphenolic compounds, while teff is rich in carbohydrates and minerals and has a comparable crude protein content to wheat flour [8]. Among the cereal grains mentioned, rice flour is the most widely used in GF noodles, primarily due to its neutral flavor, compatibility with various formulations, and small granule size, which contribute to desirable textural properties [12]. However, corn, sorghum, millet, and teff, although they have higher nutritional value, present challenges in cooking loss (CL) and water absorption (WA). Common ingredients in noodle formulation include flour, salt, and water, whereas hydrocolloids, proteins, and enzymes are frequently employed to improve the quality of GF noodles. The GF noodles formulations vary depending on the desired texture, flavour, and nutritional content.

Understanding the cooking properties of GF noodles is essential. The key crucial elements that determine the quality of cooked noodles are CL, cooking yield, and WA. CL refers to the solids leaching during cooking and indicates noodles' resistance to disintegration [13]. High-quality noodles exhibit less than 10% CL [14, 15]. High CL (> 10%) is associated with poor texture, sticky, turbid cooking water [16], and leads to disintegration of noodle structure and loss of starch and nutrients. Cooking yield reflects the weight gain of noodles during cooking, which reflects the amount of water absorbed [17]. WA is defined as a water-binding capacity during cooking [18]. Noodles with an excessive WA typically have a soft and sticky texture, while noodles with low WA have a firm/hard and coarse texture [17]. In rice-based formulations, WA typically ranges between 15% and 250%, depending on ingredient composition, where WA in the range 15%–50% categorized as low, 51%–100% as moderate, and 101%–250% as high.

GF products often have poor texture [19] and weak flavour [20], primarily due to the absence of gluten, a critical component for a cohesive noodle matrix. Desirable noodles should have low CL, high firmness, and less stickiness, which is related to the specific structural arrangements of starch and proteins [20]. Thus, to obtain high-quality GF noodles, additives with adequate technological processes are necessary.

Although the role of hydrocolloids in GF noodle systems has been extensively reviewed, significant gaps remain in mechanistic integration, particularly for cereal-based formulations. Existing literature often summarizes additive types without systematically linking hydrocolloid molecular characteristics (e.g., charge, branching, hydration behavior) to multi-scale effects on starch–protein interactions, microstructural development (SEM), thermal transitions (DSC), crystallinity changes (XRD), and ultimately to cooking and sensory performance. Furthermore, the relationship between instrumental parameters (e.g., CL, firmness, and WA) and consumer acceptance thresholds, along with industrial applicability and technology readiness levels (TRL), remains insufficiently clarified.

This review addresses these gaps by proposing a hierarchical and integration structure–function–sensory framework specifically for cereal-based GF noodles, in terms of formulation, molecular characteristic, microstructure, cooking performance, and consumer perception. Besides, critically synthesizes multi-scale characterization techniques to support mechanistic interpretation of starch-hydrocolloid interactions. In addition, this review also introduces a TRL perspective to bridge laboratory findings with industrial scalability, economically viable production, and regulatory consideration. This work offers a roadmap for predictable functional additive design and application in next-generation cereal-based GF noodle systems.

## Challenges of gluten-free noodle production

GF noodles present several challenges due to the absence of gluten, a key component responsible for structuring integrity and elasticity in noodles. SWOT (strengths, weaknesses, opportunities, threats) analysis has become a crucial tool for evaluating product commercialization potential [21], which involves a thorough assessment of internal and external factors that may have impacted the product. Figure 2 summarizes the outcomes of the SWOT analysis, highlighting the dual aspects of opportunity and constraint that characterize GF noodle development. From a strength's perspective, GF noodles provide a nutritionally safer alternative for individuals with CD, while offering a platform for product innovation using alternative cereal grains (rice, corn, millet, sorghum, teff) and functional ingredients such as hydrocolloids and proteins [22, 23], which also promote dietary diversity.

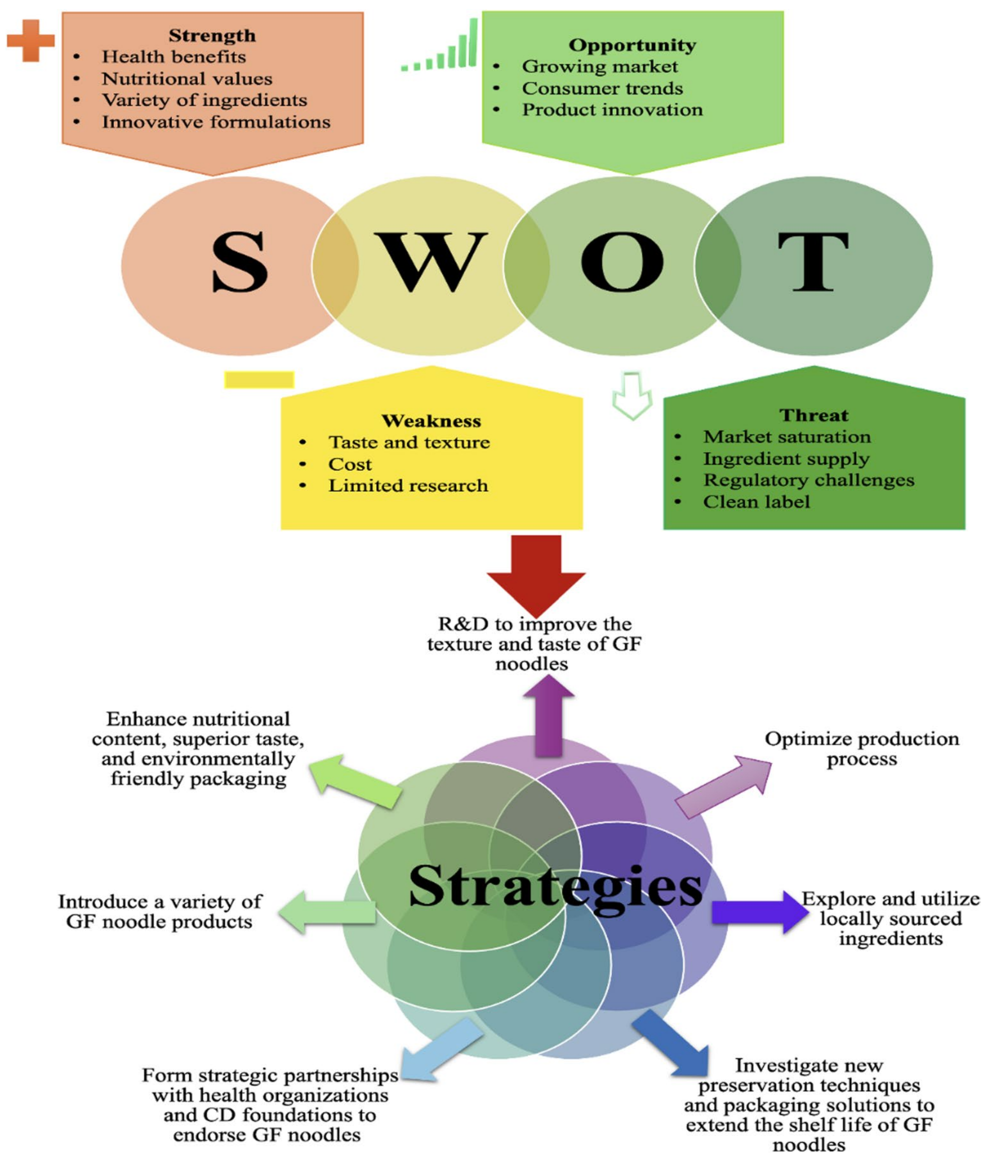



**Fig. 2** SWOT analysis of GF noodles

Nonetheless, the production of GF noodles presents several drawbacks, most notably high CL (>10%) and uncontrolled WA, which result in fragile texture, surface stickiness, and non-uniform cooking quality (Table 1). Formulations exhibiting CL values exceeding 10% typically exhibit poor cooking stability, resulting in undesirable texture and appearance. Excessive CL indicates poor matrix cohesion, often arising from weak starch–starch and starch–protein interactions or from incompatible flour blends. For example, sole extruded rice exhibits high CL (31.03%), whereas incorporating 25% pea starch reduced CL to 14.12% [18]. These findings emphasize that managing CL is vital to improving the cooking stability and sensory appeal of GF noodles.

Although significant advancements have been made in GF cereal-based noodles using functional additives, such as hydrocolloids, proteins, and enzymes, the effective application remains challenging. In some cases, excessive levels of additives may negatively affect the sensory and noodle texture. Thus, the selection of appropriate types and concentrations of the additives is critical, and further research is needed to optimize performance and consumer acceptance.

Despite many drawbacks mentioned, the demand for GF noodles is growing simultaneously with the number of CD cases [22], which is creating opportunities for market expansion. Even so, safety concerns in the GF product diet regarding the risk of heavy metal bioaccumulation in urine and blood, which includes elevated levels of arsenic, mercury, lead, and cadmium [30], pose a potential threat to consumer safety.

GF products' taste remains a challenge due to the undesirable texture and flavor. Consequently, the commercialization of GF noodles requires a comprehensive consideration, including product quality, regulatory restrictions, and marketing. The designation GF product was officially adopted in 1976 by the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) of the United Nations [31]. In addition, the European Union (EU) has enforced the Codex Alimentarius standard through Regulation No. 828/2014, implemented by the European Commission [32]. The robust quality control protocols, through stringent testing and documentation, are necessary to meet GF requirements and avoid cross-contamination with gluten products. Beyond regulatory and safety considerations, the increasing consumer demand for 'clean label' products adds another layer of complexity. Modern consumers often perceive many hydrocolloids and functional additives as ultra-processed ingredients, which can conflict with the clean label expectation for natural and minimally processed foods.

In light of the SWOT analysis, propose strategies that integrate scientific researchers, industrial partners, and regulatory bodies are necessary. The strategies include more scientific research on the GF formulation to imitate gluten characteristics, besides adding functional or

**Table 1** Cooking qualities of cereal-based GF noodles

| Type of based | Type of noodle | Cooking qualities | References |
|---|---|---|---|
| Rice starch | Starch noodle | Rice starch<br>CL:18.27% | [24] |
| Rice flour and pea starch | Extruded rice noodle | Rice flour<br>CL: 31.03%, WA: 33.37%$^{Wu}$<br>Rice flour + 25% pea starch<br>CL: 14.12%, WA: 25.55% $^{Wu}$ | [18] |
| Rice flour and pregelatinized high-amylose maize starch | Retort process rice noodle | Rice flour<br>WA: 242.6%$^{Wu}$<br>Rice flour + 15% amylose starch<br>WA: 183.8%$^{Wu}$ | [25] |
| Finger millet and rice flour | Rice noodle | Rice noodle<br>CL: 22.57%<br>30% finger millet<br>CL: 14.33% | [26] |
| Corn starch | Corn starch noodle | Corn starch<br>CL: 12.6%, Yield: 55.1% | [27] |
| Corn starch and buckwheat flour | GF noodle | 60% corn starch + buckwheat flour<br>CL: 10.30% | [28] |
| Corn, mocaf, and rice flours | Dry noodle | 50%: 30%: 20%<br>CL: 13.4% | [17] |
| Sorghum flour, mung bean, and sago starch | Sorghum flour, mung bean, and sago starch noodle | Sorghum flour, mung bean, and sago starch<br>30: 30: 40<br>CL: 11.86% | [29] |

* $^{Wu}$ WA values were calculated on the uncooked noodle basis

Note: *CL* represents cooking loss; *WA* represents water absorption; *Yield* represents cooking yield; *GF* represents gluten-free superfood components to the formulation. Flour modifications are required to improve the viability of specific grains for GF noodle production and to overcome their inherent constraints. Nevertheless, the modifications might have an impact on the flavour and texture of the finished product. Next, focus on preservatives or packaging options to improve the stability and shelf life of GF noodles. On the other hand, strengthening a consistent supply of locally accessible GF alternative grains or ingredients is necessary for large-scale production, which also helps to reduce production costs. And finally, establish regulatory mechanisms and standardize documentation and labelling requirements for safe production and control product quality.

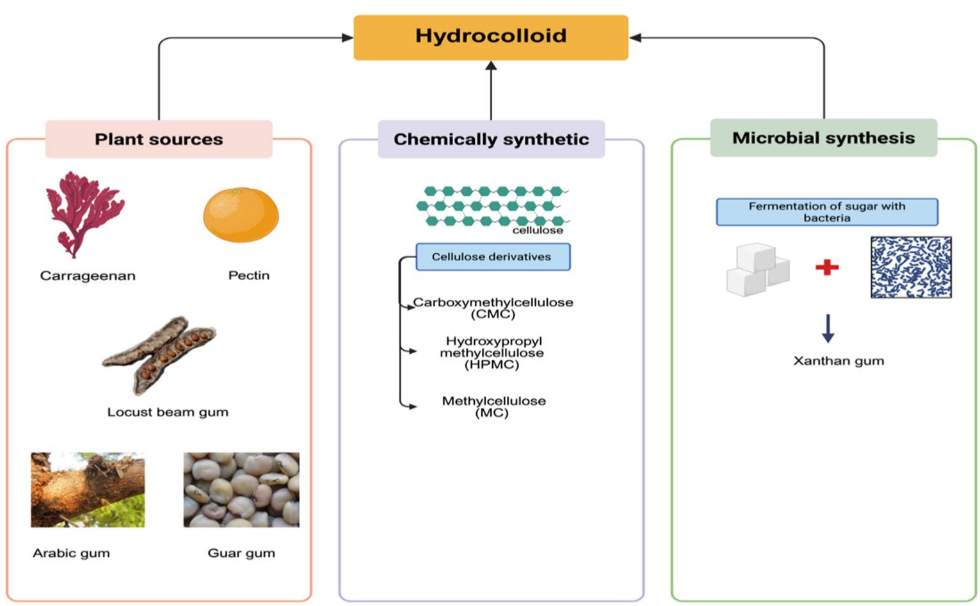
## The role of hydrocolloids

Hydrocolloids improve the texture, moisture content, viscosity, and overall quality of GF noodles [33, 34]. The effectiveness of hydrocolloids in GF formulations is primarily determined by their colloidal properties, such as water-binding capacity, hydration rate, viscosity, and response to temperature changes; the viscosity of most hydrocolloids decreases with rising temperature [23]. Additionally, their functional behavior is influenced by the type, concentration, processing parameters, and interactions with other components in the system [34].

Hydrocolloids are a group of water-soluble polysaccharides with diverse chemical structures and are widely used in the food industry as gelling agents, thickeners, emulsifiers, stabilizers, and foaming agents [7]. They can be categorized into different groups based on their origin (Fig. 3). Hydrocolloids from plant sources include agar, locust bean gum (LBG), guar gum (GG), carrageenan, pectin, arabic gum, and tragacanth gum [34]. Chemically synthetic hydrocolloids such as carboxymethylcellulose (CMC), hydroxypropyl methylcellulose (HPMC), and methylcellulose (MC) are derived from cellulose modification. Microbial biosynthesis of hydrocolloids included xanthan gum (XG) [34]. The water solubility of hydrocolloids also differs among their origin. For example, XG, GG, and CMC require cold water for effective hydration, whereas LBG and carrageenan dissolve in hot water [34]. Typically, hydrocolloid can be added either in dry mixing with flour or pre-hydration prior to dough formation, which describes the water availability and the gel network development. Dry mixing allows the hydrocolloid to compete with the starch granules for water. Conversely, pre-rehydration ensures that hydrocolloid is swelled and viscous, leading to competitive water binding and results in difference network cohesion [34]. The difference impact the noodle properties, such as cooking loss. Despite hydrocolloids' functional properties, some consumers view them as artificial, posing a challenge for GF product marketing [22].

Functionality of hydrocolloids in GF noodle systems can be interpreted through a structure–function framework, where molecular interactions govern supramolecular organization and ultimately determine macroscopic cooking and textural performance. During starch gelatinization, hydrocolloids interact with amylose and amylopectin via extensive hydrogen bonding, increasing continuous-phase viscosity and promoting the three-dimensional gel network that partially compensates for the absence of gluten [12, 35]. At the molecular level, their high density of hydroxyl groups enables competitive water binding, which regulates starch granule swelling, delays gelatinization transitions, and

**Fig. 3** Sources of hydrocolloids



restricts the diffusion of solubilized starch molecules into the cooking medium [36]. This regulation of water mobility and polymer chain reassociation leads to reduced amylose leaching and delays amylopectin recrystallization, resulting in improved matrix integrity, reduced CL, enhanced cooking yield, and greater textural stability during storage [7, 37]. This regulated molecular hydration and polymer–polymer interactions are the source of the desirable viscoelastic behavior in the finished product.

Lu et al. [38] reported that the interactions between starch and hydrocolloids, including hydrogen bonding and steric effects, significantly improved gel integrity, water retention, and reduced retrogradation. This work provides mechanistic insights into the design of high-performance starch–hydrocolloid composites by connecting structural change to functional performance. During gelatinization, coupled physicochemical processes of hydration, crystalline disruption, molecular leaching, and network stabilization are involved in starch–hydrocolloid interactions (Fig. 4). Upon heating in excess water, the hydrogen bonds in the crystalline lamellae are gradually broken, causing starch granules to absorb water and swell. Higher temperatures cause granular integrity to deteriorate and break, which leads to amylose leaching and the loss of double-helical order in amylopectin. Through hydrogen bonding and physical crosslinking, hydrocolloids compete for water to enter swelling granules and interact with amylose and amylopectin chains. Retrogradation is limited by these interactions, which also decrease polymer chain mobility, reduce intermolecular reassociation, and inhibit amylopectin recrystallization. After total granular collapse, hydrocolloids improve water-holding capacity and reduce free water mobility by forming a continuous hydration film around starch residues and inside the continuous phase. Simultaneously, interactions with leached amylose help to create a three-dimensional composite network that strengthens gel structure and improves rheological stability.

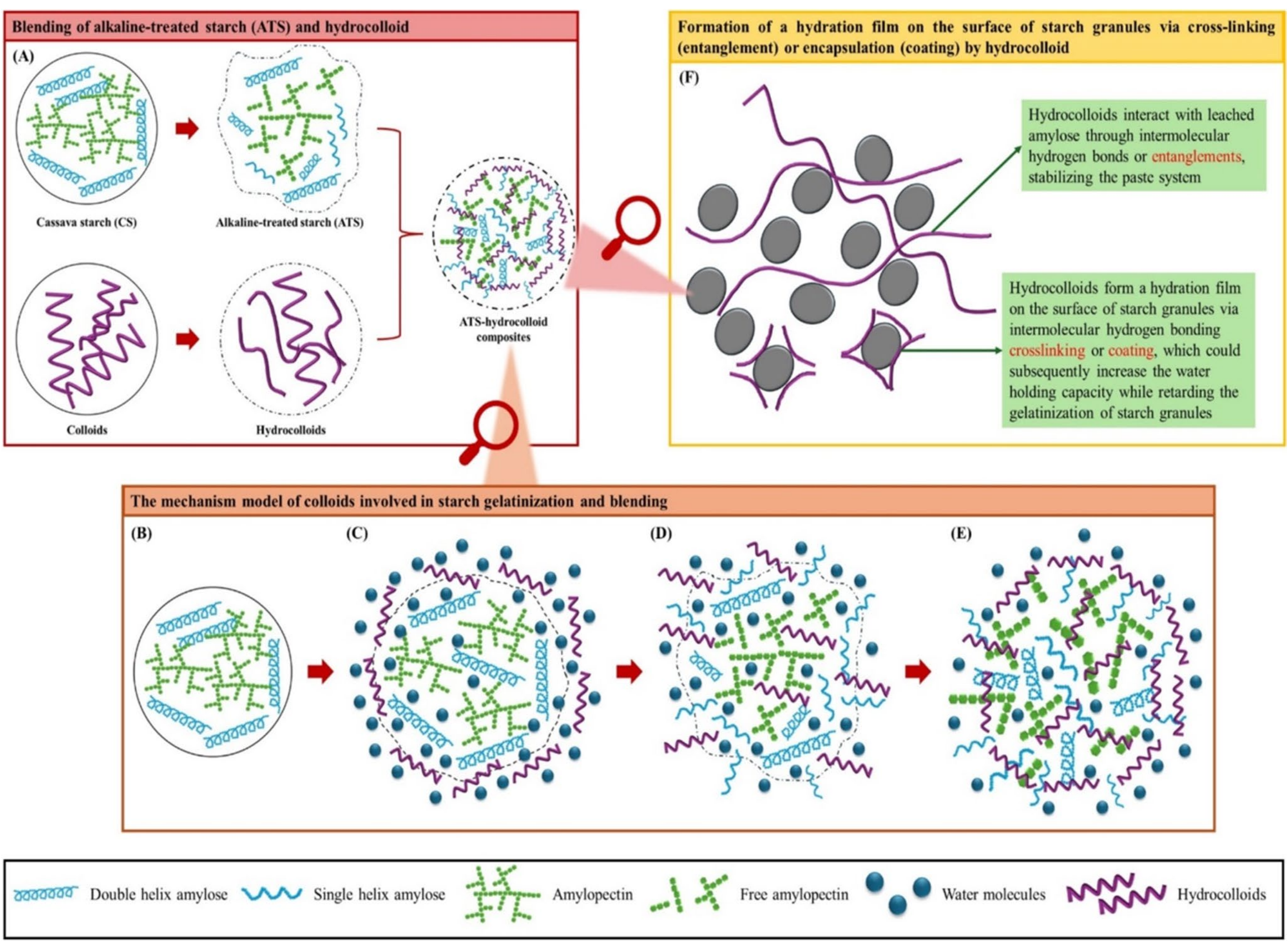



**Fig. 4** Schematic diagram of starch–hydrocolloid interactions during gelatinization: (**A**) blending of starch and hydrocolloid; (**B**) suspension in water; (**C**) granule swelling upon heating; (**D**) granule rupture with amylose leaching and amylopectin disordering, accompanied by hydrocolloid penetration; (**E**) total granular collapse with inhibition of amylopectin reassociation; and (**F**) formation of a hydrocolloid hydration film and interactions with leached amylose, stabilizing the paste system [38]

Beyond starch, the structure–function relationship becomes more complex in minor cereals such as millet, sorghum, and teff, where protein architecture differs fundamentally from wheat gluten. These cereals are rich in prolamins and glutelins with relatively high hydrophobicity and limited capacity for elastic network formation [39]. The intrinsic protein structure lacks the intermolecular cross-linking density required to form cohesive viscoelastic matrices, although several millet varieties possess moderate protein contents (~9–12%) [39]. Consequently, structural breaks often arise in GF dough systems that jeopardize elasticity and cooking stability.

Hydrocolloids may mitigate these structural deficiencies by mediating starch–protein–water interactions at multiple hierarchical levels. Non-ionic hydrocolloids such as GG, konjac glucomannan, and HPMC mainly interact with starch granules through hydrogen bonding and physical chain entanglement. Their flexible and highly hydrated polymer chains closely associate with amylose and amylopectin molecules via hydroxyl (-OH) groups, forming hydrated networks surrounding swollen starch granules (Fig. 5). At the molecular level, hydrogen bonding between hydrocolloid hydroxyl groups and polar amino acid residues can stabilize partially unfolded protein conformations. Hydrocolloids regulate protein hydration shells by redistributing water within the composite matrix, which lessens uncontrollable aggregation during thermal processing and promotes more homogeneous gel formation [40]. In proso millet cookie formulations [41], non-ionic hydrocolloids like HPMC have demonstrated improvements in dough handling and structural uniformity. This is probably due to steric stability and improved polymer entanglement, which prevent phase separation between protein-rich and starch-rich domains. Improved gas cell stability and larger specific volume in foxtail millet biscuit formulations have also been linked to increased dough viscosity and hydrogen-bonding capability, indicating improved structural continuity during heating [42].

In contrast, ionic hydrocolloids such as XG, CMC, and alginate contain negatively charged functional groups (e.g., –$COO^-$) that introduce electrostatic interactions into the starch system (Fig. 5). These charged functional groups produce relatively rigid and extended polymer conformations because of intermolecular electrostatic repulsion along the hydrocolloid backbone. Their high charge density strongly enhances water immobilization and continuous-phase viscosity, forming a protective viscous layer around starch granules during heating. This barrier reduces molecular mobility and suppresses amylose leaching, thereby lowering CL and improving cooking stability.

From a structure–function perspective, these findings suggest that hydrocolloids function as structural modulators that integrate various biopolymers into a cohesive composite network. However, the mechanistic elucidation of protein–gum interactions in GF noodle matrices remains limited. Advanced analytical tools, including spectroscopic, rheological, and microstructural techniques, are required to link molecular interaction forces to network architecture, enabling the rational design of next-generation GF noodles with optimum starch–protein–hydrocolloid interactions.

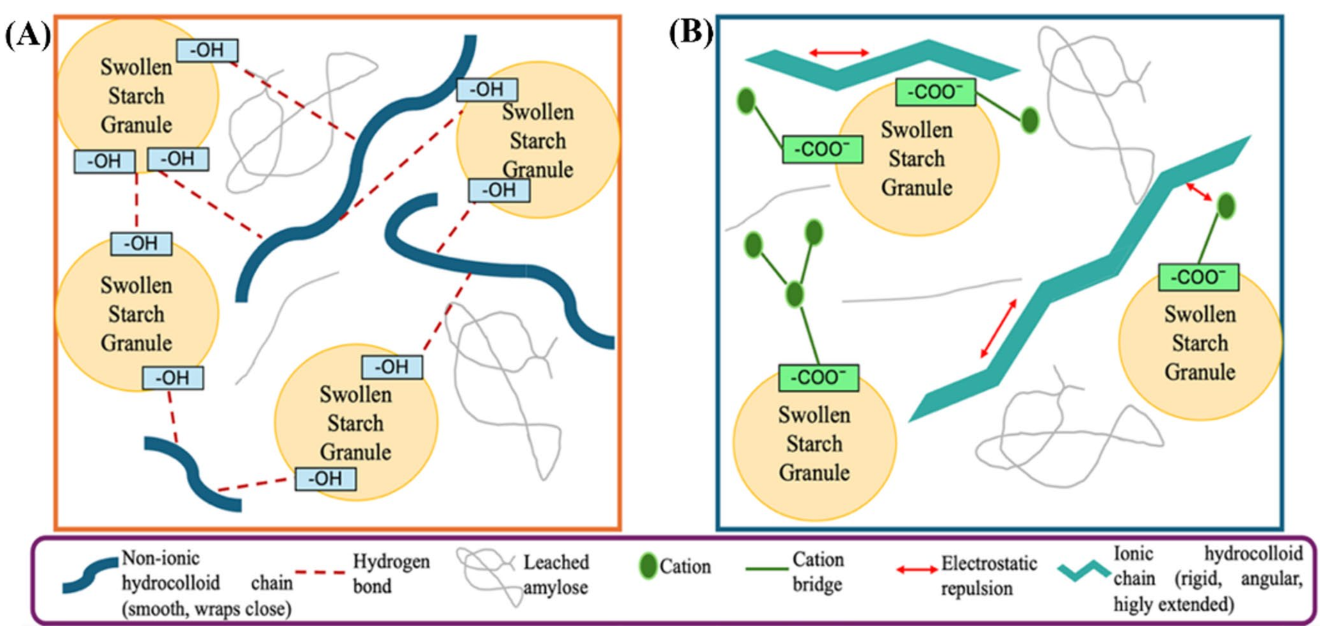



**Fig. 5** Schematic diagram of molecular interaction between ionic/non-ionic hydrocolloids and starch granules: (**A**) non-ionic hydrocolloids (GG/HPMC/Konjac); (**B**) ionic hydrocolloids (XG/CMC/Ca-ALG)

In addition to technological benefits, hydrocolloids offer health-promoting properties, which include anti-diabetic activity, bowel function, reduction of osteoporosis risk, prevention of coronary heart diseases, type 2 diabetes mellitus, and colon cancer [43].

## Effect of hydrocolloids on the cooking qualities of cereal-based noodles

Hydrocolloids such as XG, GG, CMC, HPMC, calcium alginate (Ca-ALG), canna starch, winged bean flour, and konjac flour function as structural modifiers in GF cereal-based noodles, fundamentally altering molecular interactions within starch-dominant matrices. Table 2 summarizes GF cereal-based noodle formulations incorporating different hydrocolloids, demonstrating their significant influence on cooking quality. Notably, the inclusion of these hydrocolloids consistently maintained CL below 10%, indicating their efficacy in minimizing solid loss during cooking. Improved CL, WA, and yield are often reported as bulk indicators of functionality; these macroscopic properties are the result of molecular-level interactions that control microstructural organization during gelatinization and subsequent thermal processing.

The functionality of each hydrocolloid is governed primarily by its molecular architecture, including chain rigidity, branching degree, charge density, and hydration behavior. For example, XG possesses a stiff, highly charged cellulose-like backbone with trisaccharide side chains. Its high charge density promotes strong water binding and continuous-phase viscosity improvement, leading to the formation of a hydrated film around the starch granules as they heat up. This viscous matrix reduces molecular mobility and limits amylose diffusion into the cooking medium, thus lowering CL. Kaur et al. [10] demonstrated that 0.25% XG or GG reduced CL in corn starch noodles from 0.46% to 0.13%. However, the reinforcement impact of XG may vary depending on starch composition and amylose content, as it mainly thickens the surrounding medium instead of creating significant intermolecular hydrogen bonds with amylose. Cai et al. [44] reported that 5% XG in hydrothermal glutinous rice flour achieved the highest WA (68.4%), while Raungrusmee et al. [12] obtained a WA of 62% using 2.5% XG in rice starch noodles. The formation of a hydrated film around starch granules during heating enhances XG-amylopectin interactions and increases viscosity, thereby improving water retention and minimizing starch leaching. However, the effectiveness of XG depends strongly on starch composition and amylose content because its rigid conformation mainly thickens the surrounding medium rather than forming extensive intermolecular bonding with amylose.

In contrast, GG and CMC exhibit greater conformational flexibility, enabling stronger interactions with starch polymers. GG is a flexible and non-ionic galactomannan that enhances matrix cohesion at the molecular level, primarily by forming strong hydrogen bonding with hydroxyl groups of amylose and amylopectin. Its flexible backbone limits the amylose diffusion into cooking water and promotes physical cross-linking by facilitating chain entanglement inside the gelatinized starch network. Kraithong and Rawdkuen [46] showed that incorporation of 0.2% GG reduced CL in red jasmine rice noodles from 6.01% to 5.07%. Similarly, CMC reduced CL to 5.32%, whereas XG increased CL to 7.25%. The better performance of CMC is associated with its linear anionic structure and evenly distributed carboxymethyl groups, which facilitate extensive hydrogen bonding and interpolymeric association with leached amylose [46]. Consequently, CMC promotes the formation of finer and more uniform pore structures that restrict solid diffusion while maintaining hydration. Srikaeo et al. [47] further reported that CMC produced the lowest CL (0.81%) and highest WA (257.17%) in fermented rice noodles, highlighting its strong structural compatibility with rice-based systems that lack protein scaffolding.

The distinct performance of XG, GG, and CMC illustrates the importance of molecular compatibility between hydrocolloids and starch matrices. Although XG strongly increases viscosity through water immobilization, its rigid helical structure limits molecular entanglement with starch chains. Excessive hydration in the continuous phase may therefore induce microphase separation, weakening intergranular cohesion and increasing amylose leaching during cooking. The flexible backbones of GG and CMC facilitate closer interaction with starch molecules, leading to improved network integration and reduced CL. Although using similar hydrocolloid, resulted in variation trends, which likely influenced by type of starch, amylose content, flour composition, processing conditions, and hydrocolloid concentration and origin. Chemically modified hydrocolloids such as CMC generally form more homogeneous and fine-pored structures due to controlled substitution patterns, whereas naturally derived gums such as XG and GG may exhibit greater structural heterogeneity arising from biosynthesis and extraction conditions. Such heterogeneity can influence hydration uniformity, pore formation, WA, and CL.

This is supported by a significant discrepancy in the CL values was noted between Kraithong and Rawdkuen [46] and Srikaeo et al. [47], despite the use of similar hydrocolloids (CMC, GG, and XG), is likely due to variations in noodle composition, base flours (red jasmine rice vs. fermented rice flour), processing conditions, and, importantly, the concentrations of hydrocolloids applied. The effect of hydrocolloid origin and structure is another decisive factor

**Table 2** Cooking qualities of GF cereal-based noodles in the presence of hydrocolloids

| Type of based | Type of additives | Cooking properties | References |
|---|---|---|---|
| GRF | XG | Control (wheat)<br>WA: 61.6%$^{Wdough}$<br>GRF<br>WA: 61.3%$^{Wdough}$<br>GRF hydrothermally treated + 5% XG<br>WA: 68.4%$^{Wdough}$ | [44] |
| Rice starch | XG | Control (wheat flour)<br>CL: 0.7%, WA: 19.24%$^{Wu}$<br>2.5% XG<br>CL: 2.67%, WA: 62%$^{Wu}$ | [12] |
| Fermented rice flour | GG | 0.5% GG<br>CL: 3.95%, Yield: 218.14%<br>1.5% GG<br>CL: 3.70%, Yield: 229.05% | [45] |
| Red jasmine rice flour | XG, CMC, and GG | Control (red jasmine rice flour)<br>CL: 6.01%<br>0.2% XG<br>CL: 7.25%<br>0.2% GG<br>CL: 5.07%<br>0.2% CMC<br>CL: 5.32% | [46] |
| Rice flour | XG, CMC, and GG | Control (fermented rice flour)<br>CL: 1.06%, WA: 194.75%$^{Wd}$<br>XG<br>CL: 1.13%, WA: 210.83%$^{Wd}$<br>CMC<br>CL: 0.81%, WA: 257.17%$^{Wd}$<br>GG<br>CL: 0.98%, WA: 210.77%$^{Wd}$ | [47] |
| Rice flour and mung bean starch | XG, CMC, GG, and HPMC | XG<br>CL: 14.46%. Yield: 228.79%<br>CMC<br>CL: 10.34%. Yield: 270.32%<br>GG<br>CL: 10.84%, Yield: 297.26%<br>HPMC<br>CL: 8.5%, Yield: 270.32% | [37] |
| Rice flour | Canna starch | Control (rice flour)<br>CL: 1.3%, Yield: 132.1%<br>Native canna starch<br>CL: 1.6%, Yield: 157.8%<br>Cross-linked starch<br>CL: 1.5%, Yield: 155.0%<br>Retrograded starch<br>CL: 1.8%, Yield: 156.1%<br>Retrograded debranched starch<br>CL: 2.7%, Yield: 139.9% | [48] |
| Corn starch | XG and GG | Control (corn starch)<br>CL: 0.46%<br>0.25% XG<br>CL: 0.13%<br>0.25% GG<br>CL: 0.13% | [10] |

**Table 2** (continued)

| Type of based | Type of additives | Cooking properties | References |
|---|---|---|---|
| Corn and mocaf flour | Winged bean and konjac flour | 15%-winged bean flour<br>CL: 1.44%<br>15% konjac flour<br>CL: 0.06% | [49] |

* [Wu] WA values were calculated on the uncooked noodle basis

Note: *CL* represents cooking loss; *WA* represents water absorption; *Yield* represents cooking yield; *XG* represents xanthan gum; *GG* represents guar gum; *CMC* represents carboxymethyl cellulose

affecting noodle cooking performance. Chemically modified hydrocolloids, such as CMC, obtain uniform and fine-pored networks due to their controlled substitution patterns, while naturally derived gums like XG (microbial) and GG (plant-based) are more sensitive to environmental conditions during biosynthesis and processing, resulting in heterogeneous pore structures. Such heterogeneity may lead to uneven hydration, affecting WA and CL. In addition, galactomannan (in GG) has flexible chains and high hydration capacity, mainly increasing viscosity through chain entanglement. Its branched yet flexible structure facilitates water retention and elasticity, particularly in starch-dominant systems. However, its efficiency depends on concentration and matrix composition because its interaction with amylose is mainly physical rather than chemical. Excessive inclusion may lead to heterogeneous swelling and uneven pore formation, affecting WA and CL variability.

Hydrocolloid performance becomes more complex in composite starch systems. Sutheeves et al. [37] reported relatively high CL values in rice flour–mung bean starch noodles despite the incorporation of XG (14.46%), CMC (10.34%), GG (10.84%), and HPMC (8.5%). This behavior likely reflects differences in gelatinization characteristics and molecular organization between rice and mung bean starches. Mung bean starch contains higher amylose content and stronger amylose–amylose interactions, which may promote excessive leaching and disrupt network uniformity during cooking. Differences in swelling kinetics, crystalline structure, and gelatinization temperature between starch components may further hinder synchronized gel formation, weakening the composite matrix despite increased viscosity and cooking yield.

Hydrocolloids capable of secondary gelation processes provide additional structural reinforcement. For instance, when HPMC is heated, hydrophobic interactions form a three-dimensional network that stabilizes swollen starch granules during cooking, exhibiting thermogelation activity. In rice flour–mung bean starch noodles, HPMC produced the lowest CL (8.5%) [37]. Similarly, Ca-ALG uses the "egg-box" paradigm to form ionic crosslinks in the presence of $Ca^{2+}$, creating a physically crosslinked matrix that encapsulates starch granules and limits solute diffusion. In these systems, the major mechanism shifts from viscosity enhancement to structural immobilization.

Starch-based hydrocolloids, such as canna starch, modify structure through gelatinization kinetics. Noodles with low CL (< 3%) and high yield (> 139%) are produced via modifications, including cross-linked or retrograded canna starch, which alter swelling behavior and improve resistance to granule rupture [48]. During cooking, their relatively low gelatinization temperature accelerates starch hydration, promoting rapid network consolidation. Thus, starch structural modification offers another route to network reinforcement.

Functional flours such as konjac and winged bean contribute additional mechanisms. Konjac flour, which is rich in high-molecular-weight glucomannan, exhibits remarkable water-binding capacity and gel-forming ability. Its long flexible chains creäte dense entangled networks, which can significantly lower CL (0.06% at 15% inclusion) [49]. This effect happens from starch molecules' strong water immobilization and physical entrapment. Winged bean flour improves structure and produces a composite network formation for cooking stability through protein–starch–fiber interactions.

Overall, effective reduction in CL requires the continuous starch–hydrocolloid network supported by hydrogen bonding, chain entanglement, and potentially weak electrostatic interactions, to increased viscosity. The balance between gum conformational flexibility, charge density, molecular weight, and compatibility with the amylose/amylopectin ratio of the starch system determines whether hydrocolloids function as network reinforcers or only as viscosity modifiers. These findings underscore the need for system-specific optimization in GF noodle formulations.

Collectively, these findings support a hierarchical structure–function framework: (i) hydrocolloid molecular characteristics (charge, branching, rigidity, hydration capacity, gelation mechanism) (ii) interaction type with starch (hydrogen bonding, entanglement, ionic crosslinking, thermogelation) (iii) microstructural development (pore uniformity, network density, granule encapsulation) (iv) macroscopic outcomes such as CL, WA, yield, firmness, and elasticity. As a result, variation in performance across studies is attributed to many factors, including hydrocolloid type, amylose content, starch granule morphology, processing conditions, and concentration-dependent phase behavior.

A hierarchical structure–function framework is proposed (Fig. 6) to integrate the data from formulation, processing, and sensory studies. Despite extensive reports showing improvements in CL, WA, and texture after hydrocolloid incorporation, the mechanistic pathways linking molecular design to sensory quality remain fragmented. Structural integrity in GF cereal-based systems relies only on engineered starch–hydrocolloid–protein interactions. Therefore, hydrocolloid molecular characteristics, including charge density, chain conformation, branching architecture, and hydration behavior, must be understood as primary structural determinants. The proposed framework integrates formulation variables, molecular attributes, interaction mechanisms, microstructural organization, cooking behavior, and sensory perception into a single multi-scale model. This roadmap provides a mechanistic basis for appropriate formulation design, process optimization, and accelerated translation from laboratory innovation to industrial implementation by clearly connecting ingredient formulation to network formation and consumer-relevant outcomes.

## Synergistic effects of hydrocolloids and others on the cooking qualities of cereal-based noodles

In addition to the hydrocolloid individual role, hydrocolloids have demonstrated synergistically with other additives such as dietary fibers and salts in improving the cooking properties of GF noodles (Table 3). These synergistic

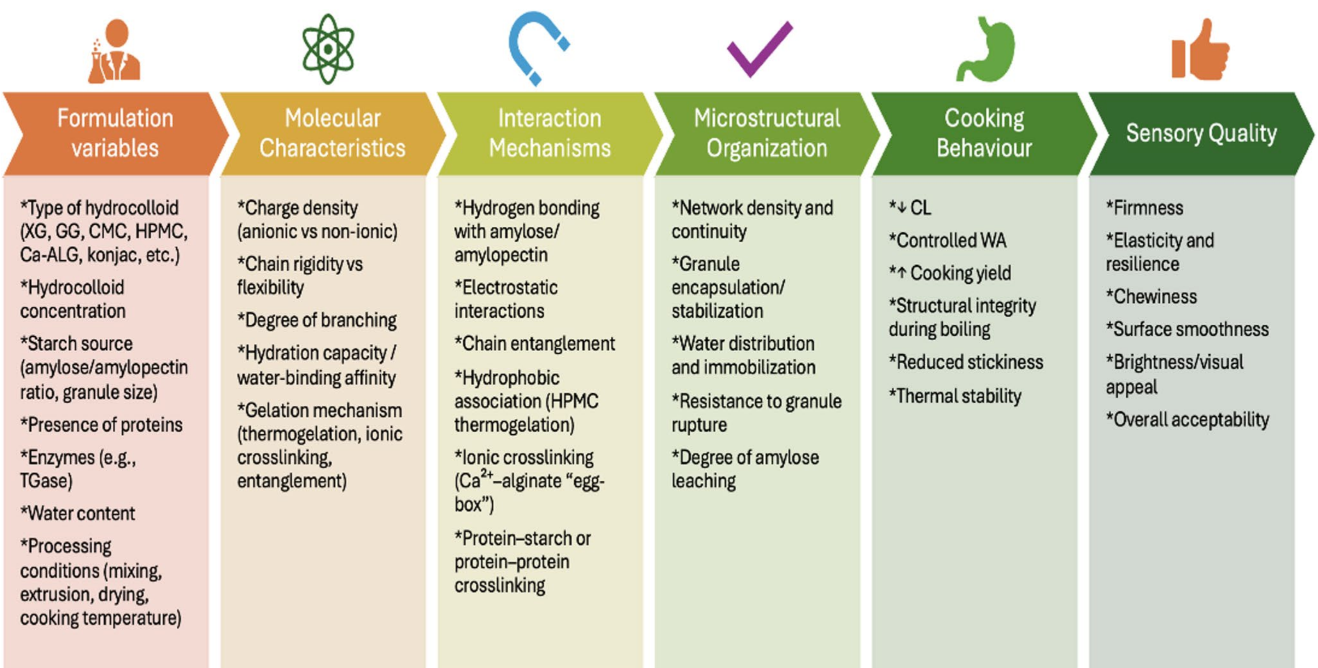



**Fig. 6** Proposed structure–function framework for GF cereal-based noodles. Formulation variables determine hydrocolloid molecular characteristics, which govern interaction mechanisms with starch and protein components. These interactions dictate microstructural organization during gelatinization and cooking, ultimately controlling cooking behaviour and sensory quality. The framework provides a mechanistic roadmap linking ingredient selection to consumer-relevant textural and quality attributes

**Table 3** Recent (2020 onwards) research on optimal hydrocolloid formulation in GF cereal-based noodles with low cooking loss

| Type of based | Type of additives | Concentation | Cooking loss (%) | References |
|---|---|---|---|---|
| Rice starch | XG and inulin | 5% XG | 2.19 | [12] |
| | | 2.5% XG + 5% inulin | 2.24 | |
| Rice flour | High amylose maize starch (HAMS) and Ca-ALG | 10% HAMS + 1% Ca-ALG | 1.05 | [50] |
| Maized-based composite flour | XG and Ca-ALG | 0.6% XG | 2.51 | [35] |
| | | 0.9% Ca-ALG | 2.2 | |
| Red jasmine rice flour | GG | 0.2% GG | 5.07 | [46] |

Note: *XG* represents xanthan gum; *HAMS* represents high amylose maize starch; *GG* represents guar gum; *Ca-ALG* represents calcium chloride and sodium alginate; maized-based composite flour composed of ratio 47:5:19:9:20, of maize flour, soy protein isolate, buckwheat flour, quinoa flour, and millet flour, respectively interactions improve CL and WA by promoting network reinforcement and stabilization of the starch matrix during thermal processing.

Raungrusmee et al. [12] reported that incorporating inulin and defatted rice bran alongside XG in rice starch noodles significantly enhanced WA while maintaining low CL values. Their optimized formulation achieved a WA of 79.85–80.76% and a CL of 2.24–2.58%, outperforming noodles with XG alone. This improvement was attributed to the combination hydrophilic nature of inulin and the gel-forming ability of XG, which increased water retention and reduced starch leaching. However, when fiber was combined in defatted rice bran, the CL slightly increased, likely due to its coarse particle structure, which disrupted the continuity of the hydrocolloid–starch matrix and promoted microcracks during cooking.

Dahal et al. [7] reported via Box–Behnken design, an optimized composite noodle formulation contained corn flour (98.77 g), millet flour (60 g), egg (50 g), XG (1.5 g), and GG (1.47 g). The addition of XG and GG in a ratio of 1:1, significantly increased water-holding capacity and textural strength through hydrogen bonding, which improved cooking resilience and elasticity. Although hydrocolloid performance is highly dependent on the cereal matrix and processing conditions, the incorporation of XG and GG has consistently demonstrated promising functionality in starch-dominant GF noodle systems. In the systems, XG primarily contributes to viscosity development and water immobilization, whereas GG enhances flexibility, chain entanglement, and elastic recovery. Excessive XG may cause over-viscosification, phase separation, and heterogeneous pore formation, while excessive GG may promote overhydration and weaken matrix integrity. Therefore, a balanced ratio of XG and GG in the systems represent a practical strategy for improving cooking quality and structural stability in cereal-based GF noodles. However, the optimum ratio remains dependent on cereal type, amylose–amylopectin ratio, processing conditions, and hydration behavior.

Cross-linked systems represent another effective strategy for improving cooking stability. Kang et al. [51] demonstrated that incorporating alginate with calcium chloride ($CaCl_2$) significantly improved the cooking quality of the rice noodles containing okara. Alginate, a negatively charged hydrocolloid, forms a gel through ionic cross-linking with $Ca^{2+}$ ions, resulting in a denser and more cohesive network that limits starch swelling and solid leaching during cooking. Similarly, Lubowa et al. [50] found that $CaCl_2$ and sodium alginate synergistically improved the cooking performance of high-amylose maize–rice noodles.

Jiang et al. [35] reported the composite noodles from corn, buckwheat, quinoa, and millet flours combined with various hydrocolloids. The result revealed that 0.9% Ca-ALG achieved the lowest CL (2.2%), followed by 0.6% XG (CL = 2.51%) and 1% carboxymethyl cellulose–sodium (CMC–Na) (CL = 3.3%). The superior performance of Ca-ALG was attributed to the formation of a stable ionic gel network that effectively restricted the migration of soluble starch and protein molecules into the cooking medium. This study reinforces that the hydrocolloid type and interaction with flour components determine final noodle quality, particularly when combining different cereal bases with varying amylose content and granule morphology.

Since the performance is very matrix-dependent, no single hydrocolloid can consistently optimize GF cereal-based noodle quality. In starch-dominant systems such as corn starch, low inclusion levels of XG or GG (≈0.25–0.5%) demonstrate remarkable efficiency in reducing CL due to increased viscosity development and chain entanglement that limit amylose diffusion. However, CMC at 0.5–1.0% appears to be more consistently effective in rice flour systems, where moderate amylose leaching and weak protein structure dominate. CMS's linear cellulose backbone facilitates the creation of cohesive networks without undue phase separation and makes hydrogen bonds with amylose chains easier. Through thermogelation or ionic crosslinking mechanisms, hydrocolloids such as HPMC or $CaCl_2$–alginate (≈ 1%) may provide greater structural reinforcement in more complex composite matrices (e.g., rice–mung bean blends). Although konjac flour exhibits the lowest reported CL at high inclusion levels (~ 15%), formulation cost and sensory impact may limit its practical application. Collectively, these findings indicate that the best hydrocolloid selection must consider starch composition, amylose content, hydration behavior, and processing intensity, rather than assuming uniform functionality across gluten-free systems.

## Effect of hydrocolloids on the morphology of cereal-based noodles

High-resolution SEM analysis provides direct visualization of the transformation of hydrocolloid molecular characteristics into network organization in GF noodle matrices. Microstructural variations, however, should not be interpreted descriptively; rather, they are indicative of underlying molecular interactions that are controlled by polymer architecture, charge density, and hydration behavior.

Srikaeo et al. [47] reported that the incorporation of gums promoted porous structures compared to control rice noodles, confirming that hydrocolloids actively restructure starch networks during gelatinization. Among the tested gums, CMC produced evenly distributed air cells with relatively uniform pore size, whereas XG and GG created larger, heterogeneously distributed pores. These variations can be explained by molecular structure. CMC is a linear, moderately flexible anionic cellulose derivative capable of forming extensive hydrogen bonds with leached amylose. This promotes cohesive network formation and more homogeneous phase distribution, leading to controlled pore development. The observation of high WA and low CL is explained by the uniform microstructure, which reduces localized stress concentration during boiling.

In contrast, XG has a rigid backbone and high charge density, which significantly raises the viscosity of the hydrocolloid-rich phase surrounding swollen starch granules. At low concentration, this enhanced matrix viscosity can improve structural stability; however, at higher concentrations, it may promote partial phase separation between starch-rich and hydrocolloid-rich domains. The formation of larger and uneven pores in XG- or GG-containing noodles reflects partial segregation between starch-rich and hydrocolloid-rich domains. Sutheeves et al. [37] observed that XG incorporation resulted in a non-continuous matrix with large voids and hollows, whereas CMC yielded smaller pores and fewer structural defects. According to Raungrusmee et al. [52], XG induced slight porosity and hollow structures compared to resistant rice starch alone.

The high-shear thinning behaviour of XG can also explain the variations in microstructure. When the system is at rest, XG creates a very thick and viscous mixture. However, the use of mechanical force causes its viscosity to decrease during mixing, extrusion, and cooking. Heterogeneous pore evolution may result from the localized expansion of trapped steam or air cells and the uneven swelling of starch granules due to the temporary decrease in structural resistance. Viscosity rises once more when shear stops, potentially "locking in" irregular structures. Collectively, these findings suggest that excessive water immobilization combined with shear-dependent viscosity modulation may change the swelling dynamics and affect matrix uniformity in cereal-based GF noodles.

Starch–gum mixtures often show partial separation, where some regions have more hydrocolloid while others contain more amylose and amylopectin. The degree to which the starch and gum interact determines the uneven distribution, which is known as phase separation. In the absence of hydrocolloids, gelatinized starch forms a network mainly through connecting amylose chains during cooling. This amylose reassociation helps control swelling and maintain structural integrity. When hydrocolloids are added, the behavior changes. Different network architectures can be generated by the leached amylose chains interacting with the hydrocolloid through hydrogen bonding, physical entanglement, or ionic crosslinking, depending on the type and concentration of the gum [47].

Ionic crosslinking hydrocolloids produce different microstructures. When $Ca^{2+}$ is present, sodium alginate (SA) and Ca-alginate (Ca-ALG) form ionically crosslinked "egg-box" networks that strengthen the gel matrix and minimize pore size. Zhang et al. [53] reported that the uniform and orderly pore distribution observed in SA-containing noodles demonstrated improved network organization, due to the combined effects of short-term starch retrogradation and alginate crosslinking. The $Ca^{2+}$-mediated junction zones stabilize swelling starch granules during gelatinization and cooling, restrict the mobility, reduce pore size, and improve matrix continuity. Srikaeo et al. [54] reported that SA generated denser microstructures compared with XG and GG. The $Ca^{2+}$-mediated crosslinking immobilizes water and stabilizes swollen starch granules, improves matrix continuity, and reduces CL. Lubowa et al. [50] found that the combination of high-amylose maize starch with Ca-ALG produced a denser, more compact structure with fewer surface voids than control noodles. The tighter network results from synergistic gelatinization of high-amylose starch and ionic alginate crosslinking, illustrating the relation of molecular bonding mechanisms and the matrix.

Konjac glucomannan (KGM) and its derivatives further highlight the importance of hydrocolloid–starch hydrogen bonding. Zeng et al. [55] reported that the addition of deacetylated konjac glucomannan (DKGM) produced a compact and uniform network with smaller pores due to hydroxyl-mediated hydrogen bonding with free starch chains, promoting double-helix formation and three-dimensional network reinforcement. However, when hydration is too high, KGM's strong hydrophilicity may also promote water penetration into starch granules, occasionally enlarging pores or causing cracks [56]. This demonstrates that to prevent over-expansion, hydration capacity needs to be balanced.

GG has been shown to produce uniform and continuous structures that inhibit structural damage caused by ice crystal formation during freezing [45, 57]. Its flexible GG chains strongly bind water, reduce water migration, and limit large ice crystal growth. This water immobilization effect stabilizes microstructure and improves textural resilience. Bhavadharani et al. [58] reported that millet–GG noodles exhibited smoother and denser matrices with fewer cracks, which improved firmness and mouthfeel.

Collectively, SEM observations verify that microstructure is a physical manifestation of molecular interactions. Linear polymers of hydrogen bonding (CMC, KGM) promote homogeneous networks and controlled pore formation. Rigid, highly charged gums (XG) increase viscosity, but may generate heterogeneous porosity dependent on concentration and processing. Ionic crosslinking hydrocolloids (SA, Ca-ALG) create compact, reinforced matrices with less void formation. These microstructural differences directly influence water diffusion, amylose leaching, mechanical stability, and ultimately sensory attributes such as firmness, elasticity, and surface smoothness. Therefore, SEM analysis should be understood within a more comprehensive structure–function framework. Hydrocolloid molecular architecture governs interaction mechanisms with starch, which determine pore evolution and matrix continuity during gelatinization. These microstructural outcomes ultimately control cooking behavior and textural perception.

## Effect of hydrocolloids on the thermal properties of cereal-based noodles

The thermal properties of GF noodles, which are primarily determined by starch gelatinization and retrogradation behaviour, serve as a crucial indicator of processing stability and cooking quality. Techniques like DSC are essential for characterizing the starch thermal behavior and subsequent microstructural development within the structure-function framework (Fig. 6). Changes in onset ($T_o$), peak ($T_p$), and conclusion ($T_c$) temperatures, as well as enthalpy (ΔH), reflect alterations in molecular mobility, crystalline stability, and water distribution arising from starch–hydrocolloid interactions.

The effect of hydrocolloids on starch gelatinization can be explained through three mechanisms. First, competitive hydration occurs when hydrophilic polymers such as XG and DKGM bind water and restricts water availability to starch granule swelling. Second, interpolymer interactions, including hydrogen bonding and electrostatic interactions, which stabilize the granule surface structure. Third, hydrocolloids restrict polymer chain mobility, which modifies the energy required for crystalline melting and gel formation. For example, elevated gelatinization temperatures in systems containing XG [52] or DKGM [55] enhanced granule stabilization via surface adhesion and water competition, resulting in increased thermal resistance. Conversely, lower enthalpy values in some systems indicate partial disruption of short-range molecular order, reflecting modifications in crystalline or amorphous domains.

Raungrusmee et al. [52] reported higher $T_p$ in XG-containing noodles compared to those formulated with inulin or defatted rice bran. The increase in $T_p$ reflects XG's strong water-binding capacity and high charge density, which reduces starch plasticization and requires greater thermal energy for crystalline disruption. Similarly, Zeng et al. [55] demonstrated that increasing DKGM content elevated $T_o$, $T_p$, and $T_e$ while decreasing ΔH. The temperature shift suggests that hydrogen bonding between DKGM and starch granules limits water penetration and stabilizes crystalline regions. Simultaneously, decreased enthalpy indicates partial reorganization of ordered structures due to competitive hydration or constrained molecular mobility. The decrease in glass transition temperature (Tg) further suggests increased chain mobility in the amorphous phase. Thus, these findings illustrate that hydrocolloids can simultaneously reinforce crystalline domains and modify amorphous regions, thereby influencing cooking stability and post-cooking texture.

In some systems, hydrocolloid incorporation does not significantly alter gelatinization transitions. Sutheeves et al. [37] reported that CMC, HPMC, GG, and XG did not significantly change the thermal properties of rice-based noodle dough. This suggests that, at the tested concentrations, these hydrocolloids primarily modified the phase viscosity without substantially disrupting crystalline regions within starch granules. Such findings highlight that not all hydrocolloids directly interfere with starch crystallites; some instead act post-gelatinization by reinforcing the surrounding matrix.

Similarly, Huang et al. [59] reported low total enthalpy ($\Delta H_t$) in XG-complexed rice noodles, suggesting low short-range molecular order. Lower enthalpy values imply fewer or less stable crystalline junction zones, resulting in softer textures or different retrogradation behavior. Dahal et al. [7] observed high enthalpy in hydrocolloid-containing noodles, indicating that starch–hydrocolloid associations restricted molecular mobility and required greater energy input for gelatinization. The differences across studies highlight that hydrocolloid thermal transitions are highly dependent on polymer structure, concentration, starch source, and water availability.

However, several drawbacks are revealed when considering cereal-based GF noodle systems. Most studies focus on single-cereal matrices, predominantly rice or corn, despite substantial differences in amylose content, granule structure, and endogenous protein composition across cereals such as millet, sorghum, or teff. Without a systematic cross-cereal comparison, it is impossible to generalize hydrocolloid-induced thermal shifts because the starch source controls hydration kinetics and crystal stability. Another drawback is the limited evaluation of hydrocolloid concentration and processing. Before DSC testing, molecular organization is changed by water content, mixing intensity, extrusion, steaming, and drying. Consequently, thermal transitions measured on isolated dough samples may not fully represent structural evolution under realistic industrial conditions. Therefore, integrating DSC within a multiscale structure–function framework requires systematic comparison across cereal matrices, inclusion of composite biopolymer systems, and arrangement of thermal characterization with processing pathways. This integration enables more accurate prediction of interaction hydrocolloid molecular properties on gelatinization behavior, microstructure formation, and ultimately the cooking and sensory quality in cereal-based GF noodles.

## Effect of hydrocolloids on the crystallinity of cereal-based noodles

XRD provides insight into the interaction of hydrocolloid molecular characteristics on starch crystallinity that relates to physical stability and retrogradation kinetics of GF cereal noodles. Kraithong et al. [46] reported that hydrocolloid incorporation did not alter the overall V-type diffraction pattern of extruded noodles, indicating that the amylose–lipid complexes formed by heat and shear were preserved. However, XG significantly reduced peak intensity and relative crystallinity, whereas GG and CMC had little effect. The reduction in crystallinity with XG likely reflects its rigid backbone, high charge density, and strong water-binding capacity, all of which interfere with amylose chain reassociation during cooling. This suppression of ordered recrystallization produces a less compact and less cohesive matrix, which helps to explain the reported degradation in texture. Therefore, XG molecular rigidity and electrostatic repulsion lead to reduced structural order and mechanical stability.

Huang et al. [59] reported that increasing XG content progressively reduced crystallinity and diminished V- and B-type structures. The suppression of ordered reassembly was due to intermolecular interactions and steric interference from XG, where highly charged and rigid hydrocolloids retard starch recrystallization and weaken long-range order. In contrast, Chantieng et al. [60] demonstrated that gelatin addition increased crystallinity (33.4%), producing sharper diffraction peaks and improved molecular alignment within the starch–protein matrix. The resulting protein network likely promoted closer chain packing and facilitated amylose reassociation, leading to improved structural strength and thermal stability. Conversely, the anionic and highly sulfated polysaccharide carrageenan decreased crystallinity (31.6%) and expanded diffraction peaks. This indicated a partial disruption of ordered domains and formation of a more flexible matrix. Agar exhibited only minor changes (30.8%) in crystallinity due to its weaker molecular interaction with starch. These findings demonstrated that hydrocolloid branching and charge characteristics significantly affect chain alignment, crystalline packing, and permeability, ultimately influencing both textural firmness and digestibility.

Zeng et al. [55] further showed that DKGM did not change crystal type (A-, B-, and V-type peaks remained) but significantly decreased relative crystallinity (9.68–14.46% versus 16.62% control). The decrease in crystallinity was attributed to steric hindrance and competitive hydration, as DKGM molecules surround starch chains and limit ordered reassembly during retrogradation. Such disruption reduces network rigidity and retrogradation tendency, which improves storage stability and yields a softer texture. Similarly, Song et al. [56] found that KGM alone or in combination with soy protein isolate (SPI) and transglutaminase (TGase) partially preserved A-, B-, and V-type structures. During cooling, starch chains re-associated via hydrogen bonding despite crystalline disruption caused by gelatinization. This highlights the dynamic interplay between hydrocolloid–starch interactions and post-processing recrystallization, emphasizing that cooling and molecular compatibility critically determine final microstructure.

Furthermore, during the frozen storage, GG addition produced the lowest relative crystallinity in the early stages [45]. This was likely due to GG forming hydrogen bonds with amylopectin side chains, which inhibited short-chain crystallization. This transformation in the sub-crystalline state suggests decreased retrogradation kinetics, which explains improved freeze–thaw stability observed in GG-containing systems.

Despite the widespread use of XRD to characterize crystalline transitions in cereal-based GF noodles, its contribution to understanding predictive structure–function relationships is still limited. Most studies report relative crystallinity without quantitatively linking these changes to critical macroscopic factors like CL, textural firmness, or sensory perception. Furthermore, the explanation of crystalline disruption or stabilization is limited by insufficient characterization of hydrocolloid molecular properties, such as molecular weight distribution, branching structure, and charge density. Future research should integrate XRD with complementary multi-scale techniques and mechanical validation to establish a quantitative correlation between hydrocolloid molecular properties, crystalline modulation, microstructural development, and final cooking and sensory quality.

## Technology readiness of GF cereal-based noodle in the presence of additives

To strengthen the practical relevance of research, the TRL classification for hydrocolloid-modified cereal-based GF noodles should be defined using explicit measurable criteria rather than qualitative judgment. Table 4 summarizes the readiness status of major hydrocolloid systems and processing strategies based on four measurable dimensions: (i) degree of scientific validation and mechanistic understanding, (ii) robustness under relevant processing conditions (e.g., extrusion, drying, freezing), (iii) reproducibility of cooking and textural performance, and (iv) commercial feasibility, including cost, regulatory approval, and scalability. Establishing these criteria enables clearer differentiation between laboratory innovation and industry-ready technology.

**Table 4** Utilisation processing technologies applied in GF noodles and associated functional and rheologies properties

| Type of based | Key additives | Processing technology | Cooking properties | Pasting properties | TRL* | References |
|---|---|---|---|---|---|---|
| Rice flour | SPI, Tgase, and GDL | Extrusion process | - | - | 7–8 | [61] |
| | - | Annealing<br>HMT | Control (rice flour)<br>CL: 0.75% | Control (rice flour)<br>PT: 76.38 °C<br>FV: 4216.56 cP<br>PV: 3038.04 cP<br>SB: 1920.96 cP<br>BD: 734.16 cP | 6–7 | [62] |
| | | | Untreated rice starch<br>CL: 0.44% | Untreated rice starch<br>PT: 82.45 °C<br>FV: 2973.48 cP<br>PV: 2618.04 cP<br>SB: 1011.96 cP<br>BD: 332.52 cP | | |
| | | | Annealed<br>CL: 0.76% | Annealed<br>PT: 83.75 °C<br>FV: 3466.56 cP<br>PV: 2511.96 cP<br>SB: 1428.96 cP<br>BD: 474.48 cP | | |
| | | | Heat-moisture treated<br>CL: 0.29% | Heat-moisture treated<br>PT: 84.48 °C<br>FV: 2829.00 cP<br>PV: 2511.96 cP<br>SB: 1428.96 cP<br>BD: 158.04 cP | | |
| | - | HMT | - | Control (rice flour)<br>PT: 80.80 °C<br>FV: 4973.16 cP<br>PV: 3806.04 cP<br>SB: 2147.88 cP<br>BD: 981.96 cP<br>TV: 2824.08 cP<br>HMTPT: 91.56 °C<br>FV: 1654.20 cP<br>PV: 1638.00 cP<br>SB: 230.16 cP<br>BD: 213.96 cP<br>TV: 1424.04 cP | 6–7 | [63] |
| Rice flour and pea starch | - | Extrusion process<br>-Type of screw: twin-screw<br>-D: 36 mm<br>-Speed: 100 r/min | Control (rice flour)<br>CL: 31.03%, WA: 33.37% | Control (rice flour)<br>PT:82.35 °C<br>FV: 3086 cP<br>PV: 2326 cP<br>SB: 1397 cP<br>BD: 636.5 cP<br>TV: 1689 cP | 7–8 | [18] |
| | | | Rice flour + 25% pea starch<br>CL: 14.12%, WA: 25.55% | 25% pea starch<br>PT:77.88 °C<br>FV: 2910 cP<br>PV: 2049 cP<br>SB: 1385 cP<br>BD: 524.5 cP<br>TV: 1525 cP | | |

**Table 4** (continued)

| Type of based | Key additives | Processing technology | Cooking properties | Pasting properties | TRL* | References |
|---|---|---|---|---|---|---|
| GRF | XG | Annealling<br>Speed: 510 rpm<br>T: 90 °C<br>t: 30 min<br>Powder to water ratio: 3:7 (% w/w) | Control (wheat)<br>WA: 61.6% | PV:4408 cp.<br>FV: 777 cp. | 6–7 | [44] |
| | | Sheeting process-NS: 6 mm wide | GRF<br>WA: 61.3% | | | |
| | | | Hydrothermally-treated GRF<br>WA: 66.6% | | | |
| | | | GRF hydrothermally-treated + 1% XG<br>WA : 66.9% | | | |
| | | | GRF hydrothermally-treated + 5% XG<br>WA: 68.4% | | | |
| Corn starch | - | Extrusion process | Corn starch<br>CL: 0.46% | Corn starch<br>PT: 78.76 °C<br>PV: 2341 cP<br>FV: 3151 cP<br>SB: 1656 cP<br>BD: 846 cP | 7–8 | [10] |
| Corn starch and buckwheat flour | - | 110% hot water (100 °C)<br>Sheeting process | 60% corn starch + 40% buckwheat flour<br>CL: 10.30% | - | 6–7 | [28] |
| | - | Fermentation process | - | Control (unfermented)<br>PT:77.1 °C<br>PV:1790 cP<br>FV:2110 cP<br>SB: 780 cP<br>BD: 460 cP | 4–5 | [64] |
| | | | | 19 days fermentation<br>PT:80.7 °C<br>PV:1720 cP<br>FV:1570 cP<br>SB: 170 cP<br>BD: 320 cP | | |
| | - | Extrusion process | Corn starch<br>CL: 12.6%, Yield: 55.1% | Corn starch<br>PT: 73.05 °C<br>PV: 4307 cP | 7–8 | [27] |
| Sorghum flour | - | Extrusion process<br>Pre-heating mixture treatment | Hammer + Roller<br>CL: 11.9%, WA: 205% | Hammer + Roller<br>PV: 9036 cP | 6–7 | [65] |
| | | | Roller<br>CL: 9.2%, WA:193% | Roller<br>PV: 9720 cP | | |
| Pearl millet | - | Extrusion<br>-T: 74 °C<br>- screw speed: 178 rpm | CL: 18.01% | - | 6–7 | [6] |

*TRL estimation based on industrial validation status and scalability

Note: *T* represents temperature; *t* represents time; *NS* represents noodle strand; *CL* represents cooking loss; *WA* represents water absorption; *Yield* represents cooking yield; *PT* represents pasting temperature; *PV* represents peak viscosity; *FV* represents final viscosity; *TV* represents through viscosity; *SB* represents setback viscosity; *BD* represents breakdown viscosity; *D* represents diameter; *HMT* represents heat-moisture treatment; *XG* represents xanthan gum; *LBG* represents locust bean gum; *GG* represents guar gum; *SPI* represents soy protein isolate; *GDL* represents glucono-δ-lactone

At lower readiness levels (TRL 1–3), hydrocolloid systems are primarily supported by bench-scale experimentation and mechanistic characterization using techniques such as DSC, XRD, and rheology. This includes novel combinations such as konjac glucomannan–starch complexes or multi-component matrices incorporating protein crosslinking enzymes. These systems demonstrate gelatinization behavior, crystallinity, or retrogradation; however, they often lack validation under continuous industrial extrusion, high shear, and large-batch variability. As a result, their performance remains restricted to proof-of-concept demonstrations.

At intermediate readiness levels (TRL 4–6), formulations containing established hydrocolloids such as XG, GG, CMC, or HPMC have been assessed beyond laboratory mixers and tested in pilot-scale extrusion or semi-industrial noodle-processing lines. Improvements in CL, firmness, and structural stability are reproducible under scaled conditions. However, cereal-based GF matrices often exhibit higher sensitivity to moisture variation and processing parameters than wheat-based systems. This requires further optimization to ensure tolerance to thermal gradients, screw speed fluctuations, and prolonged storage. Crucially, validating freeze–thaw stability and retrogradation control remains a critical step before wider commercialization. Table 4 shows that freeze–thaw stability, retrogradation kinetics, and shelf-life validation remain insufficiently addressed in many intermediate-TRL studies, representing a major bottleneck toward industrial transition.

High readiness levels (TRL 7–9) in cereal-based GF noodles are comparatively limited. Although technological feasibility has been established, formulation decisions are driven more by economic efficiency, ingredient availability, labeling requirements, and regulatory compliance. Table 4 highlights that only a relatively small number of established ingredients, particularly XG, GG, CMC, and HPMC, currently exhibit sufficient industrial maturity due to their regulatory approval, commercial availability, relatively predictable rheological behavior, and compatibility with existing noodle-processing infrastructure. In contrast, specialty polysaccharides, despite promising laboratory performance, rarely reach this stage due to high ingredient cost, supply constraints, or limited large-scale validation. Translation of cereal-based GF hydrocolloid systems to higher TRLs requires overcoming several scale-up barriers. Hydrocolloids that exhibit favorable structural effects at bench scale may undergo molecular degradation, incomplete hydration, or changed rheological behavior under industrial shear and thermal pressures. Furthermore, long-term storage stability, retrogradation kinetics, and textural change during distribution remain insufficiently validated in many studies. Regulatory frameworks and growing demand for "clean label" formulations may also restrict the application of certain modified gums.

A critical barrier to transforming from laboratory (TRL 4–6) to industrial scale (TRL 7–9) is the techno-economic viability. For instance, the high cost of Konjac flour, which offers very low CL (0.06%) [49] can prohibit commercial application. Alternatively, the low cost hydrocolloid must be balanced against consumer preference, due to growing demand for "clean label" from chemical modified or synthetic hydrocolloid. Robust techno-economic feasibility analysis, including cost and supply consistency, is essential to allign the best for GF cereal-based formulation with regulatory compliance.

Overall, the integration of the TRL framework and the comparative analysis presented in Table 4 demonstrated that hydrocolloid research in cereal-based GF noodles has achieved substantial mechanistic and formulation-level progress; however, commercial maturity remains limited to a relatively small number of established ingredients and processing systems. Advancing the systems from conceptual innovation to scalable deployment requires the integration of molecular-level structure–function understanding, pilot-scale validation, techno-economic assessment, and regulatory evaluation. Such efforts are essential to bridge the gap between laboratory and commercially feasible cereal-based GF noodle technologies.

## Textural quality of GF cereal-based noodle

The evaluation of sensory qualities is fundamental to the successful development of consumer-acceptable GF noodles. Parameters such as CL and WA provide indirect indicators of structural integrity, and sensory perception reflects the underlying microstructure formed during hydration and gelatinization. High-quality GF noodles are characterized by smooth, continuous strands and minimal surface stickiness [50]. Excessive CL correlates with surface roughness, strand breakage, and pasty mouthfeel and is often associated with consumer rejection. Similarly, WA must remain within an optimal range; too little hydration produces a hard core and poor chewability, whereas too much water uptake results in swelling-induced softening and loss of elasticity. Therefore, instrumental measurements are only relevant when explained in relation to sensory rejection or acceptance thresholds.

The changes from structure to perception are mediated by the hydrocolloid molecular architecture. XG is a highly charged and rigid polysaccharide that improves continuous-phase viscosity and forms hydrated matrices that entrap swollen starch granules. This viscous stabilization reduces amylose leaching and supports elastic deformation during mastication. Raungrusmee et al. [12] demonstrated that rice starch noodles containing 2.5% XG achieved sensory scores comparable to wheat noodles, correlating with low CL (2.2–2.7%) and controlled WA (≈62–80.8%). The improved mouthfeel can be attributed to the formation of a cohesive hydrocolloid–starch network that limits structural collapse during cooking. However, excessive XG (e.g., 5%) in hydrothermally treated glutinous rice flour resulted in lower panel rankings [44] likely due to over-viscosification and excessive water immobilization, which may produce dense or gummy textures. The concentration-dependent effect illustrates that viscosity stabilization reduces CL, while excessive network rigidity compromises chewiness and mouthfeel.

Comparative studies further emphasize the impact of molecular features on texture perception. Sutheeves et al. [37] reported that HPMC and GG improved overall acceptability in rice–mung bean starch noodles, while CMC and XG produced comparatively softer structures. HPMC is a non-ionic cellulose derivative capable of thermogelation; upon heating, hydrophobic associations form a transient three-dimensional network that stabilizes starch granules during cooking. This thermally induced gel network enhances elasticity and resilience, contributing to desirable chewiness. In contrast, even though CL values are acceptable, excessive hydrogen bonding from CMC at higher concentrations may generate extremely rigid networks that result in brittle textures. GG, with its flexible galactomannan chains and high hydration capacity, promotes smoothness and moderate elasticity via chain entanglement and uniform water retention.

Additionally, hydrocolloids also affect optical and surface characteristics, which in turn affect sensory perception. Uniform pore distribution and decreased starch exudation contribute to smoother strand surfaces and improved brightness. Lubowa et al. [50] reported that incorporating 1% Ca-ALG with high-amylose maize starch improved noodle brightness and structural integrity. Similarly, high amylose content in red jasmine rice flour enhanced firmness and visual appeal through strong gel formation and controlled reassociation during cooling [46]. These findings indicate that long-range molecular ordering and controlled water mobility not only influence mechanical stability but also shape and visual sensory.

In addition to hydrocolloids, cereal–legume blends and protein-based systems further illustrate structure–function relationships. Lavanya et al. [66] demonstrated that a teff–sorghum–soybean blend (50:30:20) achieved high overall acceptability due to complementary protein–starch interactions that enhanced flavor and structural cohesion. Similarly, Levent [67] found that the addition of chia seed flour (CSF) improved taste scores for cooked GF noodles, while Chen et al. [26] reported that incorporating 20% finger millet improved smoothness and resilience, likely linked to fiber-mediated water redistribution and strengthened matrix density. Ojukwu et al. [61] optimized SPI, TGase, and glucono-δ-lactone (GDL) to produce noodles with compact microstructures and high sensory scores. Chewiness and structural integrity were improved by the reinforced network formed by TGase's covalent cross-linking of proteins, which made up for the absence of gluten. Meanwhile, Cao et al. [68] reported that whole-grain rice noodles supplemented with SPI satisfied consumer expectations for quality and sensory appeal.

The findings demonstrate that the textural quality and sensory acceptance of GF cereal-based noodles are closely governed by the interaction between hydrocolloids, flour composition, and water dynamics. Hydrocolloids effectively bridge the gap between structure and perception: by lowering CL and optimizing WA, they create uniform, elastic, and cohesive noodles that meet consumer expectations. Notably, the relationship between instrumental measurements and sensory perception is non-linear. Moderate increases in firmness often enhance chewiness and elasticity, whereas excessive firmness leads to hardness and reduced palatability. Very low CL may improve structural clarity, but may also result in dense textures if water mobility is excessively limited. Predictive models on cereal-based GF systems that link hydrocolloid molecular characteristics to optimal instrumental ranges and sensory acceptance thresholds are still underdeveloped.

In summary, most hydrocolloid-enhanced GF noodle formulations remain at an intermediate TRL (4–6). Industrial translation (TRL 7–9) requires integration of formulation, rheological modeling, process engineering (mixing, extrusion, drying), and sensory optimization.

## Colour characteristic of the GF cereal-based noodle

Colour and visual appearance are critical determinants for consumer acceptance of GF noodles. Colour represents the first sensory cue perceived by the consumer [69]. Instrumental colour analysis is commonly conducted using the CIELAB system, where L* represents lightness (0 = black, 100 = white), a* indicates the red–green axis (positive = red, negative = green), and b* reflects the yellow–blue axis (positive = yellow, negative = blue). These parameters provide a quantitative measure of the visual and product uniformity, closely linked to composition, hydration balance, and cooking behavior.

The colour and visual of GF noodles are significantly influenced by the choice of flour and additives. Incorporating CSF into rice-corn noodles has been observed to decrease L* and b* while increasing a*, potentially affecting consumer acceptance [67]. To counteract such colour changes, the addition of natural antioxidants like sweet potato flour, known for its high phenolic content, is recommended to minimize Maillard reaction-induced browning [70]. Similarly, sorghum flour, rich in tannins, imparts a brown colour to noodles, increases the b* value and yellowness, especially at higher concentrations [71]. On the other hand, moringa leaf flour, which is abundant in chlorophyll, introduced a greenish-brown tint, while cassava flour contributes to increasing brightness (high L* values), improving the overall visual appeal of the noodles [71].

Amylose content and starch type also affect noodle colour by influencing WA and the extent of browning during thermal processing. Substituting rice flour with high-amylose maize starch resulted in lighter-coloured noodles, characterized by high L* and low a* and b* values due to low content in proteins and lipids that participated in browning reactions during cooking [25]. Conversely, the addition of pigmented flours like red jasmine rice flour decreased brightness and increased redness and yellowness due to natural pigments such as proanthocyanidins [46]. Similarly, unripe glutinous rice flour (UGRF) reduced lightness and increased greenness and yellowness, which was influenced by its chlorophyll content [4]. Contrarily, the addition of egg powder enhanced the b* and reduced -a* values, yielding a more appealing yellow hue in fresh and cooked GF noodles [72]. Formulations combining egg, corn flour, and millet flour have demonstrated high b* values, improved yellowness [7].

Hydrocolloids also exert notable effects on noodle colour through their influence on hydration, film formation, and surface gloss. For example, fermented rice noodles supplemented with XG, CMC, and GG exhibited improved L* values (greater brightness) and moderate shifts toward greenness and yellowness, indicating smooth surface formation and controlled browning [47]. A high level of konjac flour decreased L* and revealed a darker colour to the noodles [73]. Even so, varying concentrations of hydrocolloids do not significantly affect the appearance. For instance, shifting XG concentrations to 2.5% does not significantly alter the L*, a*, or b* values [12]. These suggest that the colour impact may depend on the specific noodle composition and formulation.

Dissanayake and Jayawardena [74] found that noodles made from 100% finger millet received superior colour acceptability compared to partially blended flour. Accordingly, the formulations can achieve consumer acceptance when structural stability is maintained with adequate hydration control. Meanwhile, corn starch–based formulations exhibited appearance profiles comparable to commercial wheat noodles, suggesting that pure starch systems can deliver acceptable visual quality [27].

In summary, the colour characteristics of GF noodles (L*, a*, and b* values) are influenced by a complex interplay of flour type, hydrocolloid type, concentration, and hydration dynamics. Strategic optimization of the parameters enables the production of GF noodles with visual and sensory qualities comparable to traditional wheat noodles, marking an important step toward technological maturity and consumer-ready product development.

## Processing techniques

Processing technologies play a significant role in the structural framework of GF noodles by modifying starch–protein interactions in the absence of gluten. Key technological approaches include heat–moisture treatment (HMT) [62], extrusion cooking [18], aging and annealing [75], and fermentation [64]. These techniques induce physicochemical transformations in cereal matrices, altering crystalline order and macromolecular interactions to achieve targeted functionality.

HMT and annealing enhance starch crystalline stability and reduce excessive swelling, leading to improved thermal tolerance and paste stability. These technologies are positioned at TRL 6–7 due to pilot validation and emerging industrial adoption. Industrial scalability extrusion cooking, which combines thermal and mechanical energy to induce starch gelatinization and protein denaturation, has reached TRL 7–8. Aging treatments remain at TRL 5–6, while controlled fermentation strategies for minor cereals are classified at TRL 4–5, due to scale-up challenges.

To prevent excessive depolymerization or structural weakness, these technologies must be optimized over the moisture, temperature, and shear conditions. Pasting parameters serve as critical structure–function indicators, which pasting temperature (PT) reflects thermal stability, peak viscosity (PV) indicates swelling capacity, trough viscosity (TV) captures shear stability, breakdown viscosity (BD) measures resistance to thermomechanical disruption, setback viscosity (SB) reflects retrogradation tendency, and final viscosity (FV) represents gel consolidation during cooling [76].

Progression from TRL 4–6 to TRL 7–9 depends on establishing strong correlations between rheological and product performance, such as CL, water absorption, and textural resilience. Table 4 systematically classifies major GF noodle processing technologies according to their current TRL status, providing a framework for benchmark technological maturity and commercialization readiness.

### Hydrothermal

HMT and annealing are examples of hydrothermal treatments. Annealing involves exposing starch to excessive (~70%, v/v) or moderate (~40%, v/v) water content at temperatures above the glass transition point but below the gelatinization temperature of starch. This process can vary from minutes to days [77]. HMT is a popular hydrothermal modification technique that physically alters starch properties by controlling moisture level (<35% w/w) and temperature (84–120 °C) for a specific period (15 min to 16 h) to achieve the desired starch quality [78]. The effectiveness of the treatment depends on various process parameters, including moisture content, temperature, and heating time, and the starch characteristics, such as botanical source, structure, and the amylose/amylopectin ratio and organization [79].

After HMT, starch could exhibit modifications in its physical and chemical properties, including a reduction in amylose leaching, improved pasting properties, and improved heat stability [27]. For example, HMT increased the PT of rice starch, and the highest PT recorded was at 84 °C. The high pasting point was due to the increase in inter- and intra-molecular hydrogen bonding of starch chains, mainly amylose. This is supported by Lorlowhakarn & Naivikul [63], who reported a similar trend; PT of rice flour increased from 80.80 °C to 91.56 °C after HMT. Nonetheless, Hormdok & Noomhorm [62] and Lorlowhakarn & Naivikul [63] reported that the PV, SB, and BD of HMT were less than those of the control (rice flour without treatment). This suggests that the HMT modified the granules into a more robust form that was resistant to swelling, heat, and shear. Excellent shear resistance was shown by minimal BD, which made HMT-treated starch suitable for noodles.

The improved starch thermal stability has made HMT a process preferred by the food industry. HMT-modified starch provides an economical and time-saving method to improve rice noodle quality and serves as an alternative to the long-term storage method [62]. The hydrothermal treatment decreases the swelling power and increases the gelatinization temperature, crystallinity, starch granular size, and thermal stability [44]. Note that hydrothermal treatment may cause the loss of integrity in the starch granules, thus reducing the flour's water-holding capacity. This reduction significantly contributes to the low PV (decreased from 5185 cP in the untreated glutinous rice flour to 4408 cP). The breakdown of the granule structure hinders the ability of starch to retain water, which impacts its swelling power and viscosity. Besides, the internal rearrangement of starch granules caused by hydrothermal treatment leads to more interactions of starch functional groups, promoting the formation of double helical amylopectin side chain clusters. This structural reorganization further reduces swelling power and affects the pasting properties of the flour. In addition, the treated flour consisted of swollen granules and leached amylose and amylopectin, causing the structure to be less compact and rigid. As a result, these flours were more susceptible to water hydration, leading to higher WA. For instance, the non-treated glutinous rice flour had less WA (61.3%) than the hydrothermally-treated glutinous rice flour (WA = 66.6%).

### Extrusion

Extrusion technology is among the most advanced and industrially scalable strategies for structuring GF noodle systems. Unlike hydrothermal treatments, extrusion integrates heat, shear, and pressure within a short time, inducing simultaneous starch gelatinization, molecular depolymerization, and protein denaturation. This thermomechanical processing restructures the starch–protein matrix, promoting macromolecular entanglement and compensating for the absence of gluten through the formation of a cohesive network.

From a structure–function standpoint, extrusion profoundly modifies hydration behavior, viscosity development, and textural resilience. Pre-gelatinization and shear-induced reorganization typically reduce PV and BD, indicating enhanced resistance to thermal and mechanical stress. Optimized extrusion conditions can significantly reduce CL by strengthening starch–protein interactions and limiting leaching during boiling. For instance, corn noodles produced via extrusion exhibited low CL (0.46%) [10] compared with those produced by sheeting (10.30%) [28], suggesting superior matrix consolidation. However, most comparative studies remain descriptive, with limited mechanistic linkage between extrusion parameters (e.g., screw configuration, shear rate, and moisture content) and molecular-level transformations governing product performance.

Despite its industrial maturity (TRL 7–8), extrusion faces challenges related to raw material variability, particularly in cereals with heterogeneous starch structure and protein composition. Next, over-processing may lead to excessive depolymerization and affect viscosity, while under-processing results in weak structural integration. Thus, future advancements should prioritize multi-scale structural characterization, real-time process monitoring, and rheological modeling to establish quantitative structure–process–function relationships, thereby improving reproducibility and accelerating technological innovation in GF noodle manufacturing.

#### Aging

Aging or long-term storage causes a dynamic structural transformation within the retrograded starch gel system [80]. The changes affect both the crystalline and amorphous regions, facilitating the association of starch chains within the amorphous matrices in the noodles' structure, hence reducing CL [75]. The aging treatment caused the starch chains to stabilize, which was facilitated by structural alterations in both the crystalline and amorphous regions. This aligns with Chen et al. [80], who observed structural transformations occurring within retrograded starch gel systems during aging treatment. As a result, the hydration capacity of the starch in the noodles was enhanced.

Although aging treatment effectively minimizes CL, it is time-consuming due to the extended storage periods under controlled conditions. This may pose challenges in fast-paced industrial settings where rapid product turnover is essential.

#### Fermentation

Fermentation is used to improve the physicochemical properties and granular structure of alternative flours or starches [64, 81]. There are two types of fermentation commonly used, which are lactic acid fermentation and spontaneous or natural fermentation. Lactic acid fermentation changed the granular structure and the pasting properties of rice starch [81]. The process modified the amorphous region and the chemical properties of the starch granule, hence altering the physical properties of flour or starch.

Yuan et al. [64] investigated the effect of the spontaneous fermentation process on the physical properties of corn starch noodles. The process involved adding tap water to the corn granules (1:3, w/v) and allowing them to ferment naturally at room temperature (26–30 °C) for 21 days. The process reduced the PV, FV, BD, and SB, besides improving the sensory quality. Although the sensory quality of noodles improved significantly after 19 days, the lengthy fermentation time poses challenges for industrial applications. Thus, the use of microbial starters or additives could accelerate fermentation while maintaining the quality.

## Future research direction

This review underscores the progress made in formulating high-quality GF noodles. Several research gaps need to be addressed, including a deeper understanding of the molecular interactions between GF formulations and clinical studies. Bridging these gaps will be crucial for advancing the development of high-quality GF products.

### Integration of novel grains and flour sources

The application of additives in GF noodle production has significantly contributed to advancements in product formulation and consumer satisfaction. The functional performance of the additives is largely determined by the interactions with cereal-based flour components, which influence the structural, sensory, and textural characteristics of the final product. Therefore, a comprehensive understanding of the interactions is essential for product standardization. The integration of novel and underutilized cereals like teff, sorghum, canary seeds, teosinte, fonio, and wild rice in the GF noodle may offer nutritional and structural advantages, such as high protein, fiber, and minerals [82–84].

Cereals with high amylose content typically reduce CL due to the denser starch networks that resist leaching. Low-amylose flours increase WA and yield soft textures. Appropriate blending of flours with hydrocolloids stabilises CL and WA, producing good quality noodles. Hydrocolloid–flour compatibility is critical; differences in protein solubility, lipid content, and fiber composition affect hydration and gelation. Additionally, flour modification techniques (such as germination, fermentation, and enzymatic hydrolysis) affect the water-holding capacity, consequently affecting the noodle characteristics and cooking quality. Thus, interdisciplinary research across food science, material engineering, and nutrition will be key to improving GF noodle quality and achieving broader market acceptance.

### Functional additives

The integration of functional additives such as proteins, enzymes, and emulsifiers presents promising strategies to improve textural properties, minimize CL, regulate WA, and simulate gluten-like structures in GF noodles. Although these components have demonstrated potential in reducing CL and enhancing structural integrity, research exploring their full functionality and application in GF cereal-based noodles remains limited (Table 5).

#### Proteins

The role of non-gluten proteins such as egg, whey protein, SPI, and zein improves gel formation, elasticity, and water-holding capacity. Egg protein is a cost-effective ingredient that is rich in essential amino acids, exhibits high digestibility [87], and facilitates water-holding capacity and gel strength in food [88]. Eggs come in two types, which are liquid and dry. Nevertheless, liquid eggs are preferred as they enhance the ultimate product's quality, although their microbiological quality needs to be monitored [89]. The ability of egg albumen to create a network with the desired

**Table 5** Cooking qualities of GF cereal-based noodles in the presence of proteins, enzymes, and emulsifiers

| Type of based | Type of additives | Cooking properties | References |
|---|---|---|---|
| Rice flour | SPI, Tgase, and GDL | - | [61] |
| Brown rice | SPI | Brown rice<br>CL: 3.83%, WA:15.99%<br>Brown rice + 9% w/w SPI<br>CL: 2.11%, WA: 34.17% | [68] |
| Rice flour | Zein | 11.9% amylose content<br>CL: 12%, WA: 73.70%<br>18.6% amylose content<br>CL: 9%, WA: 69.20%<br>25.8% amylose content<br>CL: 3%, WA: 68.55% | [19] |
| Rice flour | Zein | CL: 6.10% | [16] |
| Rice flour | Zein | CL: 1% | [85] |
| Rice flour and CSF | DATEM | Control (rice flour: corn starch)<br>CL: 6.8%, Yield: 151.1%<br>30% CSF<br>CL:6.5%, Yield: 154.4%<br>30% CSF + 0.8% DATEM<br>CL: 5.9%, Yield: 156.5% | [67] |
| Corn flour | DIMODAN® | CL: 10.50% | [86] |

Note: *CL* represents cooking loss; *WA* represents water absorption; *Yield* represents cooking yield; *SPI* represents soy protein isolate; *GDL* represents glucono-δ-lactone; *CSF* represents chia seed flour; *DATEM* represents diacetyl tartaric acid esters of mono (and di) glycerides

consistency is well-known [70]. Besides, it has several advantages, such as the ability to make a cost-effective dough, rich in essential amino acids, and highly digestible [87]. Note that egg albumen contains lecithin, which is an effective emulsifier. Lecithin promotes a lower surface tension between water and emulsified fat, including fatty acid, phosphoric acid, glycerol, choline, triglyceride, glycolipid, and phospholipid [90]. Additionally, the gelling ability and heat-induced coagulation of egg proteins play a crucial role in determining the rheological and textural properties of food products [88]. The viscous fluid produced by the egg proteins in GF dough has a function comparable to the network protein found in gluten [91].

Similarly, SPI enhances cross-linking and facilitates starch gelatinization through hydration and expansion, contributing to firmer noodle structures [68]. Zein exhibits gluten-like viscoelasticity, forming cohesive networks that strengthen dough structure [92]. Studies have shown that zein–rice starch dough mimics the rheological behavior of wheat dough [93], with β-sheet structures improving noodle structure [94]. Zein networks formed with acetic acid support the weak structure of rice-based GF dough [85], besides improving texture, particle size, and microstructural density post-cooking [95].

Despite these benefits, the functionality of proteins in GF cereal-based noodle formulations remains underexplored. Future studies should focus on protein modification, starch–protein interaction, and optimizing protein–hydrocolloid compatibility to achieve high-quality noodles.

## Enzymes

Enzymes enhance the GF noodle's rheological characteristics, handling properties, and shelf life. Tgase is one of the commonly used enzymes in GF noodles and has been effectively utilized to modify protein functionality and enhance cross-linking. TGase is a natural enzyme derived from a microorganism known as microbial transglutaminase (MTGase), non-toxic and non-pathogenic [96]. TGase can be derived from *Actinomadura* sp, *Bacillus* sp, *Streptoverticillium* sp, *Providencia* sp, *Streptomyces* sp, *Enterobacter* sp., and *Corynebacterium* sp [96]. TGase can change its protein function, encourage protein cross-linking, enhance dough rheology, and lengthen the product's shelf life [2]. TGase forms the cross-linking by forming covalent bonds between glutamine and lysine residues. Despite the advantages, TGase has many undeniable drawbacks that limit its application. The cost and concerns over the safety of genetically modified strains are difficult to define. Therefore, it is difficult to meet the application at the industrial level. Pyranose 2-oxidase (POx) is another type of enzyme that promotes gelation in GF products by facilitating inter- and intramolecular crosslinking between proteins in the flour [97]. POx promotes the formation of S–S bonds between thiol groups in proteins, the cross-linking of arabinoxylans (components of cereal cell walls), and the cross-linking between proteins and arabinoxylans [98].

Glucose oxidase (GOx) is an enzyme which widely used in the food industry to extend the shelf life of products [99]. GOx catalyzes the oxidation of β-D-glucose into D-glucono-δ-lactone and hydrogen peroxide ($H_2O_2$) in the presence of oxygen [100]. The $H_2O_2$ further oxidizes sulfhydryl groups in proteins, facilitating protein cross-linking through the formation of disulfide bonds [101]. According to Aprodu and Banu [102], GOx enhanced dough consistency when psyllium and pea fiber were added to corn flour. The proteins in corn flour, which contain a high free sulfhydryl groups, facilitate protein aggregation through disulfide bond formation under the action of GOx.

Despite their functions, the application of enzymes in GF cereal-based noodle formulations remains underexplored, especially on the synergistic effects of enzymes and other additives.

## Emulsifiers

Emulsifiers are amphiphilic compounds widely applied in noodle formulations to improve dough handling and cooking performance [103]. The emulsifiers include diacetyl tartaric acid esters of mono- and diglycerides (DATEM), distilled monoglycerides (DMGs), polysorbate 40 (P40), and commercial blends such as DIMODAN® [86, 103]. Among these, P40 and DATEM are primarily used to strengthen dough networks, while DMGs are valued for their softening effect [103]. Zia-ud-Din et al. [103] demonstrated that DATEM more effectively reduced CL in fresh potato noodles than DMGs and P40, suggesting its superiority for this application. Levent [67] demonstrated that incorporating 30% chia seed flour (CSF) and 0.8% DATEM into rice–corn noodles reduced CL from 6.6% to 5.9% and increased yield, attributed to CSF's water-binding capacity and DATEM's emulsifying action.

In a different approach, Qi et al. [104] examined the effects of adding 0.2% (v/v) emulsifiers such as soybean lecithin, Tween-80, and Span-80 to frying oil used for instant noodles. Although these surfactants lowered the interfacial tension between oil and noodle surface, their addition unexpectedly increased oil uptake during frying.

Regardless of the recognized benefits of emulsifiers in enhancing the quality of GF noodles, research on their application across diverse GF cereal-based formulations remains limited (Table 5). A comprehensive investigation encompassing GF cereals and emulsifier types is necessary, aiming to improve texture, cooking quality, and overall consumer acceptance.

### Clinical studies

Some studies have suggested the safety of GF products for celiac patients [105]. However, the lack of diagnostic facilities and in vivo research highlights the necessity for well-designed clinical studies in the population. Therefore, cooperation between the healthcare sector, the food industry, and researchers is essential to facilitate the innovations into clinically validated and commercially viable production. Such collaboration can provide valuable insights into the long-term safety, nutritional adequacy, and functional suitability of GF noodles for individuals with CD and other gluten-related disorders, besides promoting evidence-based dietary solutions.

## Conclusions

Cereal grains such as rice, corn, sorghum, and millet provide the structural foundation for GF noodles, yet their lack of gluten necessitates targeted functional design to achieve acceptable cooking and sensory quality. This review emphasizes that product performance depends on the mechanistic interplay between starch molecular architecture, hydrocolloid characteristics (e.g., charge, branching, hydration behavior), and processing conditions. Through competitive hydration, interpolymer interactions, and modulation of chain mobility, hydrocolloids facilitate cohesive network formation that reduces CL, regulates WA, and enhances firmness and elasticity. Instrumental parameters, including CL, thermal transitions, and crystallinity, must be interpreted in relation to sensory acceptance, as consumer perception reflects the microstructure established during gelatinization and retrogradation. The relationship between structural reinforcement and palatability is non-linear, underscoring the need for predictive structure–function–sensory models. Although advances in multi-scale characterization (e.g., DSC, XRD, rheology, SEM) have improved mechanistic understanding, integrated frameworks linking molecular design to consumer perception remain underdeveloped in cereal-based GF systems. In addition, the colour and surface characteristics of GF noodles are influenced by the natural pigments and Maillard-active compounds present in the base flours, while the inclusion of hydrocolloids and natural antioxidants helps regulate browning and maintain desirable L*, a*, and b* colour values. Most hydrocolloid-enhanced formulations remain at laboratory or pilot readiness levels. Achieving commercial maturity requires validation under industrial processing, storage stability assessment, techno-economic feasibility analysis, and regulatory alignment. Future progress will depend on interdisciplinary collaboration to translate molecular insights into scalable, nutritionally meaningful, and consumer-accepted GF cereal-based noodle products.

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## Declarations

**Competing interests** 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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