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Use of non-conventional raw materials in the production of gluten-free pasta – a review

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ABSTRACT

Currently, about 5% of the earth's population suffers from gluten-related disorders. Modern technologies for gluten-free diets and filling the protein deficit are aimed at manufacturing gluten-free (GF) pasta products using non-conventional plant raw materials with high biological value. GF grains and crops (rice, corn, buckwheat, amaranth, quinoa, etc.) are used to produce GF pasta products. However, there is a scarcity of studies that comprehensively understand GF flour addition on the nutritive, sensory and cooking properties. Therefore, the scope of this literature review covers the main types of non-conventional raw materials for GF pasta products and summarizes the research on pasta products made from them. Results indicate that the rheological and sensory attributes of pasta made from pure GF flours such as rice or corn still requires a deeper study of technological processes in producing GF pasta. Incorporating nutrient-dense ingredients such as amaranth, quinoa, sorghum, and chia flours not only enhances the nutritional profile of gluten-free pasta but also offers opportunities for diverse culinary applications. The improvement of sensory attributes in rice-, corn-, buckwheat-based pasta, coupled with the effective use of cooking enhancers like xanthan gum, transglutaminases, inulin, and alternative starches, paves the way for creating more palatable gluten-free options. As techniques such as high-temperature treatment, extrusion cooking, and starch pregelatinization become more refined, future developments may focus on optimizing these processes to further improve the texture, taste, and overall quality of gluten-free pasta. Continued research and innovation in ingredient selection and processing technologies will be crucial for meeting the growing demand for gluten-free products that do not compromise on culinary experience or nutritional value.

Keywords: gluten-free pasta; review; celiac disease; gluten-free flour

INTRODUCTION

Gluten is a protein found in wheat, rye, barley and other grains **[1]**. Most cereal grains are traditionally divided into glutenins, structural and biologically active proteins, and prolamins. Prolamines are mainly found in grains and flours as relatively simple and small molecules, while glutenins are rich in disulfide bonds and have significant molecular weight **[2]**.

Currently, about 5% of the earth's population suffers from gluten-related disorders **[3]**. In recent years, a new pathology, also associated with gluten intake but characterised by specific, different features from celiac disease, has attracted particular attention from researchers. Currently, it is called "gluten sensitivity" (GS) **[4]** or "non-celiac gluten intolerance" (NCGI) to be more reasonable **[5]**. Gluten intolerance, as well as celiac disease, is associated with eating foods containing gluten. The gluten-free diet should be followed by people suffering from hereditary metabolic disorders such as celiac disease, as well as in the case of individual intolerance to cereal protein. The consumption of gluten-containing foods manifests itself in these people by inflammation of the intestinal mucosa **[6]**. Also, scientific research has shown that if one adheres to a gluten-free diet, it benefits the body (helping to lose weight) and reduces the progression of chronic diseases **[7]**.

Pasta is one of the most popular food products of the population and is included in the list of everyday goods **[8]**. Modern technologies for gluten-free diet and filling the protein deficit are aimed at manufacturing gluten-free (GF) pasta products using non-conventional plant raw materials with high biological value **[9]**. Cereal and legume-based products still dominate the world's population's diet as the main vegetable protein supplier. GF grains and crops (rice, amaranth, buckwheat, quinoa, etc.) produce many commonly used products, including bread, pasta, snacks. They remain the most accessible to all categories of consumers due to their high nutritional value **[10]**. However, GF products are less likely to be found in some countries **[11]**.

Recently, many findings have been investigated to enhance organoleptic qualities and nutritional and practicality profiles to meet the prospering demand for high-quality gluten-free pasta products. However, when GF raw materials are used for pasta production, the GF pasta properties might also vary. There needs to be more studies that comprehensively understand GF flour addition on the nutritive, sensory and cooking properties. Therefore, the aim of this literature review covers the main types of non-traditional raw materials for pasta products and summarises the research on pasta products made from them.

Literature search and description of studies

A systematic scientific literature search about gluten-free pasta was performed to identify English papers using Web of Science database. The search was performed on the 16th of April, 2024. In addition, manual screening was performed to find other papers on GF pasta products using other sources (PubMed, Google Scholar). Figure 1 demonstrates the number of papers published between 2000-2023 on "gluten-free pasta" according to Web of Science database. A total of 628 research and review articles in English were found, with 74 articles published in 2019.

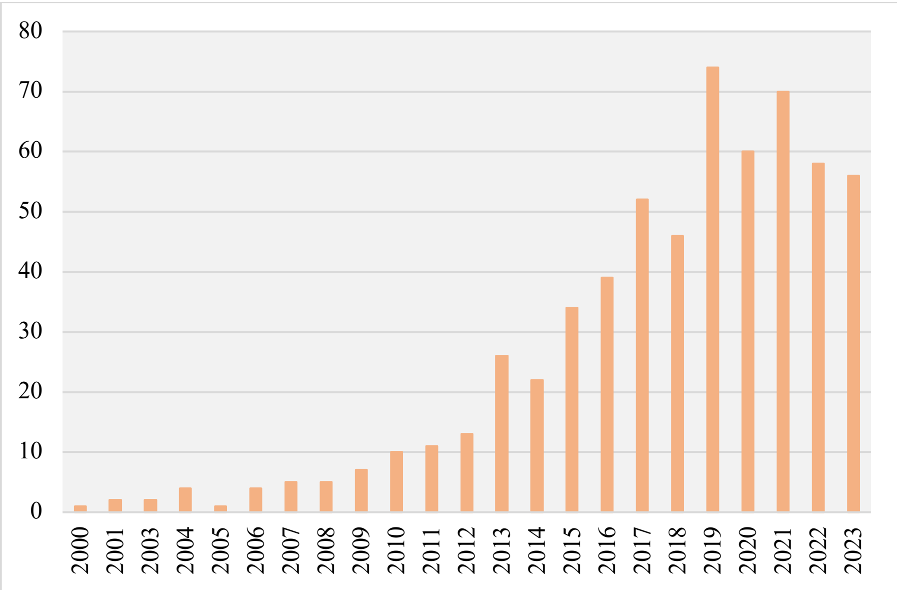

Figure 1 Number of papers published between 2000 and 2023 on the topic "gluten-free pasta", according to the Web of Science database.

TECHNOLOGICAL OPPORTUNITIES TO DEVELOP GLUTEN-FREE PASTA

Additives in GF pasta production

A gluten-free alternative will undoubtedly help in solving the problem of improving public health. When switching to a gluten-free diet, it is necessary to ensure the availability of all essential nutrients in sufficient quantities. Thus, an improvement in the nutritional or functional characteristics of the gluten-free paste is achieved by mixing different types of GF flours. Gluten gives wheat-based products their characteristic texture, integrity and other properties. Gluten serves such an important function, but unfortunately, its consumption can cause serious medical complications, such as celiac disease in a certain percentage of the population **[12]**. Most GF pasta products on the market exhibit poor cooking and sensory qualities compared to wheat flour-based pasta. The use of GF raw materials implies some changes in the production technology of gluten-free pasta **[13]**. The critical rheological properties of the paste are hardness, elasticity and stickiness, which may be affected by the lack of gluten.

Nowadays, hydrocolloids, starch and various proteins are used to improve the quality of GF pasta as potential gluten substitutes. The hydrocolloids can be thickeners, gel-formers, stabilisers and, in some cases, emulsifiers. Using hydrocolloids to produce GF pasta products allows significant progress in the functional and technical properties of finished products. Published studies of hydrocolloids have shown that their type considerably affects the characteristics of fresh and cooked noodles. At the same time, the degree of their influence depends on the level of hydration used in pasta making. For example, 0.5% xanthan gum in GF tiger nut noodles and adjusting the amount of water showed low cooking losses and high elasticity **[14]**. The hydrocolloids, including xanthan gum (XG), guar gum (GG), and sodium alginate (SA) were found to enhance the elasticity and viscosity of the pasta from the GF proso-millet pasta, with 2% XG showing the highest elasticity **[15]**. Another study showed that the best overall quality, lower glycemic index, and increased water-insoluble fibre content was achieved when 2% carboxymethyl cellulose or chitosan was added to pasta based on corn and oat flour **[16]**. Furthermore, the mixture of amaranth flour with guar gum (1%) exhibited paramount peak viscosity and minimum cooking loss **[17]**. Xanthan gum concentration of 0.6% with cassava starch GF pasta reduced cooking losses and showed the lowest elasticity, cohesiveness, etc. **[18]**. Synergism of hydrocolloids 1% glycerol monostearate and 2% xanthan gum improved the texture, cooking properties and flavour of gluten-free brown rice pasta **[19]**. In addition, using 0.1% propylene glycol alginate and 0.5% fatty acid monoglycerides and gelatinisation of mixed flours resulted in GF pasta with the best cooking quality and texture **[20]**. Interestingly, alternative hydrocolloids such as gledis gum and bream gum used in chakpea pasta showed similar physiochemical characteristics to pasta made with traditional hydrocolloids. In contrast, pasta made with gledis gum was more favoured according to sensory analyses **[21]**.

Dietary fibre is often a process additive or secondary quality-enhancing ingredient **[22]**. Adding dietary fibre to the pasta can create products low in calories, fat and cholesterol. The dietary fibres that have been utilized in GF products are β-glucan, oligofructose, inulin, carob fibre, polydextrose, etc. **[23]**. Corn pasta with inulin at 5% and 7.5% concentrations demonstrated greater stretching, shear viscosity, and higher elasticity **[24]**. The presence of inulin in pasta increased optimum cooking time, cooking loss, swelling and water absorption index, and deterioration of textural characteristics **[25]**. Dietary fibre (inulin) was justified as an enrichment agent in instant pasta from non-traditional raw materials **[26]**. A study of high-fibre fenugreek, chickpea and tiger nut flours showed that the soluble and insoluble fibre composition was balanced in GF pasta **[27]**. Unripe plantain flour (UPF) and Hi-Maize 260 as a source of dietary fibre were added to GF pasta, and the results showed that spaghetti with UPF demonstrated shorter cooking time and less cooking loss **[28]**. 20% dietary fibre could form a stronger protein-starch network, thereby reducing swelling and cooking losses of pasta enriched with sweet potato **[29]**.

Starch plays a critical role in forming the structure. Glucose residues connected by glycosidic bonds represent starch molecules. Polymerisation of glucose molecules occurs by forming two polysaccharide structures: linear *amylose* and branching *amylopectin* **[30]**. Depending on the rate and degree of cleavage by amylolytic enzymes of the intestinal microflora, starch is divided into glycaemic, which are easily digested, partially resistant and resistant starch. The latter are not adsorbed in the human small intestine. However, once in the large intestine and rectum, they become available for fermentation by bacteria, thus performing the function of dietary fibre **[31]**. This is why they are currently considered among the most persistent foodstuff prebiotics. Rapid gelatinisation and good viscosity retention after gelatinisation are the main properties of starch, as high dough viscosity is essential for creating the structure of gluten-free food products.

Consequently, eliminating wheat flour also sheds starch from the product. Starches from alternative sources such as potato, tapioca, cassava, and corn have been added to GF recipes **[32]**, **[33]**. The supplementation of resistant starch (RS) considerably increased the finished pasta products' elasticity; the samples showed lower stickiness values at RS substitution levels above 100 g kg-1 **[34]**. Modified starches have also been analysed within gluten-free pasta. Modified banana starch (15%), modified potato starch (15%) and taro flour (70%) provided optimum cooking time, cooking loss and elongation **[35]**. Cervini et al. (2021) showed that 15 g/100 g of annealed sorghum starch in rice-based pasta resulted in the highest total dietary fibre and resistant starch **[36]**. Moreover, partially replacing rice flour with legume flour increased resistant starch content **[37]**. In addition, 30% green plantain flour in GF pasta demonstrated good cooking quality and high resistant strach content **[38]**. Ferreira et al. (2015) showed that pasta samples containing sorghum flour (40 %), rice flour (20 %) and potato starch (40%) showed better culinary qualities **[39]**.

Enzymes are often selected based on their ability to prompt the formation of cross-links between polymers in the product formulation, thereby inducing network formation identical to what would occur if gluten were present in the product formulation **[40]**. Enzymes such as glucose oxidase, transglutaminase, tyrosinase, and laccase have been studied recently. It was shown that higher TG concentration and prolonged kneading increased macaroons' elasticity, cohesiveness and chewability. In contrast, TG concentration of 1.5% and 10 minutes of kneading significantly increased the content of phenolic compounds **[41]**. In another study, transglutaminase in gluten-free corn noodles showed a reduction in cooking losses and total organic matter **[42]**. Supplementing the oxidative enzyme POx to quinoa paste with 12% rice or pea protein improves elasticity **[43]**. The best sensory evaluation and cooking properties were obtained with 140 mg kg-1 TG enzyme in yellow pea noodles **[44]**. Transglutaminase and egg protein in taro-based pasta demonstrated a positive effect on cooking time and increased weight of cooked pasta while hurting pasta firmness **[45]**. Adding TG to millet pasta increased digestibility, cooking loss, and water absorption **[46]**.

Physical modifications

A technology using high-temperature treatments was proposed to improve the properties of GF pasta. It is proved that the thermal treatment of rice and chickpea flours decreased their moisture-absorbing and swelling ability **[47]**, **[48]**. Extruded amaranth and barnyard millet provided higher final viscosity **[49]**. In addition, the germination process is considered the most effective procedure to enhance the nutritional and bioactive potential of lentils **[50]**.

The extrusion-cooking approach is a distinct technology appropriate for producing gluten-free pasta products because it involves the unification of the pre-gelatinization and moulding stages **[51]**. Extrusion cooking of pasta based on rice and amaranth flours before pasta preparation gave the best results in terms of textural characteristics **[52]**. Bouasla et al. (2019) investigated the optimum effect of extrusion cooking parameters (30% moisture content, 120 °C temperature and 80 rpm screw speed) to obtain high-quality rice-buckwheat pasta **[53]**. The extrusion cooking at 30% moisture content of dough at 80 rpm is suitable for producing rice-yellow pea pre-cooked pasta with great phenolic content and proper quality **[54]**. However, extruded maise and sweet potato pasta with orange flesh showed lower beta-carotene levels but had higher antioxidant properties and shorter cooking time **[55]**. In addition, extrusion cooking improved the nutritional composition, reduced cooking losses and improved the texture of brown rice- and maise flour- based pasta products **[56]**.

Pregelatinisation is a type of physical modification of starch by heating and mechanical shear. Pregelatinised starch is obtained by sufficient heating, subsequent drying and grinding. The addition of 30% pre-gelatinized native grain plantain flour or drum-dried green banana flour improved the functional properties of the paste **[38]**. Pregelatinised cassava starch and bagasse, amaranth flour and cassava starch resulted in fewer solids in cooking water and optimum cooking time **[57]**. The gelatinisation of mixed GF flours (buckwheat, maise, rice) produced a gluten-free pasta with good nutritional and culinary properties **[20]**. Pregelatinised flour from macerated carioca and black bean flour demonstrated increased protein and dietary fibre content compared to semolina pasta **[58]**. Pregelatinised rice flour combined with germinated chickpea flour in GF noodles significantly increased crude protein, crude fibre, amylose, antioxidant activity, reduced glycemic index and improved cooking quality **[59]**. Although the extrusion process can improve important quality parameters of GF pasta, the characteristics of wheat pasta still need to be achieved.

Furthermore, annealing is often involved in starch as a physical treatment to alter its physicochemical properties. Heat-moisture treatment of rice starch decreases the swelling power and solvability of starch **[60]**. Wang et al. (2018) revealed that the replacement of 40% of native rice starch with annealed rice starch led to increased cooking quality and sensory and texture properties of rice noodles **[61]**. Annealed sorghum starch has been proven to positively influence the optimum cooking loss, cooking time, elasticity and stickiness of rice-based pasta samples **[36]**. However, the annelisation process requires specialised equipment and careful control of temperature and moisture levels, making it more expensive to produce gluten-free pasta.

Moreover, it has been suggested that kneading in boiling water increases the bound water content and the elasticity of oat dough **[62]**. In contrast, the redox activity associated with lipoxygenase, which leads to dough kneading and extrusion deterioration, can be delayed or even prevented using low-temperature kneading or thermal pre-treatment of the legume flour **[63]**. Proper pasta drying is key to a superior quality finished product **[64]**. Pre-heating at 40 °C before drying and evaporating at elevated temperatures under high humidity enhanced the maximum hardness of GF pasta **[65]**. D'Amico et al. (2015) studied the effects of high-temperature drying (80 and 100 °C) on the texture and culinary characteristics of amaranth/quinoa/wheat or millet/white bean pasta. Moreover, the 57 °C at an operating speed of 3 m/s was suitable for minimising hot-air drying time to obtain cassava flour with a progressive water-holding capacity **[66]**. However, exposing gluten-free pasta to high temperatures for extended periods of time can lead to a loss of nutrients and natural flavours in the pasta.

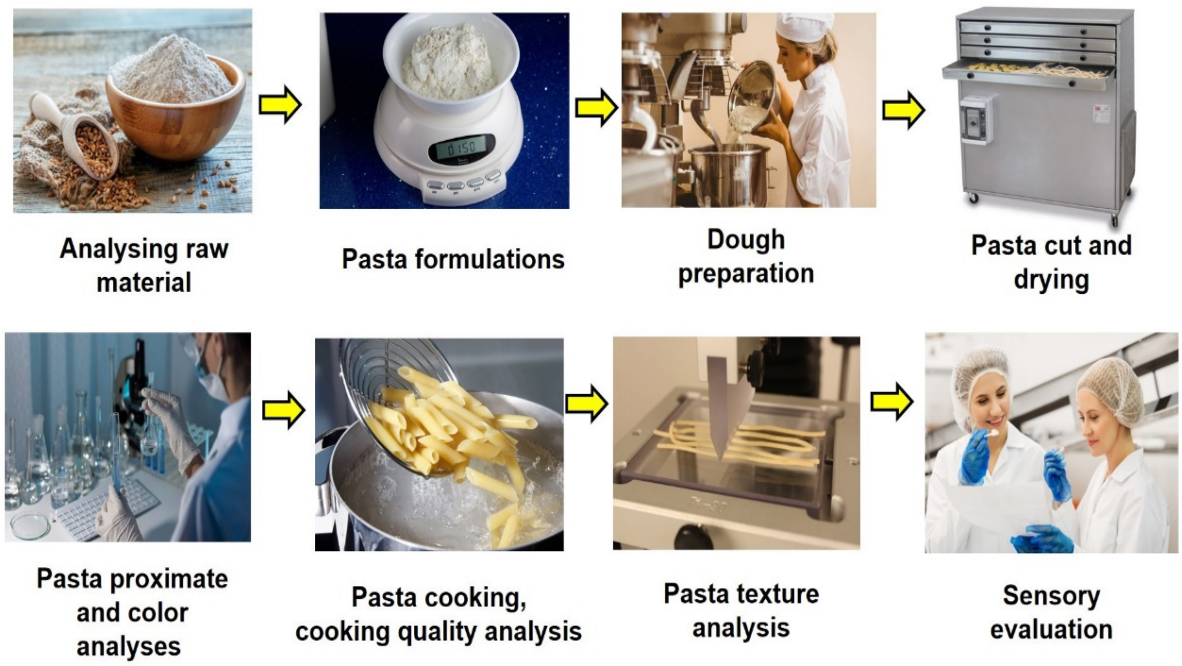

Figure 2 General technical road of studying gluten-free pasta.

NON-TRADITIONAL RAW MATERIALS FOR GF PASTA PRODUCTION

Amaranth (Amaranthus)

In recent years, a new source of raw materials for a whole range of functional foods has appeared on the world market is an ancient grain amaranth. Amaranth grain originates in Central and South America, but India also has a large distribution and variety of amaranths **[67]**. The most valuable feature of amaranth is the absence of gluten in its protein. The amaranth grain contains carbohydrates 68.1%, fat 6.04%, ash 2.04%, protein 14.6% and dietary fiber 6.7% **[68]**. Amaranth contains minerals, vitamins, and microelements, considerably enhancing its antioxidant features **[69]**, **[70]**. Mystkowska et al. (2024)

reported that amaranth flour, along with other GF flours, contained more Ca, Mg, Fe, Zn compared to gluten-containing flours obtained from the local market in Poland **[71]**. Amaranth grain has also been shown to be a source of amino acids such as histidine, leucine, isoleucine, lysine, valine, threonine etc. **[72]**. Besides, albumin is the major protein fraction in amaranth protein **[73]**.

To date, amaranth-based fresh/dried pasta has yet to be discovered. Recently, Lux et al. (2023) studied the use of amaranth flour (1:4) and water (1:6) with alginate (1.5%) resulted in good properties for dough processing and cooking **[74]** (Table 1). Furthermore, it has been shown that pasta with amaranth flour and dried amaranth leaves exhibited higher amount of protein, minerals and antioxidant capacity compared to semolina **[75]**. In addition, protein, dietary fibre, β-carotene, iron and zinc were significantly increased in cassava pasta with the addition of amaranth leaf powder **[76]**. The study's results on amaranth, buckwheat and quinoa pasta showed that amaranth-based pasta had decreased texture elasticity and cooking time. In contrast, quinoa-based pasta had increased cooking loss, but buckwheat pasta exhibited the least negative effects **[77]**. Thus, the use of amaranth in pasta manufacture still needs improvement to acquire pasta with good sensory features.

Buckwheat (*Fagopyrum esculentum*)

The buckwheat crop originated in Central and North-East Asia. Buckwheat cultivation occurred in China, from where it was introduced to Europe via Turkey and Russia **[78]**. Buckwheat flour is a unique product with exceptional flavour properties and useful qualities **[79]**. Buckwheat, unlike wheat, contains more vitamins (B3 (niacin) – 6.2-18.0 mg/100g, B6 (pyridoxine) – 0.6 mg/100g, etc.) and minerals (Mg – 231.0-390.0 mg/100g, K – 450.0-460.0 mg/100g, etc.) necessary for the human body **[80]**, is completely gluten-free and a unique source protein with digestibility of ~80% **[81]**.

Oniszczczuk et al. (2019) revealed that buckwheat flour pasta with 32 % moisture content had a higher content of total free phenolic acids than pasta with 30 and 34 % moisture content **[82]**. Furthermore, a gelatinisation study on pasta made from buckwheat flour mixed with other gluten-free raw materials (maise and rice) showed that adding 49.2-99.4% buckwheat flour to pasta showed high protein and dietary fibre content. Using 0.1% PGA 0.5% MFA and gelatinisation of mixed flours (buckwheat, maise, rice) also displayed good cooking properties **[20]**. Hydrothermal pre-treatment of wholegrain buckwheat flour pasta exhibited the potential to be implemented in buckwheat pasta production **[83]**. Interestingly, 100% buckwheat flour pasta showed the best culinary properties. However, it was the least acceptable colour than buckwheat-rice pasta, suggesting that it needs sensory properties improved **[84]**. It was revealed that the addition of buckwheat flour significantly affected the change in the pasta's textural properties and appeared more bitter than the wholegrain wheat samples **[85]**. Another interesting research revealed that supplementing buckwheat pasta with 5% silkworm powder reduced the carbohydrate content (from 59.5g to 57.3g), while enhancing protein content (from 26.2 to 28.2 g) in 100 g pasta. Although silkworm reduced the optimum preparation time and increased the acidity of the paste during storage, the addition of 10 g silkworm powder showed the highest overall acceptability **[86]**. Buckwheat-amaranth-quinoa flour-based pasta enriched with egg white powder provided high nutritional properties and low cooking losses **[87]**. In addition, sensory evaluation analysis showed that semolina pasta enriched with buckwheat showed a significant decrease in scores ($p < 0.05$) for the appearance, colour, and odour of the pasta **[89]**. Therefore, the results indicate that buckwheat pasta fortified with amaranth, quinoa, and rice, along with the addition of egg powder, can result in nutritious and consumer-acceptable pasta products.

Chickpea (*Cicer arietinum*)

Chickpea flour is a favorable raw substance for the production of gluten-free products. The analysis of literature data on chickpea flour's chemical composition and nutritional value showed that it could be used in this way. The chemical composition of chickpeas is characterised by the predominance of carbohydrates (62.95 g), protein (21.07%), and fat (2.7-6.48%) **[88]**.

The paste prepared from chickpea flour (15%) with the supplementation of maise flour had low elasticity and increased firmness, and using guar resulted in a lower glycemic index **[89]**. Also, the dough matrix and protein content were significantly improved by combining teff flour, chickpea flour, and xanthan gum in addition to buckwheat **[90]**. Moreover, the GF pasta prepared using chickpea flour (65.7%) and egg whites (34.3%) contained less fat, more protein and dietary fibre, and had good texture and taste **[91]**. Germinated chickpea flour enhanced crude protein levels, crude fibre, amylose, antioxidant activity, and total phenolic acid **[59]**. In addition, pasta made from chickpea flour, maize flour, and unripe plantain showed less total starch than in control pasta, an essential nutritional issue to consider when developing GF pasta **[92]**. Increasing the concentration of chickpeas in barley-based pasta produced pasta with increased protein and fibre content and improved colour characteristics and texture compared to control barley pasta **[93]**. Pasta enriched with two different chickpea hulls showed higher antioxidant activity, improved colour intensity, lower cooking loss and higher elasticity compared to control rice-based GF pasta, indicating that chickpeas can be used for preparing GF pasta **[94]**. In contrast, supplementation of durum wheat semolina pasta with chickpea flour and its protein isolate increased cooking losses, moisture content and swelling index **[95]**.

Chia (Salvia hispanica)

The nutritional profile and functional applications of chia seeds (*Salvia hispanica*) have garnered significant attention within both the nutritional science community and the culinary arts. Chia seeds are a good source of phenolic compounds, protein (16.5-24.2 g/100g), and dietary fibre (30.2-34.4) **[96]**. Previous research reported that partially deoiled chia flour contained more protein, fibre, and minerals compared to wheat flour **[97]**.

Replacing rice flour with 10% chia mucilage or seeds has been reported to increase dietary fibre, protein, and phenolic acids **[98]**. Enrichment of chia seed flour (20%) with diacetyl tartaric acid esters of mono (and di) glycerides (DATEM) can be used to refine the sensory properties and nutritional values of GF pasta. However, the addition of 30% chia seed flour particularly reduced the appearance of raw noodle, surface smoothness, and the chewability of cooked noodle samples **[99]**. A recent study showed that the addition of chia seed flour (15%) to quinoa flour (85%) resulted in good cooking, sensory and textural qualities as well as increased chemical composition **[100]**. Overall, there is a lack of research on recipes using chia seed flour, which could be considered for future research.

Corn (Zea mays)

Cornbread, pasta and flour have become a familiar alternative to wheat products. Corn loses out on the content of useful substances to other cereals, but it is also a baseline of vitamins B and E, copper, selenium, iron, and antioxidants, it has low-calorie content and easy digestibility **[101]**. Corn starch contains 0.38-7.70 (g/100g) crude protein, 0.32-7.13 (g/100g) crude fat, 0.32-0.62 ash **[102]**.

Combining GF maise/corn paste with other raw materials such as legumes and additives and using different processing methods shows good nutritional, culinary, and sensory characteristics. Bresciani et al. (2021) reported that 25% high-amylose corn flour displayed a rational compromise between high starch stability (4.2%) and good culinary properties in pasta with high-amylose corn in combination with conventional corn **[103]**. Furthermore, 40% corn meal and 60% brown rice flour exhibited better texture evaluations (sensory and instrumental) **[56]**. A mixture of cassava starch and corn resulted in a higher percentage of total dietary fibre, high protein digestibility and slowly digestible starch **[104]**. Broad bean and quinoa-based gluten-free corn-pasta-like products greatly increased net protein utilisation and decreased digestibility **[105]**. A previous study showed that adding 15% whey powder and 1% grape peel resulted in a good sensory profile of corn-based GF pasta **[106]**. Furthermore, it has been demonstrated that different processing methods affect corn-based pasta quality. Also, pumpkin flour (25%) influences corn pasta colour, texture and sensory properties **[107]**. Moreover, adding corn starch to corn flour changes rheological properties during the cooking stage of gluten-free pasta **[108]**. Fortification of corn and rice pasta with tempeh flour enhanced protein content (6.30-9.07%) and altered whiteness level (66.08-71.97%) **[109]**.

The optimum extraction conditions, including barrel temperature (80 ºC), rotation screw (25 rpm) and expansion ratio (1.38) with optimising cooking time (3.3 min), cooking yield (196%), swelling (210%) and cooking losses (16.3%) were obtained for corn-based GF pasta **[110]**. The hydrothermal-treated corn-field bean semolina mixture pasta displayed good cooking and texture parameters **[111]**. In addition, using extrusion (80%) and cooking (70%), GF blue maise pasta retained the greatest total phenolic content. It showed a definite second peak in viscosity due to the rearrangement of starch components during cooling **[112]**. Maise flour and oat bran enriched with additives such as carboxymethylcellulose and chitosan (2%) provided the best overall quality **[113]**. A recent study revealed that hard-grained, high-hectoliter-weight maise genotypes produce flours with elevated solvent retention due to increased damaged starch content. Consequently, extruded and cooked pasta from these flours exhibits lower water retention and absorption and greater firmness **[114]**.

Rice (Oryza sativa)

Rice, an inherently gluten-free staple grain, possesses a remarkable combination of attributes that render it an exceptional dietary choice for various individuals, particularly those with gluten sensitivities or celiac disease. This cereal is characterised by its lack of gluten, which makes it an ideal component for gluten-free diets **[115]**. In enhancing the technological attributes of rice flour products, incorporating a protein source emerges as a viable strategy, potentially leading to significant improvements in both functional and nutritional qualities. For instance, the study reported that the supplementation of soybean flour increases crude fibre (0.8-1.3%), protein (6.7-12.1%), energy value (379-389 kcal/100 g), and 15% soybean flour is the optimum amount for rice pasta to get better acceptability to consumers **[116]**. Furthermore, it has been proven that adding egg albumin provides short cooking time, low cooking losses (4.38–4.63%) and better firmness to GF pasta **[117]**. In addition, another study revealed that replacing rice flour with defatted soy flour (DSF) at a ratio of 90:10 increased the protein content of the pasta. Also, sensory evaluations indicated that the rice spaghetti formulated with rice flour, DSF, and modified starch was comparable in quality to commercial spaghetti made from durum semolina **[118]**. Bouasla et al. (2017) revealed that fortifying rice pasta with legumes enhanced fibre, protein, and ash contents while decreasing the expansion coefficient, hardness and lightness **[53]**. Moreover, formulation with 20% gelatinised rice flour was reported to have optimal cooking quality and texture properties **[119]**. Utilising the high-protein white and brown rice flour with xanthan gum and canola oil had less cooking loss and greater protein and fat content **[120]**. Interestingly, adding 10% passion fruit peel flour increased nutritional value and flavour quality of rice and corn-based pasta **[121]**. 30% pre-gelatinised native green plantain flour or drum-dried green banana flour improved the functional properties of the rice paste **[38]**. It has been reported that corn starch, rice starch, and lentil flour pasta with additives, such as transglutaminase, hydroxypropyl methylcellulose and xanthan gum, positively affected GF pasta properties **[122]**.

In addition to the basic extrusion process, recent advancements have spotlighted its multifaceted utility in treating rice flour before its application in pasta production, facilitating many functional modifications. For instance, the extrusion process resulted in considerable alterations in the digestibility of rice flour, which led to enhanced resistant starch content and lowered predicted glycemic index **[123]**. It was also reported that harsher extrusion conditions lead to low cold paste viscosity, hot paste viscosity and low final extrudate viscosity **[124]**. In addition, the low amylose rice extrudate showed a lower sticking profile and apparent viscosity, indicating a higher starch cleavage level than high-amylose rice **[125]**.

Quinoa (Chenopodium quinoa Willd.)

Quinoa seeds are a versatile enrichment agent in producing a broad range of foodstuffs, as they are characterised by a high content of essential amino acids **[126]**. The amino acid composition of quinoa proteins is close to milk proteins **[127]**, allowing the crop to compete with recognised high-protein raw materials such as barley, buckwheat, and amaranth.

In comparison to raw quinoa flour, germinated quinoa flour had more pronounced adverse effects on the cooking quality of pasta. However, it significantly enhanced the nutritional and functional attributes **[128]**. Demir & Bilgiçli, (2021) reported that gluten-free pasta with quinoa flour improved mean protein values from 8.1 to 12.7 %, total phenolic content from 0.7 mg GAE/g to 1.5 mg GAE/g, antioxidant activity from 13.4 to 28.8 % **[129]**. An increase in mineral content was also observed in gluten-free pasta at all quinoa flour addition ratios. Several studies proved that the use of quinoa flour with egg white and yucca flour might be a potential formulation to get extruded pasta **[130]**, **[131]**. For instance, Torres Vargas et al. (2021) found that the score of sensory attributes was acceptable in GF pasta prepared using extruded quinoa flour **[130]**. The pasta made with quinoa flour, cassava starch, water, and a constant egg-white factor, exhibits favourable sensory characteristics. This product shows great market potential due to its appealing taste and high protein content, making it well-accepted by consumers **[131]**. More recent, Itusaca-Maldonado et al. (2024) obtained a 100% quinoa paste with high nutritional value, cooking quality, water absorption, swelling index and minimal carbohydrates **[132]**. Hyper-protein-defatted quinoa flour positively influenced the viscosity of rice-corn-quinoa flour-based GF pasta **[133]**. It was shown that zein protein added to quinoa pasta hurt the texture of the pasta, whereas quinoa flour resulted in greater protein content and reasonable textural features **[134]**. In addition, the inclusion of hyperprotein-defatted quinoa flour enhanced the technical and functional attributes of the dough **[135]**.

Sorghum (Sorghum bicolor)

In Southwest Asia, Equatorial and Southern Africa, grain sorghum is the main bread plant manufacturing bakery and flour confectionery products. However, the protein quality of sorghum could be better because it lacks essential amino acids **[136]**. Sorghum contains 8-15% protein, 60-77% starch, 1–3.4% crude fibre, and 2.1-7.6% fat **[137]**.

GF pasta with white and brown sorghum flour was high in dietary fibre, protein, and antioxidant activity, while the greatest eGI was detected in rice (69.8) and then in corn-based pasta (66.4) **[138]**. Moreover, white sorghum flour showed greater sensory satisfaction than brown sorghum flour pasta **[139]**. Furthermore, a combination of sorghum 40%, rice 40% and potato flour 40% was found to be best regarding cooking quality **[39]**. Other recipes have also been developed that combine sorghum paste with other types of GF flours **[140], [141]**. For instance, GF is prepared using toasted soy, channa, and sorghum flour with additives comparable to the control in all quality parameters **[140]**. Gluten-free pasta was developed by combining high-protein, non-gluten flours like soy, chickpea, and sorghum flour with gums as additives to meet protein needs while avoiding allergic reactions **[141]**.

Limitations and future perspectives

It is necessary to ensure the nutritional safety of celiac disease patients, prevent disease relapses, ensure gradual social adaptation of patients and improve their quality of life **[142]**. Nowadays, GF pasta products are in a higher price category than conventional products due to the complexity of technological processes. This is further complicated by the fact that supermarkets have a rather limited range of these products. Therefore, it is advisable to establish gluten-free pasta production, which will allow the production and sale of products at a low price. Besides, many products may contain "hidden" gluten, and there may be no labelling on these products, which may cause unintentional dietary infringement **[143]**. "Gluten-free" labelling is available for products that only partially remove gluten. This amount of remaining gluten in products varies from country to country.

Currently, few recipes have been developed due to the difficulties of working with gluten-free raw materials. Although the visco-elastic properties of dough can be formed by heat treatment, this decreases the finished product's nutritional value, dietary fibre and vitamin content. Therefore, studies must be continued to evolve new recipes that respond to these issues. Rice and corn flour could be a raw material that could proficiently restore wheat- or barley-based pasta, but using 100% buckwheat, chia, quinoa or sorghum led to less promising results. On the one hand, using non-starch polysaccharides makes it possible to obtain products with high nutritional value and balanced composition. Still, the properties of these polysaccharides have yet to be sufficiently studied. On the other hand, additives such as xanthan gum, egg or whey protein powder can improve the properties of GF paste.

All the results of studies on GF pasta development indicate that the rheological and sensory properties still cannot reach the level of pasta made from conventional raw materials. The biggest challenge remains sensory characteristics such as flavour, colour, and overall appearance. Since GF is of great importance for people suffering from gluten intolerance, it requires a deeper study of technological processes in producing specialised foods.

Table 1. Studies on gluten-free pasta using different non-conventional raw materials

The main GF material	Pasta formulations	Additives	Effects	Sources
Amaranth	Whole amaranth flour	sodium alginate	Had good dough processing properties and cooking attributes.	**[74]**
	Dried amaranth leaves, amaranth seed flour, semolina	Carboxymethylcellulose, fresh egg	Exhibited higher content of protein, minerals and antioxidant capacity.	**[75]**
	Amaranth flour	gum tragacanth, guar gum, gum acacia	The best overall quality of gluten-free paste was when 1.0% guar gum was added.	**[17]**
	Amaranth and barnyard millet	refined oil (5%)	Extrusion led to higher final viscosities; preheating at 40 °C before drying at high temperatures under high humidity conditions increased the firmness.	**[49]**
	Cassava and amaranth flour	carboxymethyl cellulose	Moisture content, hardness and protein content improved, but earthy flavour was a major problem for consumer satisfaction.	**[66]**
	Amaranth flour, cassava bagasse, cassava starch	-	Pregelatinised bagasse flour, cassava starch, and amaranth flour resulted in less solids being lost to cooking water and optimum cooking time.	**[57]**
	Amaranth and rice flour	-	Extrusion cooking before pasta making gave good results in terms of textural features.	**[52]**
Buckwheat	Rice: buckwheat 50:50	-	Pasta from mixture of rice and buckwheat showed low cooking attributes and acceptable sensory characteristics.	**[9]**
	Buckwheat, maise, rice flour	monoglycerides of fatty acids (MFA), propylene glycol alginate (PGA)	gelatinisation of mixed flours with 0.1% of PGA and 0.5% of MFA showed good nutritional and cooking quality.	**[20]**
	Buckwheat flour: water 30%, 32%, 34%	-	32% moistened buckwheat pasta showed a higher total content of free phenolic acids	**[82]**
	Wholegrain buckwheat flour	-	hydrothermally treated buckwheat flour was more liked by consumers.	**[83]**
	100% buckwheat or replaced with 5, 10 and 15%, amaranth or rice flour	eggs, water and 2.0% xanthan gum	pasta made from 100% buckwheat flour was less accepted in terms of the colour, while combined pasta showed better acceptance.	**[84]**
	Buckwheat flour	bombyx moria powder 5-10g	the supplementation of silkworm powder enhanced the nutritional value of buckwheat pastereduced the optimum cooking time, and added 10 g silkworm powder showed the highest overall acceptability.	**[86]**
	Buckwheat, amaranth, quinoa	egg white powder, emulsifier	This resulted in reasonable texture firmness and low cooking loss, high cooking stability	**[77]**
	Buckwheat flour; rice flour	Pre-gelatinized rice starch; whole egg product; methylcellulose; eggs;	Adding 30% egg to the pasta formulation results in well-textured GF fresh pasta with improved nourishing features. The use of pre-cooked rice flour and methylcellulose as well as heat treatment, improved the texture of the products.	**[87]**

	Amaranth-quinoa-buckwheat 20:20:60 (AQB), millet-white bean 70:30 (MW)	Egg white powder, emulsifier	At a higher drying temperature, protein solubility and cooking loss reduced, but the elasticity and protein solubility did not reach the level of wheat pasta.	**[65]**
Chickpea	The pre- gelatinized maize flour and chickpea flour (5%, 10%, 15%, 20%, 25% and 30%)	Monoglycerides, hydrocolloids (pectin , guar flour and agar)	15% chickpea flour addition showed low elasticity and increased firmness; use of guar resulted in reduced glycemic index.	**[89]**
	Chickpea, buckwheat, teff flour	xanthan gum	The dough matrix and protein content were significantly improved.	**[90]**
	Chickpea flour	Egg white	GF pasta contained less fat (37.3%), more protein (53.8%) and dietary fibre (166.5%), and had good texture and taste	**[91]**
	Hydrothermal treated white rice (Oryza sativa L.) and germinated desi chickpea (Cicer arietinum L.)	guar gum	germinated chickpea flour enhanced crude protein level, crude fibre, amylose, antioxidant activity, total phenolic acids.	**[59]**
	chickpea, maize, unripe plantain	carboxymethyl cellulose 0.5%	Cooking losses were higher in gluten-free products with acceptance limits; total starch in GF pasta was lower than in control.	**[92]**
	chickpeas (10%, 20%, 30%, 40%) and hullless barley	and 1.5% xanthan gum	Enhanced total phenolics and flavonoids	**[93]**
	Two different chickpea hulls, rice flour, carob seed flour	Xanthan gum and	Resulted in lower cooking loss and the higher water absorption capacity and firmness	**[94]**
Chia	Milled chia seeds (5-10%) and chia mucilage (5-19%)	-	10% of chia mucilage or seeds in rice pasta increases protein, dietary fiber and phenolic acid amount.	**[98]**
	Chia *Salvia hispani*ca L. (0, 10, 20 and 30%), corn starch, rice flour	diacetyl tartaric acid esters of mono and DATEM, whole egg	Chia flour supplementation significantly increased mineral contents; DATEM enrichment (30%) showed lower cooking loss; Chia seed flour (20%) with DATEM can be used to improve sensory properties.	**[99]**
	Chia seed and quinoa flour	-	The addition of chia seed flour (15%) to quinoa flour (85%) resulted in good cooking, sensory and textural qualities as well as increased protein, dietary fibre, etc.	**[100]**
Corn/maize	High-amylose 25% and conventional corn 50%	mono- and di-glycerides of fatty acids (0.3%)	25% high amylose shows a rational compromise between high starch stability (4.2%) and certain culinary properties	**[103]**
	Corn and brown rice	-	The proportion of 40:60 CM:BR had better texture evaluations (sensory and instrumental).	**[56]**
	Corn flour, cassava starch	vegetable fat, xanthan gum, whole milk powder	a mixture of cassava starch and corn resulted in a higher percentage of total dietary fibre, high protein digestibility and slowly digestible starch.	**[104]**
	Corn:broad bean 30%:quinoa 20%	-	GF pasta demonstrated increased net protein utilisation and decreased digestibility.	**[105]**
	Hydrothermal treated corn-field bean semolina mixture 2/1 (w/w)	-	Hydrothermal-treated pasta displayed good cooking and texture parameters.	**[48]**

	maize flour	inulin	corn pasta with inulin (5-7.5%) exhibited higher elongation and shear viscosity and higher elasticity.	**[24]**
	Maise flour, oat bran enriched 22% β-glucans	egg white, 2% hydrocolloids	carboxymethylcellulose and chitosan (2%) provides the best overall quality.	**[113]**
	nixtamalised white corn flour, grape peels powder	unhydrolysed sweet commercial whey powder	The amount of 15% whey powder and 3% grape peels allows acceptable textural, physical, and sensory features.	**[106]**
	Corn flour and starch	dry egg, locust has been gums, dry egg-white, xanthan and sunflower oil	Alters in rheological attributes during cooking.	**[108]**
	wholegrain maize flours,	egg albumin, pregelatinized maize starch	Exhibited the lowest swelling index and water absorption values. The open-pollinated flint variety C6006 received a greater number of top preference selections	**[114]**
	White and blue maize, unripe plantainб chickpea	carboxymethylcellul ose	blue maise flour reserved the superlative total phenolic content after extrusion (80%) and cooking (70%), showed a definite second peak in viscosity due to the rearrangement of starch components during cooling.	**[84]**
	Cassava starch and corn flour	whole milk powder, egg, xanthan gum, vegetable fat	XG concentration of 0.6% showed the greatest potential for enhancing the paste-forming ability.	**[18]**
Rice	Rice flour	-	Extrusion conditions induced by the harsh parboiling process of paddy rice favoured the formation of effective starch networks in the flour.	**[51]**
	Oryza sativa rice, soy, tapioca starch	-	Increased protein, ash, energy value, crude fibre	**[116]**
	Organic rice bran, rice flour	egg albumen, whey and soy protein concentrates, emulsifier (distilled monoglyce ride)	The addition of egg albumin provided short cooking time, low cooking losses (4.38–4.63%) and better firmness.	**[117]**
	Rice flour, chickpea flour, yellow pea flour, lentil flour (10 g/100 g, 20 g/100 g, 30 g/100 g)	glycol	improved the dietary fibre, protein, and ash; decreased expansion ratio, increased water absorption capacity as well as cooking loss without exceeding 6%.	**[53]**
	Rice flour, defatted soy flour (DFS)	Modified cross-linked cornstarch	the rice spaghetti formulated with rice flour, DSF, and modified starch was comparable in quality to commercial spaghetti made from durum semolina	**[118]**
	Broken rice kernels (*O. sativa* ssp. Indica and Ja ponica)	rice flour gel	50:50 rice gel:rice flour ratio, 20% gelatinised rice flour gave optimal cooking quality and texture properties	**[119]**
	Rice flour, green plantain and drum-dried green banana flour	Monoglyceride, egg albumen	30% pregelatinised native green plantain flour or drum dried green banana flour improved the functional properties of the paste.	**[38]**
	High-protein white and brown rice flour,	xanthan gum, canola oil	high-protein white and brown rice pasta had less cooking loss; greater protein and fat content.	**[120]**

	commercial white and brown rice flour			
	Red rice flour, tapioca flour, white quinoa flour	psyllium husk, transglutaminase (T G)	treatment with 1.5% TG and 10 minutes of kneading considerably increased the phenolic content.	**[41]**
	Rice flour	propylene glycol alginate resistant starch distilled monoglycerides	using resistant starch markedly enhanced the elasticity of the finished pasta products.	**[34]**
	Rice flour, corn flour, passion fruit peel flour	egg, xanthan gum, oil	the addition of 10% passion fruit peel flour increased nutritional value and flavour quality	**[121]**
	Corn starch, rice starch, lentil	whey and egg white powder, xanthan gum, hydroxypropyl methylcellulose, transglutaminase	The addition of additives affected different pasta properties.	**[122]**
Quinoa	Raw and germinated quinoa seeds, semolina	-	Germinated quinoa flour had more pronounced adverse effects on the cooking quality of pasta; while significantly enhanced the nutritional and functional attributes	**[128]**
	Rice-corn semolina; Quinoa flour	guar gum	quinoa flour enhanced the protein and total phenolic content, antioxidant activity	**[129]**
	Quinoa grains	egg white, yucca starch	increased protein amount and decreased the carbohydrate value, decreased in tensile strength and an increase in water absorption and swelling.	**[130]**
	Quinoa flour, starch	egg white, yucca starch	the score of sensory attributes were acceptable	**[131]**
	100% quinoa flour	-	Optimizing the production conditions obtained a GF pasta with high nutritive value, satisfactory cooking conditions, and satisfactory technological peculiarities.	**[132]**
	Rice-corn semolina, hyperprotein quinoa flour, cassava starch, defatted high protein quinoa flour	-	hyper-protein defatted quinoa flour had positive influence on viscosity.	**[133]**
	Quinoa, lupine whole flour, potato starch, rice and pea protein	POx enzyme (pyranose-2-oxidase)	Adding the oxidative enzyme POx to quinoa paste with 12% rice or pea protein significantly improves elasticity.	**[43]**
	Quinoa flour, corn starch, corn flour	dry egg-white, dry egg, locust bean gum, xanthan, zein protein	zein protein had an adverse effect on the texture of the pasta, whereas quinoa flour resulted in greater protein content and reasonable textural features.	**[134]**
	High protein quinoa flour, hyperprotein defatted quinoa flour (HHPD), rice and maize flour, modified cassava starch	-	The inclusion of HHPD enhances the technical and functional attributes of the dough.	**[135]**
Sorghum	White and brown sorghum	egg powder, egg albumen, xanthan gum, pregelatinized corn starch	high protein, dietary fibre, polyphenol, antioxidant activity.	**[138]**
	Sorghum flour	Egg albumen, egg powder, xanthan gum, pregelatinized corn starch	white sorghum flour pasta exhibited better sensory features compared to brown pasta.	**[139]**

Sorghum, rice or corn 10–20% and potato starch 1	eggs, oil	proportion of sorghum 40%, rice 40% and potato flour 40% was found to be best regarding cooking quality.	**[39]**
Sorghum flours of five hybrids, rice flour	potato starch, psyllium, egg white	brown sorghum resulted the best otcomes for bioactive compounds.	**[140]**
Toasted soy, channa, whey protein concentrate (WPC), sorghum flour	guar gum, xanthan gum, hydroxypropylmethylcellulose	GF paste with added gum was similar to the control regarding all properties.	**[141]**

CONCLUSION

Overall, rice and maize-based pasta is the most common, but it requires the addition of nutrient-rich flours such as amaranth, quinoa, sorghum, etc., to increase the nutritional value. Despite the potential of buckwheat flour in GF pasta formulations, sensory attributes such as texture and taste still need improvement. Key additives like xanthan gum, transglutaminases, and inulin have been widely recognised for enhancing the cooking properties and structure of GF pasta. Similarly, starches from alternative sources, including potato, cassava, and corn, have shown promising results in increasing the resistant starch content, which is vital for improving GF products' nutritional and functional qualities. Finally, using high-temperature treatment of raw materials, extrusion cooking and starch gelatinisation proved to be the most suitable approaches for producing gluten-free pasta with good culinary properties. By addressing existing challenges and exploring innovative solutions, the gluten-free pasta industry has the potential to grow significantly and meet the evolving needs of consumers seeking both quality and nutrition in their dietary choices.

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