

Development and characterization of eight gluten-free pasta formulations based on quinoa, buckwheat, and amaranth enriched with tiger nut (*Cyperus esculentus* L.)

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Abstract. The aim of this study was to develop gluten-free pasta (GFP) using pseudocereals; quinoa (Q), amaranth (A), and buckwheat (B), enriched with tiger nut flour (*Cyperus esculentus* L.), and to optimise its nutritional and organoleptic qualities through a simplex-centroid mixture design. The results showed that pseudocereals significantly improved the nutritional profile of pasta, particularly in terms of protein, fiber, and minerals, increasing them to 10.43 g, 7.89 g, and 3.27 g, respectively. Cooking losses, starch degradation, and a high swelling index were observed in the gluten-free tagliatelle following cooking. Buckwheat exhibited the lowest cooking loss (16%) and reduced acidity. Quinoa and amaranth showed higher cooking losses (24% and intermediate values, respectively). The ternary mixture of the three pseudocereals yielded the best overall cooking quality. Sensory analysis revealed that the GFP presented a light brown colour, a nutty aroma, a slight bitterness, and satisfactory firmness. This study contributes to the diversification of alternatives to conventional wheat-based pasta and to the development of products tailored to consumers seeking gluten-free, nutritious, and potentially functional foods. It also aligns with a broader effort to promote the valorisation of plant-based raw materials of agri-food interest and to support the development of innovative products with higher added value.

Key words: cooking quality, nutritional values, pasta, pseudo cereal, sensory analysis, simplex-centroid mixture design.

INTRODUCTION

Consumed and enjoyed worldwide, pasta is one of the most widely consumed staple foods, owing to its simplicity of manufacture, ease of transport, long shelf-life, and

reliable nutritional and hygienic quality. Traditionally, industrial pasta is produced from durum wheat semolina kneaded with drinking water, with the possible addition of eggs, and without fermentation. The resulting dough is then subjected to appropriate physical processes such as extrusion, sheeting, or rolling followed by drying, to obtain a stable product suitable for culinary use and long-term storage (Feillet, 2000; Bresciani et al., 2022; Fouad et al., 2022).

The composition of pasta varies according to product type, including conventional, wholemeal, fresh, and gluten-free varieties. Conventional industrial pasta is primarily produced from durum wheat semolina, which provides approximately 70% complex carbohydrates and 10–15% proteins, predominantly gluten. However, in genetically predisposed individuals, gluten can trigger an autoimmune disorder of the small intestine known as coeliac disease. To date, strict lifelong adherence to a gluten-free diet remains the only effective treatment. Consequently, the demand for gluten-free pasta and other gluten-free products has increased considerably, not only among individuals with coeliac disease but also among non-coeliac consumers seeking nutritional, preventive, or lifestyle-oriented alternatives (Baldi et al., 2022; Kókai et al., 2024). This growing demand has stimulated substantial interest in the development of gluten-free products with improved nutritional, technological, and sensory characteristics (Schoenlechner, 2017; Bekkering & Tian, 2019).

Despite this expanding market, gluten-free products generally remain inferior to their conventional wheat-based counterparts in terms of technological, sensory, and nutritional quality. Limitations have been reported with respect to taste, colour, texture, appearance, structural integrity, and overall nutritional value (Mohammadi et al., 2022). In gluten-free pasta specifically, the absence of gluten is particularly challenging, since gluten proteins normally contribute to the formation of a continuous viscoelastic network that provides dough cohesiveness and ensures the structural integrity of the cooked product. As a consequence, gluten-free pasta frequently exhibits poor dough-handling properties, excessive cooking losses, weak texture, undesirable sensory characteristics, and inadequate nutritional quality. To overcome these limitations, gluten-free formulations frequently rely on combinations of starches, hydrocolloids, gums, proteins, emulsifiers, enzymes, and other technological additives (Pashaei et al., 2025). However, such approaches do not always achieve a satisfactory balance between nutritional enhancement and technological and sensory performance, highlighting the need to investigate alternative, naturally nutrient-rich functional ingredients (Carpentieri et al., 2022).

Among the ingredients receiving increasing attention, pseudocereals constitute a particularly promising group for gluten-free food development. Quinoa (*Chenopodium quinoa* Willd.), amaranth (*Amaranthus* spp.), and buckwheat (*Fagopyrum esculentum* Moench) are botanically distinct from true cereals but are consumed and processed in a similar manner. They are characterised by valuable nutritional profiles encompassing starch, dietary fibre, high-quality proteins and essential amino acids, essential fatty acids, minerals, vitamins, and a wide range of bioactive phytochemicals, including polyphenols, phytosterols, saponins, and betalains. These constituents underpin their nutritional value and potential health-promoting properties, making pseudocereals attractive ingredients for the nutritional improvement of gluten-free products (Mithila & Khanum, 2015; Pirzadah & Malik, 2020; Martínez-Villaluenga et al., 2020;

Yadav & Upasana, 2022). Their incorporation into gluten-free formulations has also been associated with modifications in technological and organoleptic properties, although the magnitude and direction of these effects depend strongly on the type and proportion of pseudocereal used, as well as on processing conditions (Schoenlechner, 2017; Hussein et al., 2025).

In addition to pseudocereals, tiger nut (*Cyperus esculentus* L.) represents a promising yet comparatively underexplored plant ingredient for gluten-free food applications. Unlike pseudocereals, tiger nut is a tuberous plant whose nutritional composition is characterised by appreciable levels of dietary fibre, monounsaturated fatty acids, particularly oleic acid, plant proteins, minerals including calcium, potassium, and phosphorus, as well as natural antioxidants and other bioactive constituents (Semdé et al., 2019; Wu et al., 2024). This composition may confer valuable functional properties and contribute to improving both the nutritional profile and sensory characteristics of formulated food products (Casini & Biancofiore, 2020). Nevertheless, compared with quinoa, amaranth, and buckwheat, the incorporation of tiger nut flour into gluten-free pasta has received considerably less scientific attention. In particular, limited information is available regarding the combined effects of tiger nut and multiple pseudocereals on the nutritional composition, cooking behaviour, textural characteristics, and sensory acceptability of gluten-free pasta (Oladunjoye & Alade, 2024).

An important scientific gap therefore remains. Previous studies have generally investigated individual pseudocereals or single alternative ingredients in gluten-free pasta formulations, while comparatively little attention has been devoted to their combined use with tiger nut flour. Furthermore, studies have often examined either nutritional composition or technological and sensory quality in isolation, rather than evaluating these dimensions simultaneously. The challenge is therefore not simply to replace wheat semolina with gluten-free ingredients, but to develop a formulation capable of achieving a satisfactory compromise between nutritional enhancement, cooking performance, structural integrity, texture, and consumer acceptability. The present study addresses this gap by investigating a novel gluten-free tagliatelle formulation based on three selected pseudocereals – quinoa, amaranth, and buckwheat – combined with tiger nut flour. This approach aims to exploit the complementary nutritional and functional properties of these ingredients while reducing dependence on conventional technological additives used to compensate for gluten absence.

Accordingly, the hypothesis of this study is that the incorporation of quinoa, amaranth, and buckwheat, combined with tiger nut flour, can yield gluten-free tagliatelle with improved nutritional quality while maintaining acceptable technological, cooking, textural, and sensory properties. To test this hypothesis, the following specific objectives were pursued: to formulate gluten-free tagliatelle using quinoa, amaranth, buckwheat, and tiger nut flour; to determine their nutritional composition; to evaluate their technological and cooking properties; to assess relevant physicochemical characteristics; to evaluate the sensory acceptability of the developed formulations; and to identify the formulation offering the most favourable overall balance between nutritional, technological, and organoleptic properties.

MATERIALS AND METHODS

Materials

In addition to xanthan gum, the gluten-free flours used in this study were quinoa (*Chenopodium quinoa* Willd.), buckwheat (*Fagopyrum esculentum* Moench), amaranth (*Amaranthus cruentus* L.), and rice (*Oryza sativa* L.). All raw materials were supplied by the company SARL DZ FOOD INGREDIENTS. Salt was purchased locally in Algiers.

Organic tiger nuts (*Cyperus esculentus* L.), identified as the Pharaoh variety, were collected in 2025 from herbalists in southern Algeria. Tiger nuts of uniform size, maturity, and weight were selected, cleaned, sun-dried for 48 hours, and ground using an RRH 400A grinder, then sieved through a 315 µm mesh sieve. The resulting tiger nut flour exhibited a characteristic light brown to yellowish-brown colour, a fine powdery texture, and a typical odour, with no visible signs of mould, insect infestation, foreign matter, or other deterioration. All flours were packaged in glass containers and stored at 4 °C for subsequent use (Babiker et al., 2021; Belmadani et al., 2024).

Pasta production process

Gluten-free tagliatelle was prepared following a slightly modified protocol from Itusaca-Maldonado et al. (2024). A simplex-centroid mixture design was employed to determine the optimal formulation, generating seven experimental formulations supplemented by a control formulation based on rice flour. The ingredients used and their respective proportions in each formulation are detailed in Table 1. Tiger nut flour was incorporated into all tagliatelle formulations at a constant level of 20%, selected on the basis of preliminary trials, which indicated that this proportion provided a suitable balance between nutritional enhancement and acceptable technological and sensory properties. This level was therefore kept constant across all formulations to allow consistent comparison of the pseudocereal blends.

Table 1. Composition of gluten-free pasta formulations

	F 1: Q	F 2: A	F 3: B	F 4: A + Q	F 5: A + B	F 6: Q + B	F 7: A + Q + B	Control
Rice flour (g)	40.00	40.00	40.00	40.00	40.00	40.00	40.00	80.00
Tiger nut flour (g)	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
Xanthan gum (g)	03.00	03.00	03.00	03.00	03.00	03.00	03.00	03.00
Salt (g)	02.00	02.00	02.00	02.00	02.00	02.00	02.00	02.00
Quinoa flour (g)	40.00	00.00	00.00	20.00	00.00	20.00	13.30	00.00
Amaranth flour (g)	00.00	40.00	00.00	20.00	20.00	00.00	13.30	00.00
Buckwheat flour (g)	00.00	00.00	40.00	00.00	20.00	20.00	13.30	00.00

F: gluten-free pasta formulations; Q: Quinoa; A: Amaranth; B: Buckwheat; A + Q: Amaranth + Quinoa; A + B: Amaranth + Buckwheat; Q + B: Quinoa + Buckwheat; A + Q + B: Amaranth + Quinoa + Buckwheat.

The dry ingredients, flour, xanthan gum, and salt were first combined and mixed, then hydrated with water to form a homogeneous dough. The dough was kneaded for two minutes and subsequently laminated using a Marcato Atlas 150 electric pasta roller, with the thickness setting gradually adjusted from 9 to 6. The tagliatelle strips were formed and pre-dried at room temperature (22 ± 2 °C) for five hours, followed by drying

in a rotary convection oven (NOVA 2000 MAX) at 50 °C for 30 minutes. After cooling for 90 minutes, the pasta was sealed in polyethylene bags and stored until further analysis. All gluten-free pasta formulations were prepared in biological triplicate.

Technological analyses of gluten-free pasta

All pasta samples were ground to a fine powder and analysed in biological triplicate. Dry matter and ash content were determined according to AOAC Official Methods 925.10 and 923.03 (AOAC, 2019), respectively. Protein content was determined by the micro-Kjeldahl method using a nitrogen-to-protein conversion factor of 6.25 (AACC Method 46–13, 2000). Lipid content was determined by Soxhlet extraction using hexane as solvent (AACC Method 30–26, 2000). Total dietary fibre content was determined using an enzymatic-gravimetric kit (AACC Method 32–07, 2000). Total carbohydrate content was estimated by the colorimetric phenol-sulphuric acid method according to Dubois et al. (1956). The crude fibre content was determined as the residue remaining after sequential treatment with hydrochloric acid and sodium hydroxide solutions; the insoluble residue was subsequently washed, dried, and weighed. Fibre content was calculated using the following equation:

$$\text{Total fiber (\%)} = \frac{\text{Dry residue weight (ash corrected)}}{\text{sample mass}} 100 \quad (1)$$

Gluten test

A qualitative gluten test was performed on doughs prepared from quinoa, amaranth, and buckwheat flours, following AACC Method 38–10 (AACC, 2000). Each dough was kneaded with saline solution and carefully washed to remove soluble components. The absence of an elastic, cohesive network upon washing confirmed the lack of gluten in all three flour types.

Hagberg falling number test

This analysis evaluates alpha-amylase activity by measuring the time (in seconds) required for a plunger to fall through a heated starch slurry, in accordance with AACC Method 56–81B (2000). A higher falling number indicates lower enzyme activity and is associated with improved pasta texture and cooking quality.

Culinary analysis of gluten-free pasta

The cooking performance of the gluten-free pasta samples was evaluated in accordance with AACC Approved Method 66–50.01 (AACC, 2009) and the Italian pasta quality standards (2014). Samples of 50 g were cooked in 500 mL of boiling distilled water at 100 °C, without added salt, for a duration that varied according to the raw material composition of each formulation, using a VORWERK Thermomix cooking appliance.

The optimal cooking time (OCT) was determined by cooking pasta strands in boiling water and testing them at 30-second intervals. The OCT corresponded to the complete disappearance of the white opaque core of ungelatinised starch, as observed when a strand was compressed between two transparent plates (Kultys & Moczowska-Wyrwisz, 2022).

The **swelling index (SI)** was calculated to assess the water absorption and hydration capacity of the pasta during cooking. Following cooking to the optimal cooking time and draining for 5 minutes, the swelling index was determined using Eq. 2 (Petitot et al., 2010; Bianchi et al., 2019):

$$SI (\%) = \frac{(\text{Weight of cooked pasta} - \text{Weight of dry pasta})}{\text{Weight of dry pasta}} 100 \quad (2)$$

Cooking loss (CL) was determined gravimetrically by evaporating the cooking water and weighing the remaining solid residue. The percentage of dry matter lost during cooking was calculated and expressed using Equation 3 (Itusaca-Maldonado et al., 2024).

$$CL (\%) = \frac{\text{Dried residue in cooking water}}{\text{Pasta weight before cooking}} 100 \quad (3)$$

The **disintegration degree (DD)** was assessed by quantifying the amount of dry matter released into the cooking water. Briefly, 25 mL of cooking water was evaporated at 105 °C to constant weight, and the remaining dry residue was weighed and expressed relative to the initial pasta mass, reported as a percentage of dry matter (Kaur et al., 2011).

Cooking water acidity was evaluated by titration in accordance with AOAC Method 947.05 (AOAC, 2011). Following overcooking of the pasta for OCT + 6 minutes, 10 mL of cooking water was titrated with 0.01 N sodium hydroxide (NaOH) solution, using phenolphthalein as the indicator. Results were expressed as titratable acidity and reported as a percentage of lactic acid equivalent (% lactic acid).

Sensory evaluation of gluten-free pasta

Sensory evaluation was conducted by a panel of 30 trained female assessors (senior undergraduate and doctoral students at ENSA), who evaluated eight cooked pasta samples, including a control, for appearance, colour, texture, firmness, and aftertaste, using a 9-point hedonic scale (1 = extremely unpleasant, 9 = excellent). The panel comprised exclusively female participants, selected on the basis of their greater willingness and availability to take part in the testing sessions. Samples were coded and presented in randomised order under standardised conditions (Petitot et al., 2010; Giménez et al., 2015).

Statistical analysis

A simplex-centroid mixture design was employed to investigate the effect of quinoa, amaranth, and buckwheat flour proportions on the nutritional, technological, and sensory properties of the developed pasta. Seven experimental formulations were evaluated, with flour proportions summing to 100%. A control formulation comprising 100% rice flour was included for comparative purposes. Analysis of variance (ANOVA) was performed to determine statistically significant effects of flour composition on the measured parameters. The influence of flour blend ratios on end-product quality was further characterised using response surface methodology (RSM).

The experimental data were analyzed using Statistica software (version 12.0, StatSoft Inc., USA). A three-component mixture design was employed to investigate the

effects of the proportions of quinoa (Q), amaranth (A), and buckwheat (B) on the selected responses. Because the proportions of the mixture components were constrained to a constant total, i.e., $Q + A + B = 1$, a mixture regression approach was used. The experimental responses, including protein content, aftertaste, firmness, and texture, were fitted using a first-order (linear) mixture model. The general form of the model was expressed as:

$$Y = \beta_Q + \beta_A + \beta_B \quad (4)$$

where Y represents the predicted response, Q, A, and B represent the proportions of quinoa, amaranth, and buckwheat, respectively, and β_Q , β_A , and β_B are the corresponding regression coefficients. The statistical significance of the fitted models was evaluated by analysis of variance (ANOVA). The adequacy of each model was assessed using the coefficient of determination (R^2), adjusted coefficient of determination (R^2 , residual mean square (MS), and the model p-value. A probability level of $p < 0.05$ was considered statistically significant.

The fitted regression equations were subsequently used to predict the responses within the experimental mixture region. The relative contribution of the three components to each response was assessed from the magnitude of the corresponding regression coefficients. Model adequacy was further considered based on the agreement between experimental and predicted values.

RESULTS AND DISCUSSION

Chemical composition and Technological characteristics of gluten free pasta

Table 2 shows an overview of the Chemical composition analysis of the gluten-free tagliatelle products produced in this study and the Hagberg Falling Number to assess the α -amylase activity in flours.

Protein content

The results showed a significant increase ($p < 0.001$) in the protein content of tiger nut (*Cyperus esculentus* L.) enriched gluten-free tagliatelle compared with the rice-based control. Protein content ranged from $6.05 \text{ g } 100 \text{ g}^{-1}$ in the control pasta to $10.43 \text{ g } 100 \text{ g}^{-1}$ in formulation F2, with the highest value observed in the blend containing rice, tiger nut, and amaranth. This increase can be attributed mainly to amaranth, which is naturally richer in protein ($14\text{--}17.80 \text{ g } 100 \text{ g}^{-1}$ dry matter) than rice and also provides a favourable amino acid profile. Its incorporation therefore enhanced the overall protein density of the gluten-free pasta. In addition, the relatively high protein content of amaranth may promote interactions with starch and water during processing, potentially affecting the structure and texture of the final product (Lorenzo et al., 2018; De Bock et al., 2021).

Among the formulations, F4, F5, F7, and F3 showed the highest protein values after F2, whereas F6 and F1 exhibited the lowest. Protein content in pseudocereals varies considerably according to species and cultivar, ranging from 13.10 to 21.50% in amaranth, 8 to 22% in quinoa, and 5.70 to 18.90% in buckwheat (Martínez-Villaluenga et al., 2020; Nandan et al., 2024).

Table 2. Chemical composition analysis of eight gluten-free tagliatelle formulations enriched with Tiger nut and the flours Hagberg Falling Number

	Fat (g)	Carbohydrates (g)	Protein (g)	Fibre (g)	MS (%)	Moisture (%)	Ash (%)	HFN (s)
F1 :Q	08.07 ^b ± 0.80	57.81 ^c ± 1.50	08.56 ^b ± 0.20	07.89 ^c ± 0.30	85.32 ^b ± 2.21	14.68 ^c ± 0.13	02.26 ^c ± 0.10	210.00 ^a ± 5.20
F2 :A	08.45 ^b ± 0.70	59.61 ^b ± 1.30	10.43 ^c ± 0.40	06.19 ^b ± 0.20	89.07 ± 3.23	10.93 ^a ± 0.34	01.96 ^b ± 0.10	195.00 ^c ± 6.30
F3 :B	07.29 ^b ± 0.40	62.42 ^a ± 1.50	09.12 ^c ± 0.34	05.32 ^a ± 0.23	89.90 ^a ± 1.83	10.10 ^a ± 0.20	04.99 ^c ± 0.20	170.00 ^c ± 3.50
F4 : A+Q	08.19 ^b ± 0.50	58.66 ^b ± 1.60	09.50 ^c ± 0.30	07.14 ^b ± 0.12	88.70 ± 3.22	11.30 ± 0.30	02.28 ^b ± 0.23	210.00 ^a ± 6.40
F5 : A+B	07.83 ^b ± 0.30	61.00 ^a ± 1.60	09.70 ^c ± 0.20	05.76 ^a ± 0.30	83.95 ^c ± 1.67	16.05 ^c ± 0.42	02.96 ^c ± 0.14	180.00 ^c ± 5.50
F6 : Q+B	07.67 ^b ± 0.40	60.00 ^a ± 2.01	08.85 ^b ± 0.12	06.71 ^b ± 0.20	82.52 ^c ± 3.44	17.48 ^c ± 0.34	02.68 ^c ± 0.16	189.00 ^c ± 3.70
F7 :A+Q+B	08.06 ^b ± 0.50	59.87 ^b ± 1.30	09.35 ^c ± 0.23	06.59 ^b ± 0.10	86.02 ^a ± 2.67	13.98 ^a ± 0.50	03.27 ^c ± 0.10	207.00 ^b ± 6.20
Control	06.60 ± 0.20	63.94 ± 1.20	06.05 ± 0.40	04.92 ± 0.11	88.93 ± 1.68	11.07 ± 0.20	01.31 ± 0.07	220.00 ± 8.40

F: gluten-free pasta formulations; Q: Quinoa; A: Amaranth; B: Buckwheat; A+Q: Amaranth + Quinoa; A+B: Amaranth + Buckwheat; Q+B: Quinoa + Buckwheat; A + Q + B: Amaranth + Quinoa + Buckwheat. All formulas contain 40% rice, xanthan gum, salt and edible tiger nuts. Each value represents mean ± SE ($n = 3$). (^a $p < 0.05$, ^b $p < 0.01$, ^c $p < 0.001$ compared with control pasta made exclusively from rice. HFN : Hagberg Falling Number.

Compared with rice flour (6.80% protein) and tiger nut (3.28–8.45%), pseudocereals generally contain higher levels of protein and offer a more balanced amino acid composition, particularly with respect to lysine, which is limited in conventional cereals such as rice and maize (Ramos-Diaz et al., 2020; Sonawane et al., 2024). These nutritional characteristics increase the functional relevance of gluten-free pasta, especially for individuals with metabolic or gastrointestinal disorders (Kumar et al., 2020; Yu et al., 2022; Kaur et al., 2023).

Fiber content

Dietary fiber content was significantly higher ($p < 0.001$) in the pseudo-cereal tagliatelle than in the rice control pasta, ranging from 4.92 to 7.89 g 100 g⁻¹. The highest value was observed in the quinoa–tiger nut formulation, followed by F4, suggesting a complementary effect between these ingredients. In contrast, the rice–tiger nut control exhibited the lowest fiber content (4.92 g 100 g⁻¹), which is consistent with the comparatively lower fiber content of its constituent ingredients (Sabah et al., 2019; Pirzadah & Malik, 2020).

The relatively high fiber levels observed in the pseudo-cereal formulations can be attributed to the presence of dietary fiber components, including polysaccharides and lignin, in pseudo-cereals, as well as the appreciable fiber content of tiger nut, which can reach approximately 14.80% (Bazine & Arslanoğlu, 2020; Yadav & Upasana, 2022). Dietary fiber is widely recognized for its beneficial effects on human health, including improved digestive function, regulation of lipid and glucose metabolism, and reduced risks of obesity, cardiovascular diseases, and inflammation (Tang & Tsao, 2017; Nandan et al., 2024).

Carbohydrate content

Carbohydrate content ranged from 57.81 to 63.94 g 100 g⁻¹ across the pasta formulations. The lowest values were recorded for F1, F2, F4, F5, F6, and F7, whereas the rice–tiger nut formulation exhibited the highest carbohydrate content ($p < 0.001$). Buckwheat alone showed a relatively high carbohydrate content, comparable to that of rice. These variations ($p < 0.01$) may be related to differences in the carbohydrate composition of cereals and pseudo-cereals, particularly their starch content (Yadav & Upasana, 2022; Khan et al., 2024; Singh et al., 2024).

Pseudo-cereals generally contain approximately 50–75% carbohydrates, mainly in the form of starch and non-starch polysaccharides (Khan et al., 2024). The comparatively lower carbohydrate contents of quinoa- and amaranth-based formulations may therefore contribute to their nutritional value as alternatives to conventional starch-rich cereal products.

Fat content

Fat content was significantly higher ($p < 0.01$) in the pseudo-cereal pasta (mean: 7.94 g 100 g⁻¹) than in the rice–tiger nut control tagliatelles (6.60 g 100 g⁻¹). Among the pseudo-cereal formulations, amaranth pasta exhibited the highest fat content, followed by quinoa- and buckwheat-based pasta. The relatively high lipid content of amaranth is consistent with previous reports and may be related to its substantial proportion of unsaturated fatty acids, particularly linoleic acid, which contributes to its favorable nutritional profile (Krichene et al., 2016; Sabah et al., 2019; Nandan et al., 2024).

Tiger nut also contributed substantially to the lipid content of the formulations. Its fat content has been reported to range from approximately 22 to 45%, with a fatty acid profile characterized mainly by oleic, linoleic, and palmitic acids, making it nutritionally comparable in some respects to olive oil (Bazine & Arslanoğlu, 2020; Haoua et al., 2023; Wu et al., 2024). In contrast, rice flour contains only about 1.50% fat (Pirzadah & Malik, 2020), which may explain the lower lipid content observed in the rice-based control.

Mineral content

Ash content, used as an indicator of total mineral content, was significantly higher in the pseudo-cereal pasta ($p < 0.001$; mean: 2.91%) than in the rice-based control (1.31%). F3 exhibited the highest ash content (4.99%), followed by F7, whereas the rice-based pasta showed the lowest value. These findings are consistent with previous reports indicating that pseudo-cereals generally provide higher levels of minerals than conventional cereals (Mithila & Khanum, 2015; Martínez-Villaluenga et al., 2020). Among the pseudo-cereals, amaranth is generally recognized as a particularly rich source of minerals, followed by buckwheat and quinoa (Kaur et al., 2023). Tiger nut may further contribute to the mineral profile of the formulations, particularly through potassium, phosphorus, magnesium, calcium, and sodium (Haoua et al., 2023).

Overall, the incorporation of pseudo-cereals and tiger nut into gluten-free pasta improved its nutritional profile compared with the rice-based control, particularly with respect to protein, dietary fiber, fat, and mineral contents, while maintaining a carbohydrate content within the range commonly observed for pasta products. These findings highlight the potential of pseudo-cereals as valuable ingredients for developing nutritionally enhanced gluten-free pasta, owing to their contribution of high-quality proteins, dietary fiber, essential minerals, and bioactive compounds (Mithila & Khanum, 2015; Yu et al., 2022).

Gluten content

Gluten analysis confirmed the absence of gluten in all formulations. This result was expected because amaranth, quinoa, buckwheat, and tiger nut are naturally gluten-free ingredients. Accordingly, no elastic gluten network was observed after the washing procedure (Alvarez-Jubete et al., 2010; Casini et al., 2022; Wu et al., 2024).

Hagberg falling number

The behaviour of the pasta during cooking was confirmed by the results of the technological quality of the flours used in this study using the Hagberg falling number (HFN) shown in Table 3. The HFN values revealed a clear effect of buckwheat incorporation on α -amylase activity and pasta quality. Buckwheat and amaranth–buckwheat formulations exhibited the lowest HFN values, indicating increased α -amylase activity and greater starch hydrolysis compared with the control. Excessive starch degradation can weaken the pasta matrix, promote the release of soluble sugars, and contribute to strand stickiness and a pasty texture, which is consistent with the higher swelling index and cooking loss observed in these formulations (Perten, 1964; Cannon et al., 2022; Guo et al., 2023). Although buckwheat contains phenolic and other bioactive compounds that may interact with digestive enzymes and potentially modulate α -amylase activity, the present results suggest that, under the processing conditions used, its incorporation did not sufficiently counteract the overall starch-degrading activity

reflected by the low HFN values. This apparent discrepancy may depend on the proportion of buckwheat, processing conditions, and the stability or bioavailability of its bioactive compounds. Therefore, buckwheat-rich formulations may require further technological optimization to improve starch stability and cooking performance. From a nutritional perspective, however, the potential interaction of buckwheat bioactive compounds with starch-digesting enzymes remains of interest and warrants further investigation through in vitro starch digestibility and α -amylase inhibition assays.

Cooking quality of free gluten pasta

The optimum cooking time. The optimum cooking time (OCT) varied significantly among the pasta formulations ($p < 0.001$), ranging from 30 s for 100% buckwheat pasta to 7 min for quinoa-based pasta. As shown in Table 3, the amaranth- and quinoa-based formulations generally exhibited longer OCTs than the rice-based control. In contrast, the incorporation of buckwheat tended to shorten the cooking time, particularly when combined with amaranth or quinoa. This trend is consistent with the findings of Ramos-Diaz et al. (2020), who reported cooking times ranging from 5 to 9 min for gluten-free pasta and observed a negative association between quinoa content and cooking time. Similarly, Sujka et al. (2022) found that the incorporation of buckwheat hulls reduced cooking time from 4.8 min for the control pasta to 3.7 min in pasta containing 20% buckwheat.

Regarding cooking quality, F3 exhibited acceptable firmness but showed a tendency to stick and partially disintegrate during cooking, resulting in a pasty texture, particularly at higher levels of buckwheat incorporation. These characteristics may be attributed to the starch–protein composition of buckwheat and the absence of a gluten network. Buckwheat components can influence water absorption, starch swelling, and the structural stability of the pasta during cooking. Therefore, its incorporation level should be carefully controlled to achieve an appropriate balance between hydration, structural integrity, and cooking stability.

The other formulations showed better resistance to disintegration and maintained their shape during cooking, which may be attributed, at least in part, to the presence of xanthan gum. The improved structural stability contributed to a firmer and more acceptable texture compared with the control pasta (Table 3).

High cooking loss is generally associated with poor cooking performance and is influenced by several factors, including the type of raw material, particularly the use of gluten-free pseudocereals, as well as the quantity and quality of proteins. In gluten-free pasta, the absence of a gluten network limits the ability of the protein matrix to retain starch during cooking, thereby increasing the release of solids into the cooking water. In addition, starch damage and a low degree of gelatinization may facilitate starch solubilization and consequently increase cooking loss. Conversely, high-temperature drying can improve the structural integrity and cooking resistance of pasta, thereby reducing the loss of solids during cooking (Milde et al., 2020; Hussein et al., 2025; Mostafa et al., 2025).

This explanation is in line with the observations reported by Lubowa et al. (2020); Lux et al. (2023), according to which the solubility of starch weakly bound to the surface of the pasta is a major factor in cooking loss. On the other hand, a high protein and fiber content can weaken the structure of the pasta, thus promoting greater release of solids into the water, as reported by Milde et al. (2020) and Mostafa et al. (2025).

Cooking loss. Cooking loss corresponds to the amount of dry matter, mainly starch and soluble proteins, released from the pasta into the cooking water.

As shown in Table 3, most formulations, including the control, exhibited cooking losses exceeding 16%, whereas the binary formulations F5, F6, and F7 showed lower values. Based on this criterion, these formulations can therefore be considered technologically satisfactory.

Table 3. Cooking quality parameters of gluten-free pasta formulated with pseudocereals and tiger nuts flours

	CL (%)	OCT (min)	SI (%)	DD (%)	LA (%)
F1 : Q	24.00 ^c ± 3.42	7.00 ^c ± 1.20	81.40 ^c ± 2.73	37.58 ^c ± 2.10	0.28 ^c ± 0.06
F2 : A	20.00 ± 2.21	6.00 ^c ± 1.10	85.40 ^c ± 3.11	55.84 ^b ± 2.60	0.24 ^c ± 0.04
F3 : B	16.00 ^c ± 2.10	0.50 ^c ± 0.03	155.40 ^c ± 4.21	22.05 ^c ± 1.20	0.08 ^c ± 0.02
F4 : A + Q	18.00 ^b ± 2.55	3.00 ^b ± 1.00	117.20 ^c ± 1.37	28.16 ^c ± 1.40	0.09 ^c ± 0.03
F5 : A + B	8.00 ^c ± 1.40	2.00 ^c ± 0.50	123.80 ^c ± 3.77	14.68 ^c ± 1.60	0.06 ^b ± 0.02
F6 : Q + B	4.00 ^c ± 1.51	1.00 ^c ± 0.20	125.00 ^c ± 4.05	14.43 ^c ± 2.30	0.10 ^c ± 0.03
F7 : A + Q + B	6.00 ^c ± 1.22	1.50 ^c ± 0.10	127.00 ^c ± 3.78	10.21 ^c ± 2.10	0.07 ^c ± 0.02
Control	21.11 ± 3.10	4.00 ± 0.23	69.80 ± 2.68	51.18 ± 3.06	0.02 ± 0.01

F: gluten-free pasta formulations; Q: Quinoa; A: Amaranth; B: Buckwheat; A + Q: Amaranth + Quinoa; A + B: Amaranth + Buckwheat; Q + B: Quinoa + Buckwheat; A + Q + B: Amaranth + Quinoa + Buckwheat. All formulas contain 40% rice, xanthan gum, salt and edible tiger nuts. Each value represents mean ± SE ($n = 3$). (^a $p < 0.05$, ^b $p < 0.01$, ^c $p < 0.001$ compared with control pasta made exclusively from rice. CL: cooking loss; OCT: optimal cooking time; SI: Swelling index. DD: disintegration degree; LA: lactic acid.

A correlation coefficient of $r = 0.91$ highlights a strong relationship between buckwheat content and baking loss. Similarly, a strong correlation was found for quinoa flour ($r = 0.8$) and amaranth flour ($r = 0.76$). These results suggest that increasing the proportion of flour in the formulation, particularly buckwheat flour, leads to an increase in cooking loss. These observations are consistent with those of Schoenlechner et al. (2010); Ramos-Diaz et al. (2020), who showed that incorporating up to 50% quinoa or amaranth into fresh buckwheat pasta led to a considerable increase in cooking losses and loss of firmness. The results show that as the optimal cooking time increases, cooking losses also tend to increase, suggesting a proportional relationship between the two parameters with a correlation coefficient of $r = 0.77$, as illustrated in Table 3.

Swelling Index. The SI results presented in Table 3 showed that the formulations exhibited a significantly higher water absorption capacity (mean: 116.46%; $p < 0.001$) than the control formulation (69.80%). The highest SI values were observed in the buckwheat-containing formulations, indicating a greater capacity to absorb water and increase in volume during cooking. This behavior may be attributed to the relatively high protein and dietary fiber contents of pseudo-cereal flours. In GFP, these components can enhance water absorption and retention within the starch–protein matrix. In particular, dietary fibers may form a viscous matrix that retains water and contributes to the stabilization of the pasta structure in the absence of gluten. This may improve cooking and textural properties while also increasing the nutritional value of the product. These findings are consistent with previous studies (Mercier et al., 2016; Sultan et al., 2020; Kostetska et al., 2023; Pinel et al., 2024).

Degree of disintegration (DD). The DD is an indicator of pasta structural stability during cooking, with higher values reflecting greater breakdown and a greater release of soluble components into the cooking water. As shown in Table 3, the amaranth- and rice-based formulations exhibited the highest DD values, which may be related to their limited ability to develop a cohesive protein and starch matrix in the absence of gluten. This weaker structure may promote starch leaching into the cooking water (Özyurt et al., 2015; Hussein et al., 2025). In contrast, the other GFP (F1, F3, F4, F5, F6, and F7) exhibited significantly lower DD values than the control pasta ($p < 0.001$), indicating greater structural stability during cooking. This is particularly relevant for GFP, in which maintaining structural integrity is a major technological challenge. Among the formulations, F7, containing the three pseudo-cereals, tiger nut, and xanthan gum, showed a marked reduction in DD compared with the control ($p < 0.001$), highlighting the potential synergistic effect of these ingredients on cooking stability (Giuberti et al., 2015; Fouad et al., 2022).

The lower DD values may be attributed to the interactions among starch, proteins and dietary fibers during cooking. Starch gelatinization is accompanied by water absorption and structural changes within the pasta matrix, while proteins and dietary fibers may contribute to the retention of starch and other soluble components within the structure. Consequently, a more cohesive matrix can limit the release of dry matter into the cooking water and improve cooking stability (Cordelino et al., 2018; Zaky et al., 2022; Zhang et al., 2025). The incorporation of xanthan gum may further reinforce the pasta matrix by increasing viscosity and improving structural cohesion during cooking (Nascimento et al., 2014; Petri, 2015; Scarton et al., 2021; Casini et al., 2022; Kostetska et al., 2023; Mostafa et al., 2025).

Cooking water acidity. As shown in Table 3, the quinoa, amaranth, and buckwheat based pasta formulations exhibited significantly higher acidity levels than the rice-based control, with a mean value of 0.082% compared with 0.02% for the control ($p < 0.001$). Although the mechanisms underlying these differences are not fully established in the literature, the higher acidity may be associated with the release or diffusion of organic acids and amino acids, partial hydrolysis of starch and proteins, and changes in the mineral balance during cooking. In addition, the presence of phenolic compounds in pseudo-cereals and tiger nut may contribute to the observed differences in acidity. Similar observations have been reported by Bonafaccia et al. (2003), Özyurt et al. (2015), and Diamante et al. (2019).

Sensory quality of gluten free pasta. As shown in Table 4, visual inspection revealed light and dark speckles in the pasta, mainly attributable to the incorporation of whole tiger nut flour, which influenced its overall appearance. The rice-based control exhibited a pale beige colour and a mild, neutral taste, providing a suitable reference for comparison. In contrast, the pseudo-cereal formulations displayed distinct colour characteristics: buckwheat imparted a reddish hue, amaranth maintained a relatively light colour, whereas quinoa resulted in a darker brown appearance. These ingredients also influenced the flavour profile, with amaranth and quinoa contributing slightly bitter and earthy notes, while buckwheat produced a milder flavour.

Table 4. Dried and cooked gluten-free pasta enriched with Tiger nut

	F1 : Q	F2 : A	F3 : B	F4 : A+Q	F5 : A+B	F6 : Q+B	F7 : A+Q+B	Control
Dried pasta								
50 g of pasta cooked at OCT								
Cooking parameters	Tmin = 5.00 min OCT = 7.00 min Toverc = 13 min	Tmin = 4 min OCT = 6 min Toverc = 12 min	Tmin = 10 s OCT = 30 s Toverc = 6 min 30 s	Tmin = 1 min OCT = 3 min Toverc = 9 min	Tmin = 1 min OCT = 2 min Toverc = 8 min	Tmin = 30 s OCT = 1 min Toverc = 7 min	Tmin = 30 s OCT = 1 min 30 s Toverc = 7 min 30 s	Tmin = 2 min OCT = 4 min Toverc = 10 min

F: gluten-free pasta formulations; Q: Quinoa; A: Amaranth; B: Buckwheat; A + Q: Amaranth + Quinoa; A + B: Amaranth + Buckwheat; Q + B: Quinoa + Buckwheat; A + Q + B: Amaranth + Quinoa + Buckwheat. All formulas contain 40% rice, xanthan gum, salt and edible tiger nuts. Each value represents mean $\pm$ SE ($n = 3$). Tmin: Minimum cooking time, OCT: optimal cooking times; Toverc: overcooking times for each formulation.

The naturally sweet and nutty taste of tiger nut appeared to partially mask the bitterness associated with amaranth- and quinoa-based formulations (Fig. 1). Overall, cooking enhanced pleasant cereal and toasted aromas across all formulations.

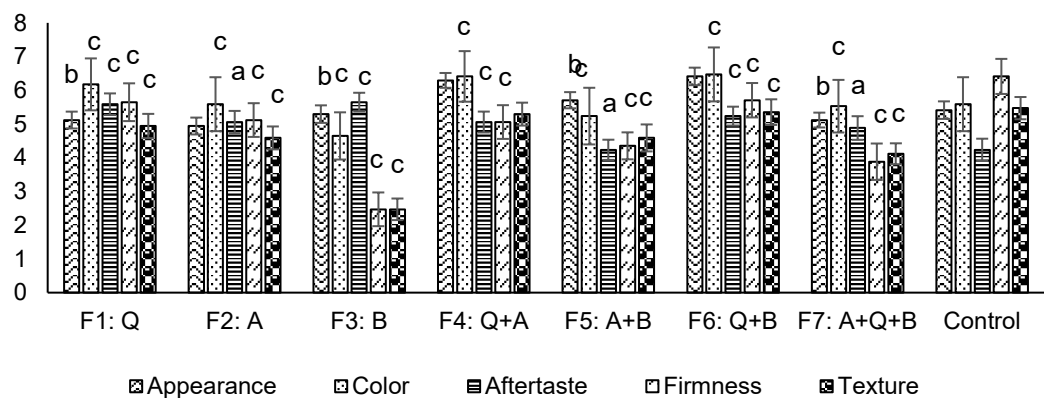


Figure 1. Average scores awarded to sensory characteristics of cooked gluten-free pseudocereals tagiatelle by the tasting panel.
F: gluten-free pasta formulations; Q: Quinoa; A: Amaranth; B: Buckwheat; A + Q: Amaranth + Quinoa; A + B: Amaranth + Buckwheat; Q + B: Quinoa + Buckwheat; A+Q+B: Amaranth + Quinoa + Buckwheat. All formulas contain 40% rice, xanthan gum, salt and edible tiger nuts. ^a *p* < 0.05, ^b *p* < 0.01, ^c *p* < 0.001 compared with control pasta.

As shown in Fig. 2, the sensory evaluation indicated that F6 received the highest overall score (5.8), slightly exceeding that of the rice-based control (5.4). Despite an unpleasant residual aftertaste reported by some panelists, F6 performed well across most sensory attributes. In contrast, F3 received the lowest overall score (4.1), mainly due to its unpleasant texture and stickiness, whereas F2 obtained the lowest appearance score (4.9).

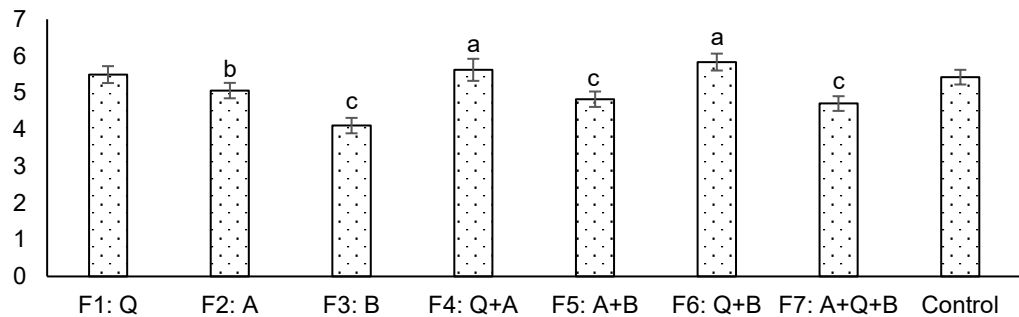


Figure 2. Overall appreciation of cooked gluten-free pseudocereals tagiatelle.
F: gluten-free pasta formulations; Q: Quinoa; A: Amaranth; B: Buckwheat; A + Q: Amaranth + Quinoa; A + B: Amaranth + Buckwheat; Q + B: Quinoa + Buckwheat; A + Q + B: Amaranth + Quinoa + Buckwheat. All formulas contain 40% rice, xanthan gum, salt and edible tiger nuts. ^a *p* < 0.05, ^b *p* < 0.01, ^c *p* < 0.001 compared with control pasta.

ANOVA validated significant differences among formulations for firmness ($p \approx 0.0000016$) and texture ($p = 0.00094$), but not for appearance, colour or aftertaste ($p > 0.05$). Correlation tests revealed a strong positive correlation between 'fermented' perception and texture ($r = 0.94$). All samples containing pseudocereals, except the F5, were described as having a more intense residual taste compared to the control.

The rice pasta had a neutral taste and was easily digestible, but it was sticky and had a lower firmness than the pseudocereal blends. The F6 was the most promising, as it had texture and firmness values closest to the control, as well as the best structure-flavour compromise. In contrast, the F3, despite exhibiting the highest swelling index, was disadvantaged by its low chewiness and sticky texture. This phenomenon is explained by the absorption of a large amount of water (SI) by the fibers of pseudocereals, which give the gluten-free dough a rougher texture and more fragile structure after kneading. These findings are consistent with those of earlier researchers who have associated culinary parameters to sensory parameters (Rungsardthong et al., 2021; Lux et al., 2023; Jongrattanaavit & Pinkaew, 2025). In this context, the incorporation of tiger nut flour may further influence these technological and sensory responses, owing to its fibre and lipid fractions. These components can modify water absorption, starch hydration, dough development, and the structural organization of the gluten-free matrix. Thus, at an appropriate inclusion level, tiger nut may complement the functional effects of pseudocereals and contribute to a more favourable technological and sensory balance, whereas excessive incorporation could disrupt matrix formation and negatively affect texture and acceptability.

Modeling and optimization of the nutritional and sensory properties of pseudo-cereal-based pastas through Mixture Design

The mixture design highlighted clear interactive effects among quinoa, amaranth, and buckwheat, indicating that the response of each quality attribute depended not only on the proportion of a given pseudocereal but also on its combination with the other components. Protein enrichment was primarily associated with increasing the amaranth fraction, whereas F1 showed a comparatively lower protein contribution. This suggests a synergistic or complementary effect of formulation composition rather than a simple additive response. The higher protein levels obtained with pseudocereal-based formulations compared with the control further confirm the nutritional advantage of replacing rice with protein-rich pseudocereals (Fig. 3).

A similar compositional dependency was observed for texture and firmness, although the response pattern differed from that observed for protein content. Quinoa-rich formulations generally provided a firmer and more cohesive pasta structure, whereas increasing the buckwheat proportion tended to reduce these attributes. This behaviour may reflect differences in the functional properties of the pseudocereal components, particularly their starch and protein characteristics, which can modify matrix formation and water interactions in the absence of gluten. The predominance of quinoa in firmer formulations is consistent with previous observations that quinoa can contribute to dough cohesion and structural integrity (Schoenlechner et al., 2010). Importantly, the response surfaces indicate that these effects were not independent: increasing quinoa improved structural properties but was also associated with a more pronounced aftertaste, whereas increasing amaranth appeared to attenuate this sensory limitation.

Thus, the incorporation of amaranth may partially compensate for the sensory drawback associated with high quinoa levels, while buckwheat produced intermediate responses (Fig. 3).

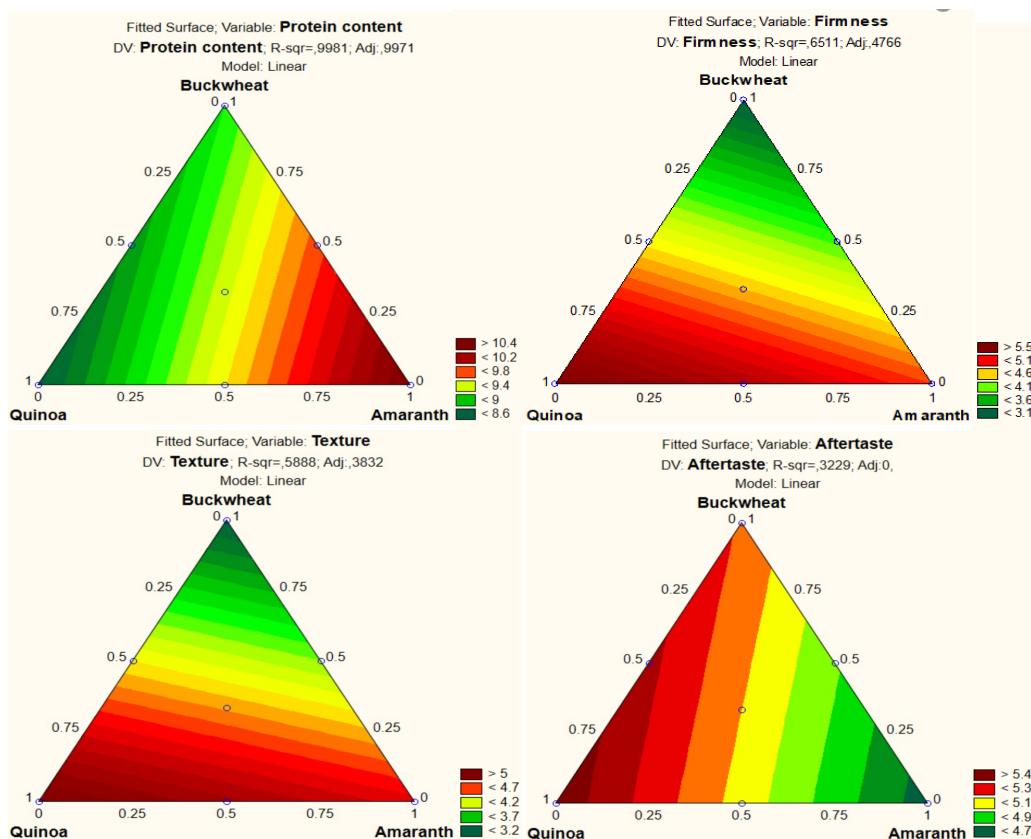


Figure 3. Response surface for protein content, firmness, texture and aftertaste according to the proportions of quinoa, amaranth, and buckwheat in a mixing plan.

The desirability analysis further demonstrated the importance of these interactions because no single pseudocereal simultaneously maximized all responses. The predicted optimum was located in an intermediate region combining quinoa and amaranth, rather than at the extreme composition of any single component. This indicates a formulation trade-off in which the nutritional advantage of amaranth and the textural contribution of quinoa can be balanced while reducing the sensory penalty associated with excessive quinoa incorporation. From a formulation perspective, the results therefore suggest that the technological and sensory performance of the gluten-free pasta is governed by the balance among pseudocereals rather than by the isolated effect of one ingredient. Depending on the formulation objective, shifting the mixture towards amaranth may favour protein enrichment and reduced aftertaste, whereas increasing quinoa may improve firmness and texture; buckwheat can be used as a complementary component, although excessive incorporation may compromise structural properties (Fig. 4).

The optimisation procedure identified formulation F4 comprising 50% quinoa flour and 50% amaranth flour as the optimal blend, with an overall desirability score of approximately 0.70, selected primarily on the basis of protein content and overall sensory acceptability. Formulation F4 exhibited a cooking loss of 18.00%, compared with 21.11% for the rice flour-based control, representing a reduction of approximately 14.7%. Although cooking performance parameters were not incorporated as response variables in the optimisation model, they provide important complementary information on the structural integrity and cooking behaviour of the optimised pasta. The lower cooking loss observed for F4 reflects superior solid matter retention during cooking, while its swelling and disintegration characteristics contribute to the textural attributes perceived during sensory evaluation. Overall, F4 simultaneously achieves the predefined nutritional and sensory objectives while exhibiting satisfactory technological performance, supporting its potential as a nutritionally enhanced gluten-free pasta alternative.

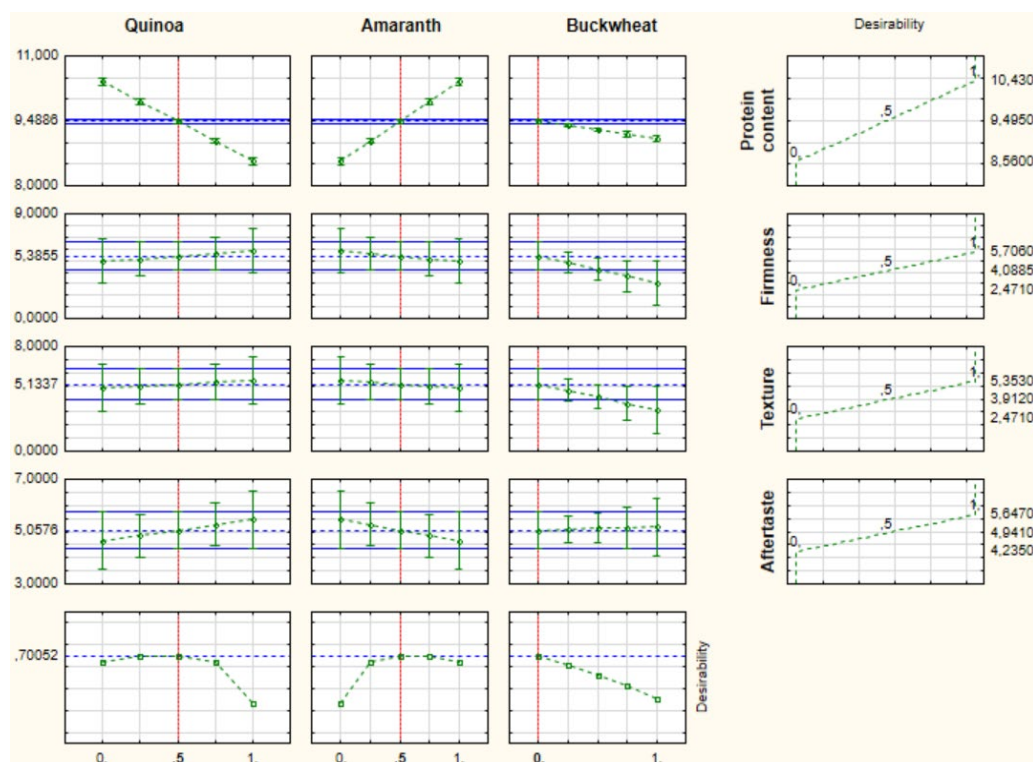


Figure 4. Profiles of the predicted effects of the ingredients on the measured responses and overall desirability.

Goodness-of-fit statistics and significance of the regression models

The adequacy of the regression models was evaluated using the coefficient of determination (R^2), adjusted R^2 , residual mean square, and model significance. The results are shown in Table 5.

The regression analysis revealed a marked difference in model adequacy among the studied responses. The model developed for protein content showed an excellent fit ($R^2 = 0.991$; adjusted $R^2 = 0.990$) and was highly significant ($p = 0.0004$), indicating that 99.1% of the variability in protein content was explained by the model. In contrast, the models developed for aftertaste ($R^2 = 0.320$; adjusted $R^2 = 0.000$; $p = 0.45$), firmness ($R^2 = 0.605$; adjusted $R^2 = 0.470$; $p = 0.12$), and texture ($R^2 = 0.580$; adjusted $R^2 = 0.380$; $p = 0.17$) were not statistically significant. These findings indicate that the experimental factors adequately described protein content, whereas the models for sensory and textural responses exhibited limited predictive and explanatory capacity. This results could be explained as protein content is experimentally determined whereas sensory and texture responses were evaluated by a panel.

Table 5. Models goodness of fit

Response	R^2	R^2 adjusted	MS residual	p -value
Proteins	0.991	0.990	0.001	0.0004
Aftertaste	0.320	0.000	0.022	0.45
Firmness	0.605	0.470	0.608	0.12
Texture	0.580	0.380	0.590	0.17

The regression equations obtained from the mixture design indicate that quinoa (Q), amaranth (A), and buckwheat (B) contributed differently to the studied responses. For protein content, the regression equation was:

$$Y \text{ Protein} = 8.57Q + 10.46A + 9.09B \quad (5)$$

Among the three components, amaranth showed the highest coefficient (10.46), followed by buckwheat (9.09) and quinoa (8.57). This indicates that amaranth made the greatest contribution to the predicted protein content of the formulations, whereas quinoa showed the lowest contribution among the three components. For aftertaste, the fitted equation was:

$$Y \text{ Aftertaste} = 5.46Q + 4.64A + 5.18B \quad (6)$$

Quinoa had the highest coefficient (5.46), followed closely by buckwheat (5.18), while amaranth exhibited the lowest coefficient (4.64). This suggests that, within the investigated mixture domain, quinoa contributed most strongly to the predicted aftertaste response. For firmness, the equation was:

$$Y \text{ Firmness} = 5.86Q + 4.90A + 3.04B \quad (7)$$

Quinoa exhibited the highest coefficient (5.86), followed by amaranth (4.90) and buckwheat (3.04). Therefore, quinoa showed the greatest contribution to the predicted firmness, whereas buckwheat had the lowest contribution. For texture, the regression equation was:

$$Y \text{ Texture} = 5.42Q + 4.83A + 3.16B \quad (8)$$

Quinoa had the highest coefficient (5.42), followed by amaranth (4.83) and buckwheat (3.16), indicating a comparatively greater contribution of quinoa to the predicted texture response.

Overall, the regression coefficients indicate that the three pseudo-cereal ingredients contributed differently to the studied responses. Amaranth exhibited the greatest contribution to protein content, whereas quinoa showed the highest coefficients for aftertaste, firmness, and texture. Buckwheat generally presented intermediate or lower

coefficients. These differences may be related to the distinct nutritional and physicochemical characteristics of the three grains, including their protein composition, starch characteristics, fiber content, and other matrix-forming components. However, because the study was based on a mixture design, the coefficients should be interpreted as the relative contribution of each mixture component rather than as independent factor effects.

Strengths and limitations

The present study has some limitations, particularly the use of a fixed tiger nut flour level, the inclusion of only female participants in the sensory evaluation, and the absence of long-term storage, nutrient bioavailability, and in vivo glycaemic assessments. Future research should therefore optimize tiger nut incorporation levels, investigate different cultivars and processing conditions, and further assess starch and protein digestibility, α -amylase inhibition, antioxidant activity, and glycaemic response. Larger and more diverse sensory panels, together with shelf-life and in vivo studies, are also recommended to further validate the nutritional, technological, functional, and consumer potential of the developed gluten-free pasta.

CONCLUSION

In conclusion, the incorporation of pseudocereal and tiger nut flours represents a promising approach for improving the overall quality of gluten-free tagliatelle. Amaranth provided the highest protein content and improved lipid quality; quinoa enhanced fiber enrichment and textural attributes; whereas buckwheat increased mineral content and cooking stability. The optimized formulation (F4 : amaranth + quinoa) provided a balanced combination of nutritional, technological, and sensory attributes, highlighting the potential of these alternative ingredients to overcome some of the quality limitations commonly associated with gluten-free pasta.

Further research should focus on storage stability, starch and protein digestibility, and nutrient bioavailability, together with broader sensory evaluation and in vivo studies. From an industrial perspective, these formulations could provide opportunities for diversifying gluten-free pasta products and valorizing nutrient-rich alternative raw materials.

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