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Development of functional gluten-free noodles using foxtail millet and tapioca

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Abstract

Noodles are widely consumed convenience foods and contribute significantly to daily energy intake. Despite their nutritional benefits, foxtail millet and jackfruit seeds remain underutilized in food processing, creating opportunities for value-added product development. Therefore, the present study was conducted to develop gluten-free composite noodles using foxtail millet flour and tapioca powder fortified with defatted soy flour and jackfruit seed powder, and to evaluate their sensory, nutritional, and storage qualities. Six formulations (T0–T5) were developed by altering the proportions of foxtail millet flour and tapioca powder and were subjected to sensory evaluation by a semi-trained panel of fifteen judges using a nine-point hedonic scale. Among the developed formulations, T3 containing 60 g foxtail millet flour, 30 g tapioca powder, 5 g each of defatted soy flour and jackfruit seed powder, and 2 g guar gum showed the highest sensory preference, obtaining a total mean score of 8.52 and an overall acceptability score of 8.9. Nutritional analysis of T3 showed moisture content of 7.38%, carbohydrate 71.62 g/100 g, protein 11.58 g/100 g, fat 2.27 g/100 g, crude fibre 4.8 g/100 g, ash 2.35%, calcium 74.90 mg/100 g, potassium 149.50 mg/100 g, iron 3.11 mg/100 g, and energy value of 353.31 kcal/100 g.

Keywords: Foxtail millet, gluten-free noodles, tapioca starch, defatted soy flour, jackfruit seed powder, composite flour

Introduction

Noodles are among the most universally consumed convenience foods in the world, valued for their versatility, low cost, extended shelf life, and broad consumer appeal. Conventionally, noodles are produced from refined wheat flour, which owes its characteristic elasticity and cohesive texture to the gluten protein network formed upon hydration and mechanical working of the dough. However, the growing global incidence of celiac disease, non-celiac gluten sensitivity, and wheat allergy, combined with increasing consumer awareness about the nutritional limitations of refined wheat products — their low fibre content, modest protein quality, and high glycaemic index — has created substantial demand for well-formulated gluten-free alternatives (Rocchetti *et al.*, 2021; Augustin *et al.*, 2020) [2, 12]. At the same time, the need to improve the nutritional quality of staple convenience foods, particularly for vulnerable population groups, has encouraged researchers to explore composite flour systems that combine the functional properties of multiple ingredients.

Foxtail millet (Setaria italica) is one of the most ancient domesticated cereal crops, cultivated widely across Asia and Africa under diverse agro-climatic conditions, including semi-arid and drought-prone environments where major cereals struggle to grow. Despite its remarkable agronomic resilience, short growing period, and rich nutritional profile — encompassing protein (10–12%), complex carbohydrates, dietary fibre, minerals including iron, calcium, and phosphorus, and a diverse array of bioactive phytochemicals such as phenolic acids, flavonoids, and carotenoids — foxtail millet remains significantly underutilized in modern food processing (Kalsi *et al.*, 2023; Sahoo *et al.*, 2025) [6, 15]. Its naturally gluten-free status, low glycaemic index, and documented health benefits including anti-diabetic, antioxidant, cardioprotective, and anti-inflammatory activities make it a particularly compelling base ingredient for functional food development. The International Year of Millets has further accelerated interest in incorporating millets such as foxtail into mainstream food products, creating a timely opportunity for value-added product development (Bandyopadhyay *et al.*, 2017) [3].

The primary challenge in developing noodles from foxtail millet lies in the absence of gluten, which is responsible for the viscoelastic dough properties, structural cohesion, and cooking stability that consumers associate with high-quality noodles. To address this, tapioca flour derived from cassava was incorporated as a structural modifier in the present study. The high amylopectin content of tapioca starch promotes extensive swelling and gel formation upon hydration and cooking, effectively compensating for the absence of gluten by providing the elastic, cohesive framework needed to maintain noodle strand integrity and improve cooking quality (Zhu, 2016; Chisenga *et al.*, 2019) [4, 19]. Defatted soy flour was incorporated as a complementary protein source, providing all essential amino acids including lysine, which is characteristically limited in cereal-based diets, thereby substantially improving the biological value of the final product (Rani *et al.*, 2019) [10]. Jackfruit seeds (Artocarpus heterophyllus), commonly discarded during fruit processing despite constituting approximately 10–15% of fruit weight, are a valuable source of resistant starch, dietary fibre, minerals, and bioactive phenolics, and their incorporation into the noodle formulation represents a sustainable approach to reducing agricultural waste while improving nutritional quality (Swami *et al.*, 2016; Ranasinghe et al., 2019) [9, 16]. Guar gum was additionally included at a low inclusion level to improve dough cohesiveness, reduce cooking losses, and improve texture stability (Mudgil *et al*., 2018) [8].

Material and Method

Materials and Chemicals

Foxtail millet flour was obtained from a certified commercial flour manufacturer, while fresh tapioca tubers were purchased from the local market. Mature jackfruit seeds were collected from household sources. Defatted soy flour, food-grade guar gum, and iodised salt were procured from a reputable commercial supplier. Analytical-grade chemicals and reagents were used for all nutritional analyses conducted during the study.

Fresh tapioca tubers were thoroughly washed to eliminate soil particles and other surface impurities. The tubers were manually peeled using stainless steel knives and cut into thin, uniform slices to facilitate efficient drying. The sliced tubers were immersed in clean water for 20 minutes to reduce cyanogenic compounds and then drained properly. Drying was carried out in a hot air oven at 60°C until the moisture content decreased below 10%. The dried slices were subsequently milled into fine flour, sieved to ensure uniform particle size, and packed in moisture-proof polyethylene pouches for storage until further use.

Fresh jackfruit seeds were cleaned thoroughly to remove adhering pulp and foreign matter, followed by manual removal of the outer white seed coat. The seeds were boiled for a short period to soften the tissue and then cut into small, uniform pieces. Light dry roasting was carried out to improve flavour and minimize the characteristic raw seed odour. The roasted seed pieces were dried in a hot air oven at 60°C until the moisture level was reduced below 10%. The dried material was then ground into fine powder using a laboratory mill, sieved to obtain uniform particle size, and stored in airtight containers under cool and dry conditions until used in noodle preparation.

Formulation of Gluten-Free Composite Noodles

Six noodle formulations (T0–T5) were developed by varying the proportion of foxtail millet flour and tapioca powder, while keeping jackfruit seed powder (5 g), defatted soy flour (5 g), and guar gum (2 g) constant across all formulations containing flour enrichments. The control (T0) consisted of 100 g foxtail millet flour and 2 g guar gum only, without any tapioca powder or functional enrichments. In treatments T1 through T5, tapioca powder was progressively increased from 10 g to 50 g in 10 g increments, with a corresponding reduction in foxtail millet flour. The detailed ingredient composition is presented in (Table 1).

Table 1: Ingredient composition of the six gluten-free composite noodle formulations (per 100 g dry blend)

Ingredients	T0 (Control)	T1	T2	T3	T4	T5
Foxtail millet flour (g)	100	80	70	60	50	40
Tapioca powder (g)	–	10	20	30	40	50
Jackfruit seed powder (g)	–	5	5	5	5	5
Defatted soy flour (g)	–	5	5	5	5	5
Guar gum (g)	2	2	2	2	2	2

Noodle Preparation Procedure

Salt (1–2% of the total flour weight) and guar gum were uniformly blended with the dry flour mixture before the gradual addition of water (30–35%). The dough was kneaded for 10–15 minutes until a smooth and cohesive consistency was obtained and then allowed to rest for 15 minutes to ensure proper hydration. The rested dough was extruded using a laboratory noodle extruder to produce uniform noodle strands. The extruded noodles were steamed for 5 minutes to promote starch gelatinisation, followed by drying in a hot air oven at 50–55°C until the moisture content was reduced to 8–10%. The dried noodles were cooled to room temperature and packed in moisture-proof polyethylene pouches for further analysis.

Sensory Evaluation

Sensory evaluation of all six noodle formulations was conducted using the method described by Swaminathan (1974) [17] with minor adaptations. A semi-trained panel of fifteen judges was selected from the college based on their availability, sensory acuity, and familiarity with noodle products. Each formulation was cooked under standardised conditions — boiled in water for a fixed time based on the optimum cooking time of each treatment — and served warm to panelists in coded containers in a randomized order to minimise order and carry-over effects. Panelists evaluated six sensory attributes — appearance, colour, flavour, texture, taste, and overall acceptability — using a nine-point hedonic scale, where 9 indicated 'like extremely' and 1 indicated 'dislike extremely'. Drinking water was provided between samples for palate cleansing, and adequate rest intervals were observed.

Nutritional Analysis

The optimized treatment (T3) was chosen for nutritional evaluation to determine its proximate and mineral composition. Moisture content was analysed following AOAC (2023) procedures by drying the sample in a hot air oven maintained at 60–70°C until a constant weight was achieved, and the percentage reduction in weight was taken as the moisture content.

Carbohydrate analysis was carried out using the Anthrone method described by Sadasivam and Manickam (1992), with absorbance readings taken at 630 nm against a glucose standard curve.

Protein content was determined by the Kjeldahl method (AOAC, 2023), where the nitrogen value obtained after digestion, distillation, and titration was converted into protein by multiplying it with a factor of 6.25.

Fat estimation was performed using the Soxhlet extraction technique with petroleum ether as the extracting solvent according to AOAC (2023).

Crude fibre content was assessed using the acid–alkali digestion procedure described by Chopra and Kanwar (1978)

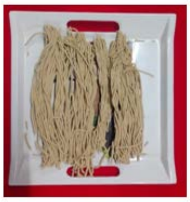
Ash content was measured through incineration of the sample in a muffle furnace at 600°C following AOAC (2023) guidelines.

The total energy value of the sample was calculated using Atwater conversion factors, and all values were expressed on a 100 g basis.

Iron estimation was carried out by a colorimetric method using potassium thiocyanate as described by Raghuramulu *et al*. (2003), and absorbance was recorded at 540 nm.

Calcium content was determined through EDTA titration according to the method outlined by Page (1982).

Potassium analysis was performed using a flame photometer following the procedure described by Jackson (1973).


T0

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T0


T3

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T3

Results

Sensory Evaluation of Gluten-Free Composite Noodles

The mean sensory scores for all six formulations are presented in Table 2. The evaluation revealed consistent and meaningful differences among treatments across all attributes — appearance, colour, flavour, texture, taste, and overall acceptability. Total mean scores ranged from 5.7 for the control (T0) to 8.52 for T3, clearly demonstrating that the progressive incorporation of tapioca powder into the foxtail millet flour base significantly improved the sensory acceptability of the noodles up to an optimum level, beyond which scores declined.

Treatment T3, composed of 60 g foxtail millet flour and 30 g tapioca powder, emerged as the most preferred formulation across all sensory dimensions. It achieved a texture score of 9.0 — the highest possible rating — reflecting outstanding firmness, smoothness, elasticity, and chewability that panelists found highly appealing. Overall acceptability was rated at 8.9, confirming T3 as the most comprehensively preferred formulation. The balanced incorporation of tapioca starch at 30 g in T3 provided the structural cohesiveness needed to compensate for the absence of gluten in foxtail millet flour, while preserving the characteristic cereal flavour, golden colour, and pleasant aroma of foxtail millet that defined the product's identity. Treatment T2 also performed well with a total mean score of 7.5, while T4 (7.7) and T5 (6.7) showed progressive declines associated with over-dilution of foxtail millet's characteristic sensory profile and changes in structural texture at higher tapioca levels. The control (T0) scored lowest across all parameters, with a total mean score of 5.7, confirming that 100% foxtail millet flour without tapioca supplementation or functional enrichment is insufficient to produce a commercially acceptable noodle product.

Table 2: Mean sensory scores of gluten-free foxtail millet composite noodle formulations (nine-point hedonic scale)

Treatment	Appearance	Colour	Flavour	Texture	Taste	Overall Accept-ability	Total Mean Score
T0	5.5	6.0	5.7	5.3	6.2	5.8	5.7
T1	6.0	6.2	6.8	6.1	6.5	6.4	6.3
T2	7.3	7.7	7.0	7.5	8.0	7.8	7.5
T3	8.1	8.5	8.0	9.0	8.6	8.9	8.52
T4	7.9	7.5	7.3	8.2	7.6	7.8	7.7
T5	6.5	7.0	6.8	6.0	7.3	7.0	6.7

Nutritional Composition of the Optimised Formulation (T3)

The nutritional composition of T3 is presented in Table 3. The formulation demonstrated a well-rounded nutritional profile that reflects the complementary contributions of foxtail millet flour, tapioca powder, defatted soy flour, and jackfruit seed powder. The carbohydrate content of 71.62 g/100 g reflects the naturally high complex carbohydrate content of foxtail millet and tapioca, providing a substantial and sustained energy substrate. The protein content of 11.58 g/100 g is a significant improvement over conventional wheat-based noodles (typically 6–7 g/100 g), attributable primarily to the high-quality plant protein contributed by defatted soy flour, with additional protein from foxtail millet and jackfruit seed powder. The fat content was notably low at 2.27 g/100 g, supporting the suitability of the product for health-conscious consumers seeking low-fat dietary options and also contributing to better storage stability by limiting the risk of oxidative rancidity. The crude fibre content of 4.8 g/100 g — drawn from the combined fibre fractions of foxtail millet and jackfruit seed powder — is considerably higher than that of refined wheat noodles, positioning the product as a fibre-enriched functional food with benefits for digestive health, satiety, and glycaemic control. The energy value of 353.31 kcal/100 g is moderate and consistent with other dried cereal-based noodle products.

The mineral profile of T3 further reinforces its nutritional value. Calcium content of 74.90 mg/100 g, potassium of 149.50 mg/100 g, and iron of 3.11 mg/100 g collectively reflect the mineral-rich composition of foxtail millet flour and jackfruit seed powder, both of which are well-documented sources of these essential minerals. The moisture content of 7.38% and ash content of 2.35% confirm that the product possesses low water activity, which is favourable for shelf stability and microbial safety during ambient storage.

Table 3: Nutritional composition of the optimised gluten-free foxtail millet noodle formulation (T3)

Nutrient / Parameter	Value (per 100g) t0	Value (per 100 g) t3	p-value	Interpretation
Moisture (%)	6.90	7.38	0.082	NS
Carbohydrate (g/100 g)	68.45	71.62	0.003	S
Protein (g/100 g)	8.65	11.58	<0.001	S
Fat (g/100 g)	2.10	2.27	0.124	NS
Crude Fibre (g/100 g)	3.2	4.8	0.002	S
Ash (%)	1.82	2.35	0.004	S

Calcium (mg/100 g)	34.40	74.90	<0.001	S
Potassium (mg/100 g)	172.80	149.50	<0.001	S
Iron (mg/100 g)	2.01	3.11	0.002	S
Energy (kcal/100 g)	336.75	353.31	<0.001	S

NS = Non-significant ($p > 0.05$); S = Significant at $p < 0.05$

Statistical interpretation

The results of the paired *t*-test indicated significant differences ($p < 0.05$) between T0 and T3 for carbohydrate, protein, crude fibre, ash, calcium, potassium, iron, and energy values, showing that the incorporation of defatted soy flour and jackfruit seed powder significantly affected the nutritional composition of the developed noodles. In contrast, moisture and fat content showed non-significant differences ($p > 0.05$), indicating that these parameters were not markedly influenced by the formulation changes. The significant increase in protein, fibre, mineral content, and energy value in T3 suggests that the optimized formulation provided improved nutritional quality compared to the control sample (T0).

Discussion

The sensory data from this study clearly establish that tapioca starch plays a decisive role in determining the structural and sensory quality of foxtail millet-based gluten-free noodles, and that there exists a well-defined optimum level of incorporation beyond which further addition becomes counterproductive. The progressive improvement in sensory scores from T0 to T3 is fundamentally attributable to the rheological contribution of tapioca starch in the dough and cooked noodle system. Tapioca starch's exceptionally high amylopectin content — typically exceeding 80% — drives extensive granule swelling and gelatinisation during both the steaming and cooking steps, forming a cohesive, elastic gel matrix that effectively substitutes for the gluten network absent in foxtail millet flour (Chisenga *et al*., 2019; Zhu, 2016) [4, 19]. This explains why T3 received the outstanding texture score of 9.0, reflecting the superior firmness, chewiness, and surface smoothness achievable at the 30 g tapioca incorporation level. These findings are consistent with those of Meherunnahar *et al*. (2024) [7], who demonstrated that composite foxtail millet noodles incorporating functional starches showed significantly improved texture, water absorption, and cooking quality compared to single-flour formulations.

The decline in sensory scores observed from T4 onward, despite continued increases in tapioca content, can be attributed to several converging effects. As tapioca starch content exceeds the structural optimum, the starch-to-protein ratio in the dough increases beyond the point where a balanced network can be maintained, resulting in a softer, more gummy cooked noodle that lacks the firm bite that consumers associate with high-quality products (Mudgil *et al*., 2018) [8]. Additionally, excessive tapioca dilution progressively diminishes the characteristic golden colour, nutty aroma, and mild cereal flavour of foxtail millet that contributed so positively to T3's sensory profile. The progressive reduction in flavour (7.3 at T4, 6.8 at T5) and colour (7.5 at T4, 7.0 at T5) scores beyond T3 reflects the progressive loss of foxtail millet's natural sensory identity at higher tapioca substitution levels, consistent with observations of Roobab and Maqsood (2024) [13] on the flavour dilution effects of high starch incorporation in millet-based noodle systems. The control T0, prepared entirely from foxtail millet flour without tapioca or functional enrichments, produced noodles with poor dough cohesiveness, rough surface texture, high cooking loss, and brittle strands — all well-documented consequences of producing gluten-free noodles from a single millet flour without structural amendment (Tereshchenko *et al*., 2013; Renzetti and Jurgens, 2016) [11, 18].

The nutritional profile of T3 represents a meaningful advancement over conventional wheat-based noodles in several key respects. The protein content of 11.58 g/100 g is substantially higher than the 6–7 g/100 g typically found in refined wheat noodles, a difference directly attributable to the inclusion of defatted soy flour, which not only elevates the total protein content but also significantly improves its amino acid completeness — particularly with respect to lysine, which is limiting in foxtail millet (Rani *et al*., 2019) [10]. This makes T3 considerably more valuable from a protein nutrition perspective than either pure foxtail millet or wheat noodles. The dietary fibre content of 4.8 g/100 g, sourced from the combined contributions of foxtail millet's bran fraction and jackfruit seed powder's resistant starch and structural polysaccharides, exceeds the fibre content of standard commercial wheat noodles by a considerable margin and places the product squarely within the category of fibre-enriched functional foods (Devi *et al*., 2014) [5]. Dietary fibre at this level is associated with improved intestinal transit, enhanced satiety, reduced post-prandial blood glucose response, and lower long-term risk of cardiovascular disease and type 2 diabetes.

The mineral content of T3 is equally noteworthy. Iron at 3.11 mg/100 g, calcium at 74.90 mg/100 g, and potassium at 149.50 mg/100 g collectively reflect the mineral-dense character of foxtail millet flour and jackfruit seed powder, both of which are well-documented sources of these essential micronutrients (Kalsi et al., 2023; Ranasinghe *et al*., 2019) [6, 10]. The iron content is particularly significant from a public health perspective, given the high prevalence of iron deficiency anaemia in India. At moderate serving sizes of 75–100 g dry noodle, T3 could contribute approximately 15–25% of the adult daily recommended intake for iron, representing a meaningful dietary contribution through a staple convenience food. The low fat content (2.27 g/100 g) and moderate energy value (353.31 kcal/100 g) further support the suitability of the product for a broad range of consumers including those managing metabolic conditions.

Conclusion

The present study has successfully demonstrated that gluten-free composite noodles of superior nutritional quality, excellent sensory acceptability, and good shelf-life stability can be produced from a well-optimised blend of foxtail millet flour, tapioca powder, defatted soy flour, and jackfruit seed powder. Among the six formulations evaluated, Treatment T3 — comprising 60 g foxtail millet flour, 30 g tapioca powder, 5 g each of defatted soy flour and jackfruit seed powder, and 2 g guar gum — was identified as the optimum formulation, achieving the highest total mean sensory score of 8.52, including an outstanding texture score of 9.0 and overall acceptability of 8.9. The nutritional composition of T3, characterised by a protein content of 11.58 g/100 g, dietary fibre of 4.8 g/100 g, and appreciable quantities of iron, calcium, and potassium, positions the product as a nutritionally enriched functional food that addresses the limitations of conventional wheat-based noodles. Shelf-life evaluation confirmed that acceptable sensory quality was maintained throughout 60 days of ambient storage, and microbial analysis demonstrated that total plate count remained within FSSAI-prescribed permissible limits with no detectable yeast or mould growth at any storage interval. The findings of this study confirm the potential of foxtail millet, jackfruit seeds, and defatted soy flour as highly promising ingredients for the development of health-promoting, gluten-free, and value-added noodle products suitable for both domestic consumption and commercial production.

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