



Finger Millet Flour-Fortified Pangas (*Pangasianodon hypophthalmus*) Sausage: Effects on Proximate Composition, Texture, Colour, and Sensory Attributes

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Abstract

The present study evaluated the effects of finger millet (*Eleusine coracana*) flour incorporation on proximate composition, texture, colour, and sensory attributes of Pangas (*Pangasianodon hypophthalmus*) fish sausages. A completely randomised design with two treatments was used: control sausages prepared with a conventional formulation without millet flour, and treatment sausages incorporating 5% finger millet flour as partial replacement for corn starch. Data were analysed using an independent-samples *t*-test at a 5% significance level. Millet incorporation significantly ($p < 0.05$) decreased moisture from 66.68 ± 4.37 to $59.36 \pm 4.15\%$, whilst increasing fat (2.76 ± 0.33 to $5.99 \pm 1.24\%$) and ash (2.68 ± 0.33 to $3.56 \pm 0.74\%$) levels. Protein content increased marginally from 11.87 ± 1.65 to $12.63 \pm 1.71\%$. Texture profile analysis showed significant increases ($p < 0.05$) in hardness (16.83 ± 0.05 to 33.02 ± 0.09 N), gumminess (9.33 ± 0.03 to 13.76 ± 0.06 N), and chewiness (8.44 ± 0.03 to 12.39 ± 0.07 N mm). Colour analysis revealed a significant reduction ($p < 0.05$) in yellowness values from 33.08 ± 0.71 to 22.38 ± 3.86 . Sensory evaluation by a 20-member panel indicated high acceptability for millet-fortified fish sausages with superior odour and taste scores. Finger millet flour is an effective functional ingredient for developing nutritionally enhanced fish sausages with improved textural and colour properties whilst maintaining sensory acceptability.

Keywords: Fish sausage, finger millet, value addition, texture profile analysis, functional foods, Pangas

Introduction

Fish and fishery-derived products are widely recognised as important sources of high-quality protein, bioavailable micronutrients, and essential fatty acids (Debnath et al., 2014; Meenu, Parvathy, Chandrababu, & Sarika, 2024). Aquatic animal foods contributed 15% of global animal protein availability in 2023, providing at least 20% of per capita animal protein supply for over 40% of the world's population (FAO, 2026). Global per capita availability of aquatic animal foods averaged 21.3 kg in 2024, with Asia accounting for 74% of total global aquatic food availability (FAO, 2026). Beyond protein, fish provide eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), long-chain ω -3 fatty acids with documented benefits for cardiovascular health, fetal neuronal development, and cognitive function (Swanson, Block, & Mousa, 2012; Noreen, Hashmi, Aja, & Atoki, 2025).

Pangas (*Pangasianodon hypophthalmus*), commonly known as striped catfish, has emerged as a commercially important freshwater species in Asian aquaculture. Introduced to India in the mid-1990s through West Bengal, the species grows rapidly, approaching 1 kg within 90 days under optimal conditions (Lakra & Singh, 2010). Its white flesh, high boneless fillet yield, absence of intermuscular bones, and mild flavour make it particularly suitable for value-added product development. However, Pangas mince often exhibits limitations in texture development, water-holding capacity, and nutritional density, necessitating functional enhancement to meet contemporary consumer expectations.

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Sausages are among the most versatile restructured fish product categories, combining comminuted mince with salt, seasonings, and functional additives to achieve desirable sensory characteristics and extended shelf life (Raju, Shamasundar, & Udupa, 2003). Although fish-based products possess exceptional nutritional value, they naturally lack dietary fibre, creating an important opportunity for functional fortification. Dietary fibres improve water-binding capacity, gelling properties, and cooking yield in restructured seafood products (Borderías, Sánchez-Alonso, & Pérez-Mateos, 2005), with oat fibre incorporation at 2.5% demonstrating improved gel strength and water-holding capacity in Indian major carp sausages (Gore, Xavier, Nayak, Tandale, & Balange, 2022). While millet flour fortification has been explored in inclusion levels ranging from 2.5 to 10%, evidence consistently indicates that moderate levels tend to offer a more practical balance between functional improvement and sensory acceptability (Elavarasan, Malini, Ninan, Ravishankar, & Dayakar, 2024). Studies on wheat fibre in restructured fish products found that 3% fibre incorporation received favourable sensory ratings, whereas products containing 6% fibre were less well accepted by panellists (Sánchez-Alonso, Haji-Maleki, & Borderias, 2007), underscoring the relevance of selecting a moderate inclusion level for initial product development.

Millet grains have gained recognition as nutrient-dense, gluten-free grains rich in protein, dietary fibre, minerals, and bioactive compounds (Saleh, Zhang, Chen, & Shen, 2013; Bhatt et al., 2023). Among these, finger millet (*Eleusine coracana*) stands out for its exceptionally high calcium content (344 mg/100 g), methionine-rich protein, and potent antioxidant phenolics including ferulic acid (Shobana et al., 2013). India remains the world's largest millet producer, a distinction reinforced by the United Nations' declaration of 2023 as the International Year of Millets (FAO, 2025).

While millet incorporation in fish sausage has been previously investigated, existing research has predominantly focused on tilapia and evaluated various millet varieties against corn flour (Elavarasan et al., 2024). The present study differs in that it focuses exclusively on finger millet, the variety with the highest documented calcium content among cereals, and represents, to the best of our knowledge, the first reported investigation of finger millet fortification in Pangas fish sausages. With this in mind, the

present study was carried out to assess the effect of finger millet flour incorporation on the proximate composition, texture, colour, and sensory attributes of Pangas sausage, hypothesising that millet incorporation would modify the proximate, textural, colour, and sensory characteristics of the product.

Materials and Methods

Fresh Pangas (*P. hypophthalmus*) with an average weight of approximately 2.5 kg were procured from the Borbazar wholesale fish market in Shillong, Meghalaya. The fish were transported to the Meat Processing Unit of the Division of Animal and Fisheries Sciences at the ICAR Research Complex for the North-Eastern Hill Region in insulated ice boxes, maintaining a fish-to-ice ratio of 1:1 under strict hygienic conditions. Upon arrival at the processing facility, the fish were stored at 4 °C until processing, which was initiated within 6 hours of procurement to ensure optimal freshness and quality. The fish were manually dressed by removing the viscera, deposited fat portion, head, and fins, then filleted to obtain boneless meat portions. The average dressing percentage was found to be 45–47%. The fillets were thoroughly washed with chilled potable water and subsequently minced using a mechanical mincer equipped with a 6-mm plate to obtain a uniform particle-size distribution. Commercial finger millet flour of food-grade quality was sourced from the local market in Shillong. The proximate composition of the finger millet flour was determined as moisture 11.50±0.42%, crude protein 7.16±0.35%, crude fat 1.50±0.12%, crude fibre 3.40±0.25%, total ash 2.50±0.18%, and carbohydrate 74.40±0.60%. All chemicals and reagents used throughout the experimental procedures were of analytical grade and procured from standard suppliers.

Fish sausages were prepared following the standardised method described by Surasani, Raju, Shafiq, Chandra, and Lakshmisha (2020) with minor modifications to accommodate the specific characteristics of Pangas mince and millet flour. The chilled fish mince was further comminuted in a stainless-steel bowl chopper for 3 min to achieve a finer particle size and improved protein extraction. Refined vegetable oil (3%) was added gradually to the comminuted mince, and mixing was continued for an additional 3 min to ensure uniform oil distribution and emulsion formation. Corn starch (5%) was then incorporated into this mixture,

followed by another 3 min of mixing to facilitate starch hydration and matrix formation. A spice mix (chilli powder, pepper, coriander, and garam masala) at 3%, salt at 2%, sugar at 1%, and a spice concentrate (ginger and garlic) at 3% were then added slowly to the batter along with chilled water (10%). Following this, finger millet flour was added, and the mixture was homogenised for 3 min to ensure complete incorporation and uniform distribution of all ingredients.

Two formulations were prepared for comparative evaluation. The control formulation consisted of fish mince without millet flour, whilst the treatment formulation incorporated 5% (w/w) finger millet flour as partial replacement for corn starch. The 5% inclusion level was adopted based on demonstrated success of dietary fibre fortification at 2.5-10% in restructured fish products (Gore et al., 2022; Elavarasan et al., 2024). The prepared mince mixture was filled into cellulose-based synthetic casings of uniform diameter using a pneumatic sausage stuffer to ensure consistent filling density and eliminate air pockets. The filled casings were manually tied at appropriate intervals to create individual sausage units of uniform size. The stuffed sausages were cooked in a water bath maintained at 90 ± 2 °C for 45 min to achieve complete thermal processing and protein gelation. Following cooking, the sausages were immediately transferred to ice water maintained at 5 ± 1 °C for 15 min to rapidly arrest the cooking process and facilitate gel setting. The cooked and cooled sausages were then stored at 4 °C overnight prior to analytical evaluation to allow complete equilibration and gel stabilisation. Samples were equilibrated to room temperature before conducting various analyses to ensure standardised testing conditions.

Proximate composition analysis was carried out to determine moisture, crude protein, crude fat, and total ash contents following standard methods (AOAC International, 2005). All analyses were performed in triplicate to ensure reliability and reproducibility. Crude protein content was determined using the micro-Kjeldahl method by converting the nitrogen content to crude protein using a standard conversion factor of 6.25. Fat content was estimated by the solvent extraction method using petroleum ether as the solvent in a Soxhlet extraction unit. Moisture content was measured by the oven-drying method at 105 °C for 16 h until constant weight was achieved. Total ash content was

quantified by incineration in a muffle furnace at 550 °C for 5 h. All measurements were recorded using a calibrated analytical balance (Shimadzu, Japan) with precision to 0.001 g.

Texture profile analysis was performed using a TA.HDplus Texture Analyser (Stable Micro Systems, United Kingdom). Sausage samples were equilibrated to room temperature for 30 min prior to analysis to eliminate temperature effects on textural properties. Samples were cut to 4 cm in height using a sharp stainless-steel cutter to ensure parallel surfaces. The samples were compressed twice to 40% of their original height using a P/75 probe (75 mm compression platen) at a constant cross-head speed of 1 mm/s with a 5-second interval between compressions. Instrumental textural parameters, including hardness, cohesiveness, springiness, gumminess, chewiness, and resilience were derived from the force-deformation curves obtained during the double compression cycle.

Instrumental colour measurements were obtained using an NR110 Precision Colorimeter (3nh Technology, Guangzhou, China). The colorimeter was placed directly on the surface of sausage samples, and measurements were recorded. The recorded colour parameters included L^* value representing lightness, a^* value indicating redness (positive values) to greenness (negative values), and b^* value denoting yellowness (positive values) to blueness (negative values). The whiteness index was calculated using the following formula described by Park (1994):

$$\text{Whiteness} = 100 - \sqrt{[(100 - L^*)^2 + a^{*2} + b^{*2}]}$$

Sensory evaluation of the sausage samples was conducted by a semi-trained panel of 20 members selected from staff and students at the ICAR-Research Complex for North-Eastern Hill Region, Umiam. Prior to evaluation, panellists were briefed on the sensory attributes to be assessed and the scoring procedures to ensure consistent understanding and application of evaluation criteria. Sausage samples were cooked in a microwave oven for 2.5 min and cut into uniform slices of 1.5 cm thickness. Each sample was assigned a random three-digit code to ensure blind evaluation and minimise bias. Samples were presented in randomised order to each panellist on clean white plates under standardised sensory laboratory conditions with adequate natural lighting and controlled ambient temperature.

Panellists assessed the samples based on colour, appearance, texture, flavour, and overall acceptability using a nine-point hedonic scale (Peryam & Pilgrim, 1957), where 1 represented “dislike extremely,” 5 represented “neither like nor dislike,” and 9 represented “like extremely”. Evaluation sessions were conducted in the mid-morning hours to avoid fatigue and ensure optimal sensory acuity.

Data from all analytical determinations, including proximate composition, texture profile, colour, and sensory evaluation, were subjected to statistical analysis using SPSS version 21.0 software (IBM Corporation, Armonk, New York, USA). An independent-samples *t*-test was performed to determine significant differences between control and millet-fortified sausage formulations for proximate composition, texture profile, and colour parameters. For sensory evaluation, a 20-member panel evaluated both control and millet-fortified sausages; the scores were paired by panellist and compared using a paired-samples *t*-test. Results are expressed as mean $\pm$ standard deviation. Proximate composition was determined in triplicate, whereas texture and colour measurements were obtained from six replicates as indicated in the respective table footnotes. Sensory evaluation was conducted using 20 panellists, with each panellist evaluating both formulations. Differences were considered statistically significant at $p < 0.05$.

Results and Discussion

The proximate composition of control and millet-fortified Pangas fish sausages is presented in Table 1. Moisture content significantly reduced ($p < 0.05$) from $66.68 \pm 4.37\%$ in control sausages to $59.36 \pm 4.15\%$ in millet-fortified sausages. This reduction was consistent with the established water-binding mechanism of dietary fibre, which involves physical entrapment of water within the porous fibre structure and chemical binding through hydroxyl groups present on fibre polysaccharides. During processing, hydration of fibre effectively immobilised water, reducing the moisture content of the final product. Studies on millet-fortified tilapia sausages revealed similar moisture reductions, with pearl millet achieving 65.94% moisture compared to 68.19% in the corn flour control (Elavarasan et al., 2024). This phenomenon was consistently observed across various fibre sources, including wheat fibre, rice bran, and inulin in restructured seafood products (Borderías et al., 2005). The reduced

moisture content in millet-fortified sausages may extend shelf life through reduced water activity, which inhibits microbial growth and enzymatic deterioration reactions, though this was not directly evaluated in the present study.

Crude protein content increased slightly from $11.87 \pm 1.65\%$ in the control to $12.63 \pm 1.71\%$ in millet-fortified sausages, though this difference was not statistically significant ($p > 0.05$). The marginal protein increase reflected the protein contribution from finger millet flour, which contained 7-8% protein with a favourable amino acid profile, particularly rich in methionine, an essential amino acid typically limiting in cereal proteins (Shobana et al., 2013). A comprehensive study evaluating nine millet varieties in tilapia sausages revealed that little millet achieved approximately 9% higher protein content at 13.40% compared to 12.25% in the corn flour control, demonstrating the protein-enriching potential of certain millet species (Elavarasan et al., 2024). Studies on chevon sausages incorporated with finger millet flour similarly showed maintenance or slight enhancement of protein content attributed to the quality protein present in ragi (Kumar, Chatli, Mehta, Verma, & Kumar, 2015). The comparable protein levels between the control and millet-fortified formulations in the present study suggested that millet incorporation maintained nutritional value from a protein perspective, whilst the concurrent increase in ash content pointed to an additional mineral contribution from the fortifying flour.

Fat content demonstrated a significant increase ($p < 0.05$) from $2.76 \pm 0.33\%$ in control sausages to $5.99 \pm 1.24\%$ in millet-fortified formulations. Finger millet naturally contained 1.5-5% fat, predominantly comprising unsaturated fatty acids including oleic acid (C18:1), palmitic acid (C16:0), and linoleic acid (C18:2) in decreasing order of abundance. Pearl millet-fortified tilapia sausages showed similar increases in fat content, with 7.62% fat compared to 4.93% in control formulations (Elavarasan et al., 2024). The increase in fat content, whilst increasing caloric density, provided nutritional benefits through enhanced satiety, improved mouthfeel, and potentially better absorption of fat-soluble vitamins. However, the extent of these functional benefits would require further investigation.

Total ash content increased significantly ($p < 0.05$) from $2.68 \pm 0.33\%$ in control to $3.56 \pm 0.74\%$ in millet-

fortified sausages, directly reflecting the notable mineral density of finger millet. Finger millet had the highest calcium content among all cereals at 344 mg/100 g, with some cultivars reaching up to 515 mg/100 g, about ten-fold higher levels compared to rice or wheat (Shobana et al., 2013). Beyond calcium, finger millet provided substantial quantities of iron (3.9 to 4.6 mg/100 g), magnesium, phosphorus, and zinc, all of which contributed to the elevated ash content. Research on iron fortification of finger millet with ethylenediaminetetraacetic acid as co-fortificant demonstrated significant increases in iron bio-accessibility, suggesting potential for further enhancement through processing optimisation (Tripathi & Platel, 2011). As individual minerals were not analysed in the sausages, the elevated ash content may reasonably be attributed to the mineral contribution of finger millet flour, though the specific mineral profile of the fortified product remains to be established.

Table 2 presents the instrumental colour parameters of control and millet-fortified sausages. The L^* value decreased from 47.85 ± 0.77 in control sausages to 45.39 ± 0.80 in millet-fortified sausages, though this difference was not statistically significant ($p > 0.05$). The reduction in lightness reflected the natural brown pigmentation of finger millet flour, which contained phenolic compounds including tannins, phenolic acids, and flavonoids that imparted characteristic colouration. Borderías et al. (2005) reported decreased lightness values in restructured fish products fortified with cereal fibre with the magnitude of change depending on fibre type, concentration, and processing conditions. Research on millet-fortified tilapia sausages similarly revealed decreased L^* values with millet incorporation in some varieties, attributed to the inherent pigmentation of millet cultivars (Elavarasan et al., 2024). The a^* value remained essentially unchanged between control (10.26 ± 0.8) and millet-fortified

sausages (10.28 ± 1.84) ($p > 0.05$), indicating that millet incorporation did not adversely affect the redness component, which is important for maintaining visual appeal in processed products. The b^* value showed a significant reduction ($p < 0.05$) from 33.08 ± 0.71 in control to 22.38 ± 3.86 in millet-fortified sausages. This reduction in yellowness was considered a beneficial modification, as excessive yellowness is associated with undesirable quality defects in sausages arising from lipid oxidation products and enzymatic browning reactions (Zeng et al., 2024).

The whiteness index improved from 37.40 ± 1.85 in control sausages to 40.10 ± 3.52 in millet-fortified sausages ($p < 0.05$). Despite reduced lightness, the substantial reduction in yellowness from 33.08 to 22.38 exerted greater influence on the overall whiteness calculation, which penalises deviation from the ideal white ($L^*=100$, $a^*=0$, $b^*=0$). This finding was consistent with other research on wheat fibre-fortified restructured fish products, which reported improved whiteness attributed to suppression of yellow pigments and reduction of oxidative colour defects (Sánchez-Alonso et al., 2007). The improved whiteness values represented a potential quality advantage, as whiteness was positively associated with freshness perception in restructured fish products.

The texture profile analysis parameters of control and millet-fortified sausages are presented in Table 3. Hardness increased substantially and significantly ($p < 0.05$) from 16.83 ± 0.05 N in control sausages to 33.02 ± 0.09 N in millet-fortified sausages, representing an increase of approximately 96%. This indicated enhanced gel strength and structural rigidity in millet-fortified sausages. Similar textural changes were observed in fibre-fortified fish products, with mechanisms involving fibre-protein interactions, water immobilisation, and formation of denser gel

Table 1. Proximate composition of control and millet-fortified Pangas fish sausages

Parameter	Control fish sausage	Millet-fortified fish sausage
Moisture (%)	66.68 ± 4.37^a	59.36 ± 4.15^b
Crude protein (%)	11.87 ± 1.65^a	12.63 ± 1.71^a
Crude fat (%)	2.76 ± 0.33^b	5.99 ± 1.24^a
Total ash (%)	2.68 ± 0.33^b	3.56 ± 0.74^a

Values are mean $\pm$ standard deviation ($n=3$). Different superscripts within the same row indicate significant differences ($p < 0.05$)

Table 2. Colour analysis of control and millet-fortified Pangas fish sausages

Parameter	Control fish sausage	Millet-fortified fish sausage
L* (Lightness)	47.85±0.77 ^a	45.39±0.80 ^a
a* (Redness)	10.26±0.8 ^a	10.28±1.84 ^a
b* (Yellowness)	33.08±0.71 ^a	22.38±3.86 ^b
Whiteness Index	37.40±1.85 ^b	40.10±3.52 ^a

Values are mean ± standard deviation (n=6). Different superscripts within the same row indicate significant differences ($p < 0.05$)

matrices. Studies on oat fibre-fortified Rohu sausages showed that fibre incorporation at 2.5-10% affected hardness, attributed to protein-protein interactions facilitated by water removal and increased gel density (Gore et al., 2022). Sherpa et al. (2023) also showed that inulin-fortified *Pangasius* sausages improved gel strength and texture profile parameters, with optimal effects observed at moderate inclusion levels that balanced textural enhancement with sensory acceptability.

Gumminess increased significantly ($p < 0.05$) from 9.33±0.03 N in control to 13.76±0.06 N in millet-fortified sausages, and chewiness increased significantly ($p < 0.05$) from 8.44±0.03 N mm in control to 12.39±0.07 N mm in millet-fortified sausages. The increased gumminess and chewiness indicated enhanced resistance to mastication, which may be perceived either as desirable substantiality or excessive firmness, depending on consumer preferences and cultural context. Springiness remained relatively stable at 0.91±0.06 in control and 0.90±0.05 in millet-fortified sausages ($p > 0.05$), indicating that elastic recovery properties remained largely unaffected. Cohesiveness decreased from 0.55±0.15 in control to 0.42±0.18 in millet-fortified sausages, though this difference was not statistically significant ($p > 0.05$). The slight reduction in cohesiveness may reflect some degree of physical interference of non-protein particles with the continuity of the protein gel network, a pattern similarly observed in dietary fibre-fortified fish products by Cardoso, Mendes, and Nunes (2008). Resilience showed a slight but non-significant reduction from 0.18±0.09 in control to 0.16±0.01 in millet-fortified sausages ($p > 0.05$), suggesting that the viscoelastic properties of the gel remained within acceptable ranges for restructured fish products.

Sensory evaluation demonstrated high acceptability for both control and millet-fortified sausages across

all evaluated attributes (Fig. 1). Millet-fortified sausages received notably high scores for odour and taste, consistent with the characteristic nutty flavour notes that finger millet contributed to the overall taste profile of processed foods. Studies on millet-fortified tilapia sausages showed that millet-included sausages presented higher overall acceptability scores than those prepared using corn flour (Elavarasan et al., 2024). Millet-fortified sausages recorded slightly lower scores for appearance and colour than the control, reflecting consumer response to the somewhat darker hue observed in instrumental measurements, though scores remained within the acceptable range. Research on low-fat fish sausages with dietary fibre demonstrated that appropriate fibre levels could maintain sensory acceptability, though excessive concentrations may negatively impact textural properties (Cardoso et al., 2008). Acceptable textural ratings despite substantially increased hardness suggested that the enhanced firmness was perceived as acceptable substantiality rather than objectionable toughness. Overall acceptability scores were nearly identical between control and millet-fortified treatments,

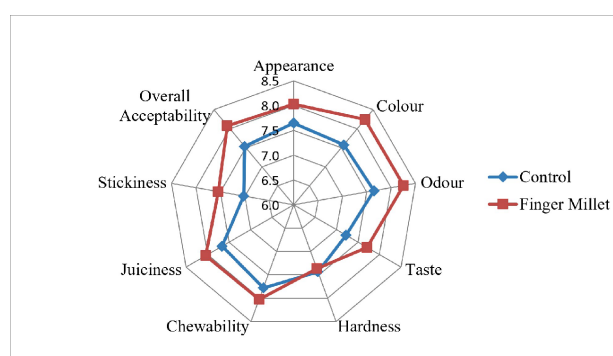


Fig. 1. Comparative sensory evaluation of control and millet-fortified Pangas fish sausages assessed by a twenty-member panel using a nine-point hedonic scale

Table 3. Texture profile analysis parameters of control and millet-fortified Pangas fish sausages

Parameter	Control fish sausage	Millet-fortified fish sausage
Hardness (N)	16.83 $\pm$ 0.05 ^b	33.02 $\pm$ 0.09 ^a
Springiness	0.91 $\pm$ 0.06 ^a	0.90 $\pm$ 0.05 ^a
Cohesiveness	0.55 $\pm$ 0.15 ^a	0.42 $\pm$ 0.18 ^a
Gumminess (N)	9.33 $\pm$ 0.03 ^b	13.76 $\pm$ 0.06 ^a
Chewiness (N mm)	8.44 $\pm$ 0.03 ^b	12.39 $\pm$ 0.07 ^a
Resilience	0.18 $\pm$ 0.09 ^a	0.16 $\pm$ 0.01 ^a

Values are mean $\pm$ standard deviation (n=6). Different superscripts within the same row indicate significant differences ($p < 0.05$)

indicating that millet incorporation did not compromise consumer appeal whilst providing measurable nutritional and functional improvements.

Incorporation of 5% finger millet flour into Pangas fish sausages reduced moisture content, increased fat and ash content, and produced a modest, non-significant rise in protein, alongside significant improvements in hardness, gumminess, and chewiness. Yellowness was significantly reduced, and whiteness index improved, while sensory acceptability, particularly for odour and taste, remained comparable to control formulations. These findings indicate that finger millet fortification at a 5% incorporation level is a promising approach for modifying the proximate composition and textural properties of Pangas sausages without compromising consumer acceptability, based on the parameters evaluated in this study. However, this study evaluated only a single inclusion level. Individual minerals were not analysed, and shelf life or economic assessment studies are yet to be established. Hence, the results should not be taken to imply an established optimum inclusion level. Further research is recommended across varied millet inclusion levels and storage conditions to validate these findings and support commercial application.

The present study had certain limitations that merit acknowledgement. The investigation was restricted to a single inclusion level of finger millet flour, without evaluation of varied incorporation levels, shelf life, or comprehensive economic analysis. The selection of a single inclusion level (5%) was based on reported success of dietary fibre fortification across a range of 2.5-10% in restructured fish products, and represented a moderate starting point

to balance functional improvement with sensory acceptability. However, the effect of other inclusion levels on sausage quality characteristics was not examined, and future studies should systematically evaluate multiple incorporation levels to identify the optimum. Additionally, shelf-life characteristics under ambient, refrigerated, and frozen storage conditions, along with microbiological quality, lipid oxidation, protein degradation, and economic feasibility, remain to be assessed in subsequent investigations. Furthermore, raw Pangas mince used in the present study was sourced at a single time point, and seasonal variation in fish nutritional and biochemical quality is recognised to influence proximate composition and processing characteristics in finfish more generally (Debnath & Sahoo, 2013; Debnath, 2025); the extent to which such seasonal variability may affect the proximate, textural, and sensory attributes of fortified Pangas sausage warrants evaluation in future work.

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