Development of a Functional Extruded Snack Using Millet, Pulse and Fruit-Processing By-products

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Abstract

Underutilised millet grains, pulse-milling husk fractions, and fruit-processing pomace represent large, low-cost, nutrient-dense streams that are routinely discarded or diverted to low-value animal feed. In this study, a functional ready-to-eat extruded snack was developed by replacing part of a pearl millet–rice grit base with graded levels of chickpea husk flour (a pulse-milling by-product) and dried orange pomace powder (a citrus-juice-processing by-product). Five treatments were prepared: T0 (control, 0% by-product), T1 (5% husk + 2.5% pomace), T2 (10% husk + 5% pomace), T3 (15% husk + 7.5% pomace), and T4 (20% husk + 10% pomace), and blends were processed on a co-rotating twin-screw extruder at a barrel temperature of 120 ± 5 °C, screw speed of 350 rpm and feed moisture of 13% (w.b.). Increasing by-product substitution significantly ($p < 0.05$) increased crude protein (9.8 to 12.7 g/100 g), crude fibre (3.2 to 12.3 g/100 g), ash, total phenolic content (1.42 to 4.35 mg GAE/g) and DPPH radical scavenging activity (21.4 to 54.1%), while expansion ratio declined and bulk density, hardness and darkness of the extrudates increased. Sensory evaluation using a nine-point hedonic scale identified T2 (10% husk + 5% pomace) as the most acceptable fortified formulation, combining an appreciable nutritional and antioxidant gain with overall acceptability scores statistically comparable to the control. Accelerated storage studies over 90 days under ambient conditions indicated satisfactory shelf stability of the packaged snack, with moisture content and peroxide value remaining within acceptable limits. The findings demonstrate that co-valorisation of millet, pulse-processing husk and fruit pomace is a technically feasible route to a fibre- and polyphenol-enriched extruded snack, offering a practical model for reducing agro-processing waste while diversifying the nutritional profile of ready-to-eat cereal snacks.

Keywords: extrusion cooking; pearl millet; chickpea husk; orange pomace; food by-product valorisation; functional snack; dietary fibre; antioxidant activity

1. Introduction

The global ready-to-eat (RTE) snack market has continued to expand rapidly, driven largely by convenience, extended shelf-life and consumer familiarity with extruded cereal-based products. However, most commercial extruded snacks are manufactured from refined maize, rice or wheat and are characterised by a high glycaemic load, low dietary fibre and negligible micronutrient density, which has raised public-health concern regarding their contribution to diet-related non-communicable disease (Asif et al., 2023). Simultaneously, food processing industries generate very large volumes of nutrient-rich by-products — husks, brans, pomace, seeds and peels — that are frequently under-utilised, composted, or used as low-value animal feed, despite retaining substantial dietary fibre, protein, minerals and phytochemicals (Ben-Othman et al., 2020; Sagar et al., 2018).

Millets (*Pennisetum glaucum, Eleusine coracana* and related species) are increasingly promoted as climate-resilient, nutritionally dense alternatives to major cereals, being naturally gluten-free and rich in dietary fibre, B-vitamins and minerals such as iron and zinc (Anitha et al., 2021). Extrusion cooking of millet-based blends has been widely reported to yield ready-to-eat products with acceptable expansion and sensory properties when processing parameters are optimised; Devi et al. (2023), for example, optimised a rice–corn–pearl millet–green gram–cowpea RTE extrudate using response surface methodology and identified 120 °C barrel temperature, 350 rpm screw speed and 10% feed moisture as the optimum condition, while Yadav and Mishra (2022) reviewed the effects of extrusion parameters and co-ingredients on the cooking, textural, pasting and nutritional properties of millet-based extrudates. More recently, Singh et al. (2025) evaluated multi-millet (proso, kodo and foxtail) extruded snacks and reported that extrusion caused only minimal losses of fibre, ash and protein while producing favourable water absorption index, water solubility index and bulk density.

Pulse-processing (dal-milling) generates substantial quantities of husk and split-seed fines as by-products; these fractions are comparatively rich in insoluble fibre, resistant starch and residual protein and have been explored as functional ingredients for extrusion. Richter et al. (2022) and the review of Richter and Ganjyal (2021) on the utilisation of food-processing by-products in extrusion reported that pea hulls exhibited appreciable starch-related pasting viscosity, making them technically compatible with direct-expansion extrusion, whereas bran-type fibrous by-products with very high insoluble fibre reduced pasting viscosity and expansion. Extrusion has also been shown to enhance the techno-functional properties of pulse flours themselves, including water absorption and solubility, through starch gelatinisation and protein modification during thermo-mechanical processing (Sinaki et al., 2023; Frontiers in Sustainable Food Systems review by Vishwakarma et al., 2021).

Fruit-processing industries, particularly citrus juice extraction, similarly generate large quantities of pomace — comprising peel, pulp and seed residues — that are rich in dietary fibre, pectin and polyphenolic antioxidants such as hesperidin, naringenin and ferulic, caffeic and coumaric acids (Asif et al., 2023). Several studies have demonstrated that incorporation of fruit pomace into extruded cereal snacks substantially increases fibre and polyphenol content and antioxidant activity, although higher inclusion levels tend to reduce expansion ratio and lighten-to-darken colour change, and can adversely affect sensory acceptability beyond a threshold level of around 15–20% (Gumul et al., 2023; Oharańczyk et al., 2023; Richter et al., 2022). Similarly, incorporation of passion-fruit-skin flour into rice–chickpea gluten-free extrudates has been reported to raise phenolic and antioxidant potential of the final snack, notwithstanding some thermal degradation of phenolics during extrusion cooking (Bender et al., 2024).

Despite the individual bodies of literature on millet, pulse by-product, and fruit pomace incorporation into extruded snacks, comparatively few studies have examined the simultaneous, combined valorisation of a pulse-milling by-product and a fruit-processing by-product within a single millet-based extrudate system, evaluating the trade-offs between nutritional enrichment, functional/physical quality and consumer acceptability in one formulation matrix. Addressing this gap is relevant both to the circular-economy objective of reducing agro-processing waste and to the public-health objective of developing more nutritionally balanced RTE snacks.

The present study was therefore undertaken with the following objectives: (i) to develop composite flour blends combining pearl millet flour, rice grits, chickpea husk flour (pulse-milling by-product) and dried orange pomace powder (citrus-processing by-product) at graded substitution levels; (ii) to process these blends into direct-expanded extrudates using twin-screw extrusion cooking under fixed optimised process conditions; (iii) to evaluate the proximate composition, physical, functional, antioxidant and sensory properties of the resulting snacks; and (iv) to assess the storage stability of the most acceptable fortified formulation over a 90-day ambient storage period.

2. Materials and Methods

2.1 Raw materials

Pearl millet (*Pennisetum glaucum*) grain and long-grain rice grits were procured from a local grain market. Chickpea (*Cicer arietinum*) husk, obtained as a by-product fraction from a commercial dal (split-pulse) mill, was collected, cleaned to remove foreign matter and stored in low-density polyethylene bags at 4 °C until use. Orange (*Citrus sinensis*) pomace — the combined peel, rag and seed residue remaining after mechanical juice extraction — was obtained from a local fruit-juice processing unit within 4 h of extraction

to minimise microbial spoilage. All raw materials were sourced within a single procurement batch to minimise lot-to-lot variability.

2.2 Preparation of composite flours

Pearl millet grain was cleaned, tempered to 14% moisture for 30 min, and milled in a hammer mill fitted with a 250 µm screen. Chickpea husk was oven-dried at 50 ± 2 °C for 6 h to below 8% moisture and pulverised in a laboratory pin mill, followed by sieving through a 250 µm sieve. Orange pomace was pressed to remove residual juice, spread in thin layers and dried in a tray drier at 55 ± 2 °C for 10 h to a final moisture content below 7%, followed by grinding and sieving through a 250 µm sieve to obtain a fine, free-flowing pomace powder. All flours were packed in laminated aluminium pouches and stored at 4 °C prior to blending.

2.3 Formulation of experimental blends

Five composite flour blends were formulated on a dry-weight basis by replacing part of the pearl millet–rice grit base with chickpea husk flour and orange pomace powder in a fixed 2:1 husk-to-pomace ratio, as summarised in Table 1. The control (T0) contained no by-product fraction, while T1–T4 contained graded substitution levels of 7.5, 15, 22.5 and 30% combined by-product (husk + pomace), respectively.

Table 1. Formulation of the composite flour blends used for extrusion (percentage, dry weight basis)

Ingredient (%, db)	T0	T1	T2	T3	T4
Pearl millet flour	50.0	46.0	42.0	38.0	34.0
Rice grits	45.0	41.5	38.0	34.5	31.0
Chickpea husk flour	0.0	5.0	10.0	15.0	20.0
Orange pomace powder	0.0	2.5	5.0	7.5	10.0
Salt	1.0	1.0	1.0	1.0	1.0
Sugar	2.0	2.0	2.0	2.0	2.0
Refined soybean oil	2.0	2.0	2.0	2.0	2.0

2.4 Extrusion processing

Blends were conditioned to a feed moisture content of 13 ± 0.5% (w.b.) by spraying a calculated amount of water and equilibrating for 30 min in sealed containers. Extrusion was carried out using a laboratory co-rotating, intermeshing twin-screw extruder (screw diameter 30 mm, L/D ratio 20:1) fitted with a circular die of 3 mm diameter. On the basis of preliminary trials and the optimum condition reported by Devi et al. (2023) for a comparable millet–pulse composite blend, the following fixed processing conditions were adopted for all treatments: feed rate 15 kg/h, screw speed 350 rpm, and barrel temperature profile of 80–90–110–130 °C across the feed, compression, metering and die zones (final zone 130 ± 5 °C). Extrudates emerging from the die were cut into approximately 3 cm lengths using a rotating cutter, dried in a hot-air tray drier at 60 °C for 20 min to a final moisture content below 5%, cooled to ambient temperature, and packed in metallised polyester/polyethylene laminate pouches under ambient atmosphere for subsequent analysis.

2.5 Proximate composition

Moisture, crude protein (N × 6.25), crude fat, crude fibre and total ash contents of the raw flours and extrudates were determined in triplicate following standard AOAC (2019) procedures. Total carbohydrate content was calculated by difference.

2.6 Physical and functional properties

Expansion ratio (ER) was calculated as the ratio of extrudate diameter to die diameter, measured using a digital vernier calliper on ten randomly selected pieces per treatment. Bulk density was determined by the seed-displacement method using rapeseed and expressed as g/cm³. Hardness (maximum breaking force) was measured using a texture analyser fitted with a three-point bend probe (test speed 1 mm/s). Water absorption index (WAI) and water solubility index (WSI) were determined according to the centrifugation method of Anderson et al., as adapted by Singh et al. (2025), by dispersing ground extrudate in distilled water at 30 °C, centrifuging at 3000 × g for 15 min, and gravimetrically evaluating the sediment (WAI) and the dried supernatant solids (WSI). Colour was measured on ground extrudate using a Hunter colorimeter and expressed as CIE L*, a* and b* values.

2.7 Total phenolic content and antioxidant activity

Total phenolic content (TPC) was extracted using 80% aqueous methanol and quantified using the Folin–Ciocalteu method, expressed as mg gallic acid equivalents (GAE) per gram of dry sample. DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging activity of the methanolic extracts was determined

spectrophotometrically at 517 nm and expressed as percentage inhibition relative to a blank, following the general approach applied to pomace-fortified extrudates by Asif et al. (2023) and Gumul et al. (2023).

2.8 Sensory evaluation

Sensory evaluation was carried out by a semi-trained panel of 20 members drawn from the institute staff and postgraduate students, following written informed consent, using a nine-point hedonic scale (1 = dislike extremely, 9 = like extremely) for colour, aroma, taste, texture/crispness and overall acceptability, in line with the panel-based approach reported by Singh et al. (2025) for multi-millet extruded snacks.

2.9 Storage stability study

The control (T0) and the sensorially optimum formulation (T2) were packed in metallised polyester pouches and stored under ambient conditions (28 ± 3 °C, 60–65% RH) for 90 days. Moisture content and peroxide value (PV) of the extracted fat were monitored at 15-day intervals to assess hydrolytic and oxidative stability.

2.10 Statistical analysis

All analyses were performed in triplicate and results are expressed as mean ± standard deviation. Data were subjected to one-way analysis of variance (ANOVA) followed by Duncan's multiple range test ($p < 0.05$) using statistical software, to identify significant differences among treatments.

3. Results and Discussion

3.1 Proximate composition

Table 2 summarises the proximate composition of the control and fortified extrudates. Crude protein increased progressively from 9.8 g/100 g in T0 to 12.7 g/100 g in T4, attributable to the residual protein retained in chickpea husk fractions even after dal milling. Crude fat declined slightly across treatments, consistent with reports that fat interacts with gelatinised starch to form starch–lipid complexes during extrusion, reducing free extractable fat (Singh et al., 2025). Crude fibre rose sharply and near-linearly with by-product level, from 3.2 g/100 g in the control to 12.3 g/100 g in T4, reflecting the substantial insoluble fibre contributed by both chickpea husk and citrus pomace; comparable fibre enrichment trends have been reported for citrus-pomace-fortified corn extrudates, where fibre content increased up to 2.1-fold relative to the control (Asif et al., 2023). Ash content also increased steadily, in agreement with the higher mineral content typically reported for pulse husk and citrus by-products relative to refined cereal flours.

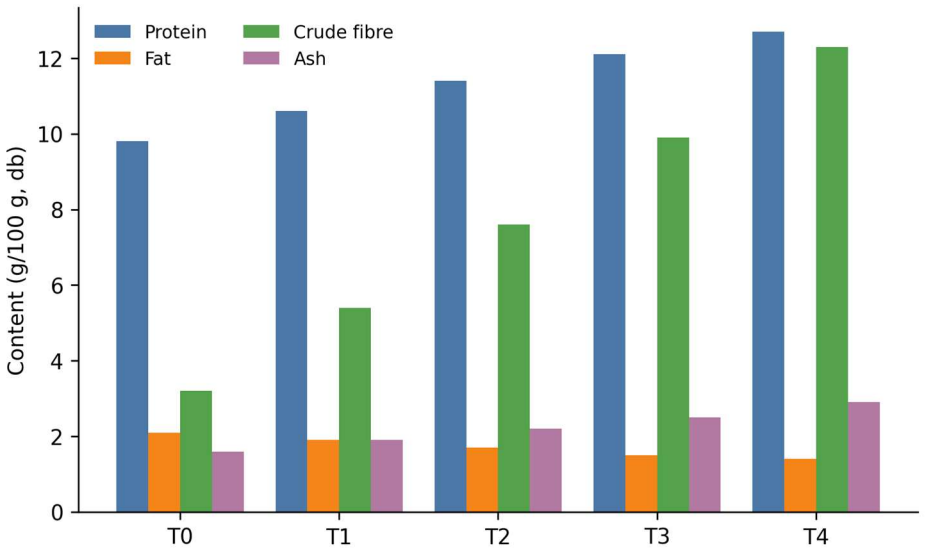


Figure 1. Proximate composition (g/100 g, dry basis) of control (T0) and fortified (T1–T4) extruded snacks

Table 2. Proximate composition of control and fortified extruded snacks (mean ± SD, n = 3)

Parameter (g/100 g, db)	T0	T1	T2	T3	T4
Moisture (%, as is)	4.1 ± 0.2	4.3 ± 0.2	4.6 ± 0.2	4.9 ± 0.3	5.2 ± 0.3
Crude protein	9.8 ± 0.3	10.6 ± 0.3	11.4 ± 0.4	12.1 ± 0.3	12.7 ± 0.4
Crude fat	2.1 ± 0.1	1.9 ± 0.1	1.7 ± 0.1	1.5 ± 0.1	1.4 ± 0.1
Crude fibre	3.2 ± 0.2	5.4 ± 0.3	7.6 ± 0.3	9.9 ± 0.4	12.3 ± 0.5
Total ash	1.6 ± 0.1	1.9 ± 0.1	2.2 ± 0.1	2.5 ± 0.1	2.9 ± 0.2
Carbohydrate (by difference)	83.3	80.2	77.1	74.0	70.8

3.2 Physical properties

Expansion ratio decreased significantly ($p < 0.05$) with increasing by-product level, from 3.85 in the control to 2.18 in T4, while bulk density correspondingly increased from 0.19 to 0.38 g/cm³ (Table 3, Figure 3). This inverse relationship between fibre-rich by-product inclusion and expansion is well documented: insoluble fibre and non-starch polysaccharides disrupt the continuity of the starch matrix, restrict bubble growth during the pressure drop at the die, and increase melt viscosity, thereby limiting expansion (Richter et al., 2022; Wang et al., 2019). A similar trend was reported for corn extrudates fortified with citrus pomace, wherein expansion ratio decreased progressively above 5% pomace inclusion (Asif et al., 2023), and for chokeberry-, blackcurrant- and cherry-pomace-fortified gluten-free corn snacks (Gumul et al.,

2023). Hardness increased from 18.4 N in T0 to 37.6 N in T4, consistent with the denser, less-expanded cellular structure of the higher-substitution extrudates. Colour lightness (L*) decreased and redness/yellowness (a*, b*) increased with pomace level, reflecting both the natural pigmentation of orange pomace and non-enzymatic (Maillard) browning reactions promoted by the residual reducing sugars in the pomace fraction during extrusion cooking, a pattern also reported by Gumul et al. (2023) for pomace-enriched corn snacks.

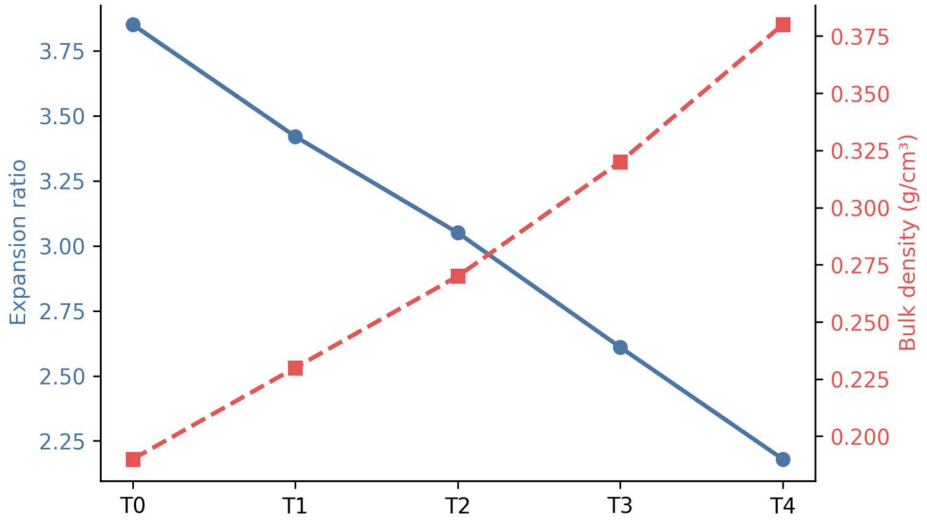


Figure 2. Effect of combined chickpea husk–orange pomace substitution on expansion ratio and bulk density

Table 3. Physical and functional properties of control and fortified extruded snacks (mean ± SD, n = 3)

Property	T0	T1	T2	T3	T4
Expansion ratio	3.85 ± 0.11	3.42 ± 0.09	3.05 ± 0.10	2.61 ± 0.08	2.18 ± 0.09
Bulk density (g/cm³)	0.19 ± 0.01	0.23 ± 0.01	0.27 ± 0.01	0.32 ± 0.02	0.38 ± 0.02
Hardness (N)	18.4 ± 1.2	22.7 ± 1.4	26.9 ± 1.5	32.1 ± 1.8	37.6 ± 2.0
WAI (g gel/g db)	5.02 ± 0.15	5.34 ± 0.14	5.71 ± 0.16	5.95 ± 0.18	6.12 ± 0.20
WSI (%)	9.8 ± 0.4	9.1 ± 0.4	8.3 ± 0.3	7.6 ± 0.4	6.9 ± 0.3
L* (lightness)	72.4 ± 0.8	68.1 ± 0.7	63.5 ± 0.9	58.7 ± 1.0	53.9 ± 1.1
a* (redness)	2.1 ± 0.2	3.6 ± 0.2	5.0 ± 0.3	6.4 ± 0.3	7.9 ± 0.4
b* (yellowness)	18.6 ± 0.5	21.4 ± 0.6	24.1 ± 0.6	26.5 ± 0.7	28.9 ± 0.8

3.3 Water absorption and solubility indices

WAI increased consistently with by-product level (5.02 to 6.12 g gel/g), while WSI decreased (9.8 to 6.9%), a pattern broadly consistent with the WAI (5.71 g/g) and WSI (5.66–6.61%) ranges reported for multi-millet extruded snacks by Singh et al. (2025). The increase in WAI is generally attributed to the greater water-holding capacity of fibre-rich husk and pomace particles and to partial starch damage during extrusion, whereas the decline in WSI reflects reduced availability of soluble dextrinised starch fragments as the proportion of non-starch, fibre-dominant ingredients in the blend increases.

3.4 Total phenolic content and antioxidant activity

TPC and DPPH radical scavenging activity increased markedly and significantly ($p < 0.05$) with by-product substitution level (Table 4, Figure 4), rising from 1.42 mg GAE/g and 21.4% inhibition in the control to 4.35 mg GAE/g and 54.1% inhibition in T4. This enhancement reflects the substantial contribution of citrus pomace polyphenols — including hesperidin, naringenin and hydroxycinnamic acids such as ferulic, caffeic and p-coumaric acid — as well as phenolics associated with the chickpea seed coat (husk) fraction. Comparable increases in phenolic content and antioxidant capacity following pomace fortification of extruded snacks have been reported by Asif et al. (2023) for citrus pomace in corn extrudates and by Gumul et al. (2023) for chokeberry-, blackcurrant- and cherry-pomace-fortified gluten-free corn snacks, in which chokeberry pomace at 20% inclusion increased total phenolic content, phenolic acids, flavonoids and antioxidant activity by approximately two- to ten-fold relative to the control. It is noted, however, that extrusion cooking is known to cause partial thermal degradation of native phenolic compounds (Bender et al., 2024); the net enrichment observed here therefore represents the balance between the additional phenolic input from the by-products and processing-related losses.

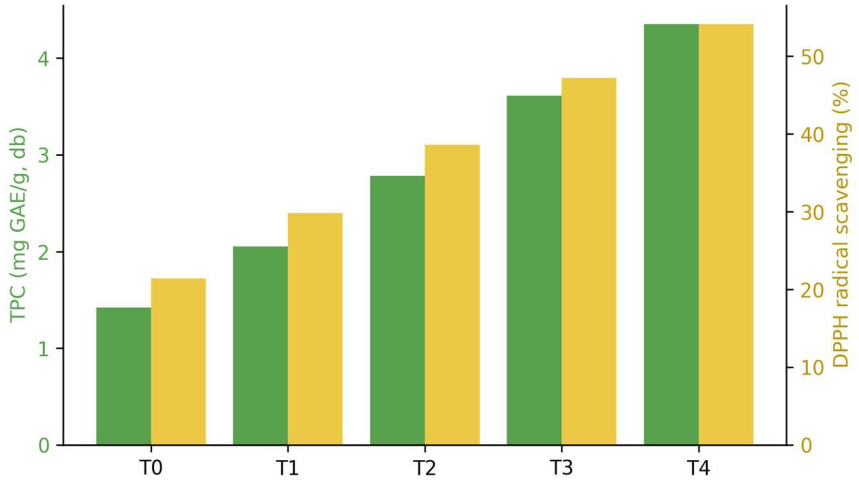


Figure 3. Total phenolic content (TPC) and DPPH radical scavenging activity of the extruded snacks

Table 4. Total phenolic content and DPPH radical scavenging activity of the extruded snacks (mean ± SD, n = 3)

Parameter	T0	T1	T2	T3	T4
TPC (mg GAE/g, db)	1.42 ± 0.08	2.05 ± 0.10	2.78 ± 0.12	3.61 ± 0.14	4.35 ± 0.16
DPPH scavenging (% inhibition)	21.4 ± 1.1	29.8 ± 1.3	38.6 ± 1.5	47.2 ± 1.6	54.1 ± 1.8

3.5 Sensory evaluation

Mean hedonic scores for colour, aroma, taste, texture/crispness and overall acceptability are presented in Table 5 and Figure 5. Colour and texture/crispness scores declined progressively with increasing by-product level, consistent with the darker colour and denser, harder texture noted in Section 3.2; this mirrors observations that fruit-pomace fortification beyond a moderate threshold (typically 15–20%) reduces sensory acceptability of extruded snacks (Gumul et al., 2023; Asif et al., 2023). Taste scores, in contrast, were highest for T1 and T2, suggesting that the mild citrus and nutty husk notes were perceived positively at low-to-moderate inclusion, before becoming more astringent/bitter at higher pomace levels (T3, T4). Overall acceptability scores of T1 (8.1) and T2 (8.0) were not significantly different from the control (T0, 8.2), whereas T3 (7.1) and particularly T4 (6.8) were significantly lower ($p < 0.05$). On the basis of the combined nutritional, antioxidant and sensory results, T2 (10% chickpea husk + 5% orange pomace) was identified as the most balanced, sensorially acceptable functional formulation and was accordingly selected for the storage stability study.

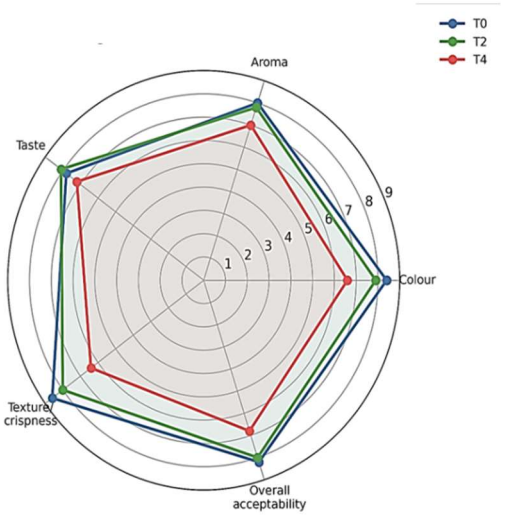


Figure 4. Sensory profile of the control (T0), optimised (T2) and highest-substitution (T4) extrudates

Table 5. Mean sensory scores of control and fortified extruded snacks (9-point hedonic scale; mean ± SD, n = 20)

Attribute	T0	T1	T2	T3	T4
Colour	8.4 ± 0.4	8.0 ± 0.4	7.9 ± 0.5	7.0 ± 0.5	6.6 ± 0.6
Aroma	8.0 ± 0.5	8.0 ± 0.4	7.8 ± 0.4	7.4 ± 0.5	7.0 ± 0.5
Taste	7.8 ± 0.5	8.0 ± 0.4	8.1 ± 0.4	7.5 ± 0.5	7.2 ± 0.6
Texture/crispness	8.6 ± 0.3	8.3 ± 0.4	8.0 ± 0.4	7.0 ± 0.5	6.4 ± 0.6
Overall acceptability	8.2 ± 0.3	8.1 ± 0.3	8.0 ± 0.4	7.1 ± 0.4	6.8 ± 0.5

3.6 Storage stability of the optimised formulation

Over 90 days of ambient storage, moisture content of both the control (T0) and the optimised formulation (T2) increased gradually (Table 6, Figure 6a), from 3.1% to 4.9% in T0 and from 3.4% to 6.1% in T2, the latter reflecting the somewhat greater hygroscopicity conferred by the higher fibre and pectin content of the pomace-fortified sample. Peroxide value increased from 0.8 to 3.4 meq O_2/kg fat in T0 and from 0.7 to 2.7 meq O_2/kg fat in T2 over the same period (Figure 6b); the comparatively lower PV development in T2 is consistent with the antioxidant protection conferred by the additional polyphenols contributed by the orange pomace fraction, which likely retarded lipid oxidation despite the marginally higher moisture uptake. Both formulations remained within generally accepted limits for RTE extruded snacks (moisture < 7%; PV < 5 meq O_2/kg fat) throughout the 90-day period, indicating satisfactory packaging performance and shelf stability under ambient storage.

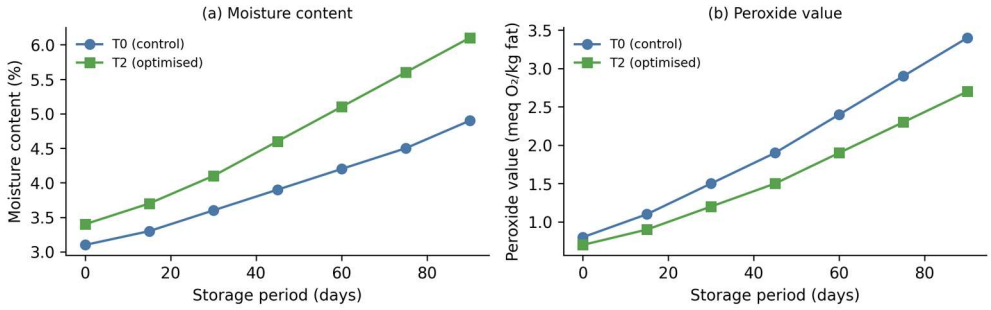


Figure 5. Changes in moisture content and peroxide value of packaged T0 and T2 extrudates during 90 days of ambient storage

Table 6. Moisture content and peroxide value of control (T0) and optimised (T2) extrudates during 90 days of ambient storage

Storage day	Moisture T0 (%)	Moisture T2 (%)	PV T0 (meq O_2/kg)	PV T2 (meq O_2/kg)
0	3.1	3.4	0.8	0.7
15	3.3	3.7	1.1	0.9
30	3.6	4.1	1.5	1.2
45	3.9	4.6	1.9	1.5
60	4.2	5.1	2.4	1.9
75	4.5	5.6	2.9	2.3
90	4.9	6.1	3.4	2.7

4. Conclusion

A functional ready-to-eat extruded snack was successfully developed by co-valorising pearl millet, a pulse-milling by-product (chickpea husk) and a fruit-processing by-product (orange pomace) using twin-screw extrusion cooking. Substitution of the millet–rice base with these by-products at graded levels significantly enhanced crude protein, dietary fibre, ash, total phenolic content and DPPH radical scavenging activity, while progressively reducing expansion ratio and lightening/darkening the extrudate colour and increasing hardness and bulk density. Among the formulations examined, the blend containing 10% chickpea husk flour and 5% orange pomace powder (T2) offered the most favourable balance of nutritional enrichment, antioxidant enhancement and sensory acceptability, with overall acceptability scores statistically comparable to the unfortified control, and demonstrated satisfactory shelf stability over 90 days of ambient storage. These findings confirm that pulse-milling husk and fruit-processing pomace, both currently under-utilised agro-industrial streams, can be jointly incorporated into millet-based extruded snacks to deliver measurable nutritional and functional benefits without materially compromising consumer acceptability, provided that combined substitution is limited to approximately 15% of the formulation. This approach offers a practical, scalable model for reducing food-processing waste while diversifying the nutritional profile of the RTE snack category. Future work should examine the in vitro glycaemic response, shelf-life beyond 90 days under varied packaging and humidity conditions, and pilot- to industrial-scale extrusion trials to validate the laboratory-scale findings reported here.

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Conflict of Interest

The authors declare no conflict of interest.

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