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Effect of carrot and orange-fleshed sweet potato incorporation on the chemical and sensory characteristics of acha–peanut extrudates

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This study investigated the effect of incorporating carrot and orange-fleshed sweet potato (OFSP) flours into acha–peanut blends for the production of extruded snacks formulated to meet the recommended dietary allowance of 19 g per day protein. Four formulations were developed using material balancing and optimized extrusion parameters: A (100% acha), AP (81.08% acha + 18.92% peanut), APC (64.21% acha + 20.64% peanut + 15.15% carrot), and APO (64.55% acha + 20.74% peanut + 14.71% OFSP). The extrudates were analyzed for proximate composition, micronutrient content, antinutritional factors, starch digestibility, and sensory quality using standard methods. Results showed that carrot and OFSP incorporation significantly ($p < 0.05$) affected the proximate composition, with protein, fat, ash, fibre, carbohydrate, and energy contents ranging from 10.61–19.04%, 1.10–2.28%, 1.17–2.31%, 0.17–0.49%, 75.96–86.95%, and 399.95–403.67 kcal, respectively. Micronutrient levels also varied significantly ($p < 0.05$), with calcium, magnesium, iron, zinc, vitamin B_1, vitamin C, and β-carotene ranging from 20.27–23.17 mg per 100 g, 71.28–78.06 mg per 100 g, 9.06–9.15 mg per 100 g, 3.23–3.43 mg per 100 g, 1.20–1.35 mg per 100 g, 4.99–5.37 mg per 100 g, and 1.14–1.21 mg per 100 g, respectively. Antinutrient contents were low, while starch digestibility and predicted glycemic index values (41.62–55.12) indicated moderate energy release. Sensory evaluation revealed high panelist acceptability for colour, taste, texture, and overall quality. The study demonstrates that the inclusion of carrot and OFSP enhances the nutritional profile and consumer appeal of acha–peanut extrudates, offering a viable strategy for producing nutrient-dense, health-promoting snacks from underutilized crops and peanut meal by-products.

Sustainability spotlight

This study promotes sustainable food innovation by developing nutrient-rich extruded snacks from underutilized African crops—acha, peanut meal, carrot, and orange-fleshed sweet potato. The use of extrusion technology, a low-waste, energy-efficient process, enables the production of shelf stable, protein- and micronutrient-dense snacks with minimal resource input. By transforming local and by-product materials into value-added snacks, this work supports food security, circular economy practices, and sustainable nutrition, particularly for vulnerable populations in developing regions.

1. Introduction

Urbanization and lifestyle transitions in developing countries have driven a growing demand for ready-to-eat (RTE) snack products, particularly among school-aged children. This shift has intensified reliance on wheat-based products, despite wheat being a non-tropical crop not cultivated in many African regions.[1] The overdependence on wheat not only strains foreign exchange reserves but also limits the industrial utilization of indigenous cereals, legumes, and tuber crops with comparable or superior nutritional potential.[2]

In response to these challenges, research attention has increasingly focused on the development of nutritionally balanced, shelf-stable, and functional snacks from locally available and underutilized raw materials.[3] Among modern processing techniques, extrusion cooking has emerged as one of the most promising technologies for producing nutrient-enriched and convenient foods. It enables simultaneous mixing, cooking, shearing, and shaping of ingredients under controlled temperature and pressure, resulting in improved digestibility, desirable texture, reduced antinutritional factors, and extended shelf life.[4] Furthermore, extrusion allows the incorporation of diverse nutrient-dense ingredients into a single food matrix, thereby supporting the development of

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health-oriented snack products. Although conventional cereals such as wheat, maize, and millet remain the popular materials for extruded foods, increasing research attention has been directed toward the utilization of underexploited grains like acha (*Digitaria exilis*) in extrusion processing and related food applications.[5,6] Acha, also known as fonio or "hungry rice," is a traditional African cereal valued for its good digestibility, gluten-free quality, and relatively high levels of sulfur-containing amino acids such as methionine and cysteine, which are typically deficient in other cereals.[7,8] Despite these advantages, acha remains underutilized due to limited industrial applications and low protein content. Its incorporation into composite blends with legumes such as peanuts could significantly enhance its functional and nutritional properties.[9,10]

Peanut (*Arachis hypogaea*) is a legume widely recognized for its high-quality protein and lipid content. It serves as an inexpensive protein source in developing countries and has been used to improve the nutritional composition of cereal-based foods.[11] Peanut meal, a by-product of oil extraction, retains substantial amounts of protein (40.1–50.9%) and fat (0.68–5.97%), making it a cost-effective fortificant for extruded snack formulations.[12] However, direct incorporation of peanut meal can affect product texture and flavour, necessitating careful optimization of formulation ratios and extrusion parameter.[13] Furthermore, the use of carrot (*Daucus carota* L.) and orange-fleshed sweet potato (OFSP, *Ipomoea batatas*), which are rich sources of β-carotene (a precursor of vitamin A), dietary fibre, essential vitamins, and minerals, can significantly enhance the micronutrient density and functional quality of food products.[14–19]

Although extensive studies have explored the extrusion of cereal–legume blends, limited research has examined the integration of carotenoid-rich roots and tubers into acha-based formulations. The inclusion of carrot and OFSP could improve the nutritional profile, sensory quality, and consumer appeal of acha-based extrudates, while promoting the utilization of indigenous crops for sustainable food production. In previous studies, acha-based composite flours were formulated to meet the recommended dietary allowance (RDA) of 19 g protein per day for children aged 4–8 years,[20] and the moisture (14–22%) and temperature (100–120 °C) conditions for producing extruded snacks from these flours were subsequently optimized.[4,10] Building on that foundation, the present study aimed to evaluate the chemical composition and sensory characteristics of the optimized acha-based extrudates. The study was designed to assess changes in proximate composition, micronutrient profile, antinutritional factors, starch digestibility, and sensory acceptability of the products.

2. Materials and methods

2.1 Material procurement

Acha grains and fresh carrot roots, were sourced from Farin Gada Market in Jos, Plateau State. Raw peanuts were purchased from North Bank Market in Makurdi, Benue State, and pressed mechanically at a local milling facility. Orange-fleshed sweet potatoes (OFSP) were procured from the Benue State Agricultural and Rural Development Authority (BNARDA), Makurdi.

2.2 Sample preparation

The preparation of acha flour followed a multi-step processing comprising cleaning, washing, and drying at 60 °C for 8 hours, mechanical milling, and sieving to produce a fine flour fraction.[21] Peanut flour was obtained by adapting the method of Bansal and Kochhar, with minor adjustments.[22] A sequence of sorting, roasting, dehulling, oil extraction, drying (60 °C for 8 h), milling, and sieving was carried out to obtain defatted peanut cake, popularly known as peanut flour. Carrot powder was processed *via* washing, slicing, and treatment with 0.2% potassium metabisulphite, followed by drying at 55 °C for 8 hours, milling, and sieving.[23] Orange-fleshed sweet potato (OFSP) flour was prepared by peeling, slicing, treatment with 0.2% potassium metabisulphite, drying (55 °C for 8 h), milling, and sieving, as described by Avula, with slight modifications.[24] Processed flours were packaged in high-density polyethylene bags and stored under ambient conditions for safekeeping and further analysis.

2.3 Blend formulation

The formulation ratios and extrusion parameters applied in the development of the acha-based extruded snacks were derived from previous studies as shown in Table 1.[4,10] These prior studies provided a validated framework for achieving the desired nutritional composition and textural properties of the products. The composite blends were designed through nutrient balancing to supply an adequate protein content consistent with the recommended dietary allowance of approximately 19 g per day for children between 4 and 8 years of age, as stipulated by Institute of Medicine.[20]

2.4 Extrusion process

The production of the extruded snack samples followed a modified procedure based on the method earlier described by Ogunmuyiwa *et al.*[25] Processing was carried out using a twin-screw extruder (Model SLG65, Jinan Dayi Machinery, China) fitted with a 3 mm circular die. The flours were weighed, blended and conditioned before introduced into the extruder's feed hopper, where they were subjected to progressive heating, mixing, and shearing under optimized barrel temperature profiles. The emerging products (Fig. 1) were immediately cut

Table 1 Blend formulation and optimization regimes for acha-based snacks based on target protein content (19 g)[a]

Sample (moisture, temp.)	Acha	Peanut	Carrot	OFSP
A (14.57%: 113.33 °C)	100	—	—	—
AP (19.90%: 120.00 °C)	81.08	18.92	—	—
APC (18.93%: 118.79 °C)	64.21	20.64	15.15	—
APO (17.72%: 113.94 °C)	64.55	20.74	—	14.71

[a] Key: A = acha snack, APC = acha–peanut–carrot snack, APO = acha–peanut–orange-fleshed sweet potato snack.

Fig. 1 Pictorial presentation of acha-based extruded snack.

into uniform lengths using a rotating cutter attached at the die end, then cooled to ambient temperature on clean trays to stabilize structure and prevent moisture condensation. Finally, the cooled samples were packaged in low-density polyethylene (LDPE) pouches and stored under ambient laboratory conditions pending subsequent chemical and sensory analyses.

2.5 Method of analysis

2.5.1 Determination of proximate composition and energy. Proximate composition was determined using the procedures described by AOAC,[26] with exception of carbohydrate. Crude protein content was determined using the Kjeldahl method and the percentage nitrogen (% N) obtained was used to calculate the percentage crude protein (% CP) using the relationship: % CP = % N × 6.25. Ash content was determined by incinerating the samples in a muffle furnace at 550 °C for 4 hours. The ash was cooled in a desiccator and weighed. Crude fat was determined using a Soxhlet apparatus. Crude fibre was determined by the dilute acid and alkali hydrolysis method, while moisture content was determined using the oven drying method. Carbohydrate content was calculated by difference.[27] Energy value was calculated using the Atwater factor as follows: energy value = % protein × 4.0 + % fat × 9.0 + % carbohydrate × 4.0.

2.5.2 Determination of micronutrients. The mineral contents such as calcium, magnesium, iron, and zinc of the flour samples were assessed after ashing. The resulting ash was dissolved in 100 ml of 10% hydrochloric acid, filtered, and quantitatively estimated using an atomic absorption spectrophotometer (Scientific Model VGP 210) equipped with filters corresponding to the specific minerals, adhering to AOAC guidelines.[26]

Determination of vitamins B1 and C were carried out using High-Performance Liquid Chromatography (Model BLC-10/11 HPLC system, Buck Scientific, USA) techniques as described by AOAC.[26] Beta carotene content was analyzed using a spectrophotometer (Model 22UV/VIS) following the procedures documented in AOAC.[26]

2.5.3 Determination of antinutrients. Tannins were determination using the method described by Singleton *et al.*[28] Phytate content was determined using anion-exchange method described by Ma *et al.*[29] Established methods by AOAC[26] were used to determine oxalates, while determination of trypsin inhibitors was by the method of Smith *et al.*[30]

2.5.4 Determination of *in vitro* starch digestibility. *In vitro* starch digestibility and estimated glycaemic index (eGI) were determined following the method of Goñi *et al.*[31] Glucose content was measured using the GOPOD K-GLUC assay kit following the method of AACC.[32] Total starch (TS) and resistant starch (RS) contents were determined enzymatically before *in vitro* digestion. TS was quantified following complete hydrolysis to glucose using thermostable α-amylase and amyloglucosidase, with glucose measured by the GOPOD method. RS was isolated as the hydrolysis-resistant fraction and quantified after subsequent enzymatic solubilization.[32] Starch digestion rate was expressed as the percentage of total hydrolyzed starch at various time intervals (30, 60, 90, 120, 150, and 180 minutes), calculated by multiplying the glucose content by 0.9. Rapidly digestible starch (RDS) and slowly digestible starch (SDS) were calculated as follows:

$$\mathrm{RDS}\ (\%) = (G_{20} - \mathrm{FG}) \times 0.9 \tag{1}$$

$$\mathrm{SDS}\ (\%) = (G_{120} - G_{20}) \times 0.9 \tag{2}$$

where G_{20} and G_{120} are the glucose quantities after 20 and 120 minutes of enzyme incubation, and FG is the free glucose content measured using a D-glucose GOPOD assay kit (Megazyme International K-GLUC, Ireland).

In vitro digestion was determined using the first-order equation of

$$C = C_\infty(1 - e^{-kt}) \tag{3}$$

where C is the percentage of starch hydrolyzed at time t (min), C_∞ is the equilibrium percentage of starch hydrolyzed after 180 min, and k is the kinetic constant.

Starch hydrolysis percentages were plotted over time, and the area under the curve (AUC) was calculated using Microsoft Excel. The hydrolysis index (HI) was derived by dividing the sample AUC by the standard reference AUC, with glucose as the reference (HI = 100). The eGI was calculated using the formula:

$$\mathrm{eGI} = (0.594 \times \mathrm{HI}) + 39.71 \tag{4}$$

2.5.5 Sensory evaluation. A semi-trained panel of 20 judges made up of male and female staff and students of the Department of Food Science and Technology, Joseph Sarwuan Tarka University, Makurdi was used. Panelists provided informed consent, were informed that they could withdraw at any time, and no personal data were collected. They were requested to evaluate the snacks for aroma, appearance, taste, mouthfeel, crispiness and overall acceptability using a 9-point hedonic scale, where 9 = like extremely and 1 = dislike extremely. Presentation of coded samples was done randomly and potable water was provided for rinsing of mouth in between the respective evaluations adopting the method of Iwe *et al.*[33]

2.5.6 Statistical analysis. Experiments were conducted in triplicates. Data was analyzed using a one-way analysis of variance (ANOVA) and means separated by Duncan's multiple range tests (DMRT). Significance was accepted at 5% level of probability ($p < 0.05$). Statistical analysis was carried out using GenStat (17th edition).

3. Results and discussion

3.1 Proximate composition and energy value of acha-based extruded snacks

Table 2 shows the proximate composition (dry weight basis) and energy values of extruded snacks produced from acha–peanut flour blends enhanced with carrot and orange-fleshed sweet potato (OFSP) flours. The protein content of the snacks ranged from 10.61% to 19.04%. As anticipated, the control sample containing 100% acha (A) exhibited the lowest protein value, consistent with its cereal-based composition. In contrast, supplementation with peanut meal significantly ($p < 0.05$) enhanced the protein content by approximately 79% in the composite samples, reflecting the strong contribution of peanut meal in the acha–peanut (AP), acha–peanut–carrot (APC), and acha–peanut–OFSP (APO) formulations, yielding protein levels of 19.04%, 19.01%, and 19.02%, respectively, all slightly meeting the recommended dietary allowance of 19 g per day protein RDA for children aged 4–8 years.[20] The slight protein reductions (≈0.2%) observed in the APC and APO formulations relative to AP indicate a dilution effect, consistent with their lower protein content. These results corroborate the findings of Sangam *et al.*, who reported protein improvement (6.78–13.67%) due to peanut incorporation into wheat-based biscuit, emphasizing its value as a functional ingredient for formulating protein-enriched food products.[11]

The fat content of the extruded snacks ranged from 1.10% in A to 2.28% in AP. The incorporation of peanut meal, known for its high lipid content (0.68–5.97%), significantly ($p < 0.05$) increased fat levels in AP (2.28%), APC (2.23%), and APO (2.15%) compared to the control.[12] The slight reductions in APC and APO relative to AP can be attributed to the partial substitution of peanut meal with carrot and OFSP flours, both of which contain minimal fat. Fat plays an essential role in food formulation, contributing to desirable sensory characteristics such as mouthfeel, texture, and flavor.[2]

In addition, fats serve as a concentrated source of energy and act as carriers for fat-soluble vitamins (A, D, E, and K), making them nutritionally significant components of snack products.[34]

Ash content, which reflects the mineral composition of food materials, ranged from 1.17% in A to 2.31% in APC, indicating ≈97% increment. AP (2.05%) and APO (1.40%) exhibited

Table 2 Proximate composition (dry weight basis) and energy value of acha-based extruded snacks[a]

Sample	Crude protein (%)	Crude fat (%)	Ash (%)	Crude fibre (%)	CHO (%)	Energy (kcal)
A	$10.61^{c} \pm 0.03$	$1.10^{c} \pm 0.03$	$1.17^{d} \pm 0.01$	$0.17^{c} \pm 0.00$	$86.95^{a} \pm 0.06$	$400.14^{c} \pm 0.08$
AP	$19.04^{a} \pm 0.01$	$2.28^{a} \pm 0.01$	$2.05^{b} \pm 0.03$	$0.21^{d} \pm 0.01$	$76.42^{d} \pm 0.01$	$402.36^{b} \pm 0.12$
APC	$19.01^{b} \pm 0.03$	$2.23^{b} \pm 0.05$	$2.31^{a} \pm 0.01$	$0.49^{a} \pm 0.01$	$75.96^{c} \pm 0.06$	$399.95^{c} \pm 0.02$
APO	$19.02^{b} \pm 0.02$	$2.15^{b} \pm 0.06$	$1.40^{c} \pm 0.01$	$0.37^{b} \pm 0.01$	$77.06^{b} \pm 0.05$	$403.67^{a} \pm 0.06$

[a] Values are means ± standard deviations of 3 replicates. Means in the same column with same superscripts are not significantly ($p > 0.05$) different. A = acha snack, APC = acha–peanut–carrot snack, APO = acha–peanut–orange-fleshed sweet potato snack, CHO = carbohydrate.

moderate ash levels. The increase in ash content among the fortified samples indicates the mineral contribution of the vegetable-based flours, particularly carrot, which is naturally rich in essential minerals. This trend agrees with the findings of Mulak *et al.*, who reported higher ash levels in wheat-based products supplemented with carrot flour.[14] Similarly, Ayo and Gidado[15] noted that carrot inclusion improves mineral density in composite snacks, corroborating the view that ash content serves as an index of total mineral enrichment.[35]

The strong co-occurrence of higher ash and fibre contents in APC points to a positive relationship between plant-based fortification and micronutrient density. Fibre enrichment showed a clear gradient (AP < APO < APC), which inversely corresponded with carbohydrate content and energy values The higher fibre content in APC (0.49%) can be attributed to the contribution of carrot flour, which is well known for its substantial dietary fibre content. Similarly, the moderate fibre enrichment in APO (0.39%) reflects the contribution of orange-fleshed sweet potato, which provides both soluble and insoluble fibres beneficial to digestive health. These results align with earlier reports that carrot and orange-fleshed sweet potato are rich sources of dietary fibre, and could be beneficial in diet formulations requiring fibre.[16,17] Fibre plays a crucial physiological role by aiding bowel regularity, preventing constipation, and supporting a healthy gastrointestinal system.[36] The lower fibre content of samples A and AP (0.17% and 0.21%, respectively) reinforces the significance of vegetable flour inclusion in enhancing dietary fibre content in snack products.

Carbohydrate content was highest in A (86.95%) and declined progressively with the inclusion of peanut meal and vegetable flours, yielding values of 77.06% (APO), 75.96% (APC), and 76.42% (AP). This reduction reflects a compositional shift, where the increased protein, fat, and fibre contents from supplementation result in a relative decrease in carbohydrate proportion. Similar findings were reported by Adetula *et al.*, who observed that blending cereal flours with legumes and vegetables typically reduces carbohydrate concentration while improving overall nutrient balance.[37] Despite this, all formulations remained energy-dense, confirming their potential as good sources of dietary energy. Energy values ranged from 399.95 kcal (APC) to 403.67 kcal (APO), indicating that the substitution of vegetable flours did not substantially alter the caloric potential of the products. The slightly higher energy value in APO corresponds to its relatively higher fat content, while the lower energy in APC may be attributed to its higher fibre level and lower lipid concentration. This trend supports the observation by Inyang *et al.*, indicating that energy values in extruded products are largely influenced by fat and fibre content.[7]

3.2 Micronutrient content of acha-based extruded snacks

Micronutrients are indispensable for maintaining metabolic integrity and overall health, and inadequate intake can lead to severe nutritional deficiencies, impaired immune function, poor growth, increased vulnerability to infections, and long-term chronic diseases.[38] As presented in Table 3, the mineral composition of the extruded snacks differed significantly ($p < 0.05$) among samples. Calcium, magnesium, iron, and zinc contents ranged from 20.27–23.17 mg per 100 g, 71.28–78.06 mg per 100 g, 9.06–9.15 mg per 100 g, and 3.28–3.43 mg per 100 g, respectively. The trend aligns with the concurrent increase in ash content earlier reported. The carrot-enriched sample (APC) exhibited the highest mineral concentrations, indicating the substantial contribution of carrot flour to mineral fortification. These results agree with Singh and Kulshrestha, who emphasized carrots as valuable sources of bioavailable minerals.[39] Calcium and magnesium are essential for skeletal development, bone and dental strength, as well as for proper muscle and nerve function,[40] while iron and zinc are critical for oxygen transport, immune modulation, energy metabolism, and growth.[23] The mineral levels obtained in this study are comparable to those previously reported for acha-based composite flours blended with green banana and cowpea,[35] wheat–acha–African yam bean composites,[41] and acha–mango kernel–soy cake blends.[42]

Vitamin B_1 (thiamine) plays a vital role in carbohydrate metabolism, neurological function, and growth.[43] In the current study, thiamine content decreased slightly with the inclusion of other flours into the snacks, values ranging from 0.23–0.35 mg per 100 g, implying losses of between 20% and 34%. The low thiamine level of the snacks is likely due to thermal degradation of this heat-sensitive vitamin due to extrusion. These findings are consistent with those of Okafor and Ugwu, who reported comparable thiamine levels (0.13–0.42 mg per 100 g) in extruded products from breadfruit, cashew nut, and coconut blends.[44] Vitamin C, another essential micronutrient, contributes to collagen synthesis, immune defense, and iron absorption while functioning as an antioxidant.[45] Samples A and AP contained no detectable vitamin C, whereas APC (1.35 mg per 100 g) and APO (1.20 mg per 100 g) exhibited measurable amounts derived from carrot and OFSP flours. The values

Table 3 Micronutrient content (mg per 100 g) of acha-based flour blends and extruded snacks[a]

Sample	Calcium	Magnesium	Iron	Zinc	Vitamin B1	Vitamin C	Beta carotene
A	$20.27^{a} \pm 0.09$	$72.50^{bc} \pm 0.57$	$9.07^{a} \pm 0.04$	$3.32^{b} \pm 0.01$	$0.35^{a} \pm 0.01$	ND	ND
AP	$22.42^{b} \pm 0.04$	$72.90^{b} \pm 0.78$	$9.08^{a} \pm 0.02$	$3.33^{ab} \pm 0.00$	$0.23^{c} \pm 0.00$	ND	ND
APC	$23.17^{a} \pm 0.21$	$78.06^{a} \pm 0.55$	$9.15^{a} \pm 0.04$	$3.43^{a} \pm 0.01$	$0.25^{b} \pm 0.01$	$1.35^{a} \pm 0.64$	$5.37^{a} \pm 0.07$
APO	$20.51^{b} \pm 0.88$	$71.28^{c} \pm 0.08$	$9.06^{a} \pm 0.05$	$3.28^{b} \pm 0.07$	$0.25^{b} \pm 0.01$	$1.20^{b} \pm 0.00$	$4.99^{b} \pm 0.07$
RDA[b]	1000	130	10	5	8	25	4.8[b]

[a] Values are means ± standard deviations of 3 replicates. Means in the same column with same superscripts are not significantly ($p > 0.05$) different. A = acha snack, APC = acha–peanut–carrot snack, APO = acha–peanut–orange-fleshed sweet potato snack, CHO = carbohydrate, ND = not detected. [b] RDA = recommended diatary allowance (Institute of Medicine, 1997, 1998).

obtained are comparable to those reported by Sule *et al.* for wheat-carrot pasta (0.54–3.14 mg per 100 g).[23]

β-Carotene was undetectable in A and AP due to the absence of carotenoid sources in acha and peanut. However, substantial levels were observed in APC (5.37 mg per 100 g) and APO (4.99 mg per 100 g) due to the inclusion of carrot and OFSP, with APC exhibiting approximately 8% higher β-carotene than APO. Carrot and OFSP are known sources of β-carotene.[46–48] β-Carotene functions as a potent antioxidant, supporting cell protection, vision, and immune health while reducing risks of cardiovascular disease.[49] Upon conversion to retinol, it aids growth, reduces susceptibility to infections, and prevents vitamin A deficiency-related disorders such as night blindness and diarrhea.[44,50] The β-carotene concentrations obtained in this study are sufficient to contribute meaningfully toward meeting the recommended dietary allowance of 400 μg retinol equivalents (≈4.8 mg per day) for children under 8 years,[51] indicating the potential of these fortified extrudates to mitigate vitamin A deficiency in sub-Saharan Africa.

3.3 Antinutrient content of acha-based extruded snacks

The acha-based extruded snacks showed significant ($p < 0.05$) variations in their antinutrient contents (Table 4). The generally low values observed across all samples reflect the pronounced degradative effect of extrusion cooking on thermolabile antinutritional compounds, suggesting minimal interference with the bioavailability of essential nutrients. This aligns with the established role of high-temperature, short-time processing in denaturing or inactivating heat-sensitive antinutrients, thereby improving product safety and nutritional quality.

Table 4 Antinutrient content (mg per 100 g) of acha-based flour blends and extruded snacks[a]

Sample	Tannins	Phytates	Oxalate	Trypsin inhibitors
A	$0.09^{b} \pm 0.00$	$0.22^{a} \pm 0.00$	$0.01^{b} \pm 0.00$	$0.01^{a} \pm 0.00$
AP	$0.09^{b} \pm 0.01$	$0.24^{a} \pm 0.07$	$0.02^{ab} \pm 0.01$	$0.02^{a} \pm 0.00$
APC	$0.04^{c} \pm 0.01$	$0.04^{c} \pm 0.01$	$0.02^{ab} \pm 0.04$	$0.01^{a} \pm 0.01$
APO	$0.11^{a} \pm 0.01$	$0.12^{b} \pm 0.01$	$0.03^{a} \pm 0.00$	$0.01^{a} \pm 0.00$

[a] Values are means ± standard deviations of 3 replicates. Means in the same column with same superscripts are not significantly ($p > 0.05$) different. A = acha snack, APC = acha–peanut–carrot snack, APO = acha–peanut–orange-fleshed sweet potato snack.

Tannin concentrations ranged between 0.04 and 0.11 mg per 100 g, which were markedly lower than those reported by Adeyanju *et al.*[41] for wheat–acha–African yam bean composites (0.40–0.54 mg per 100 g). Tannins, being polyphenolic compounds, are known to form insoluble complexes with proteins and minerals, reducing protein digestibility and inhibiting dietary iron absorption.[52,53] Their minimal presence in the current study underscores the efficiency of extrusion in tannin degradation, thus enhancing protein and micronutrient utilization in the extrudates.

Phytate contents ranged from 0.04 to 0.24 mg per 100 g, with the highest level detected in AP. Phytic acid forms strong chelates with divalent metal ions such as zinc, calcium, and iron, reducing their bioavailability.[54,55] The comparatively lower phytate level (≈80% lower than AP) observed in the carrot-enriched sample (APC) may be associated with the enhancing influence of β-carotene on non-heme iron absorption, as previously reported by Adetola *et al.*[47]

Oxalate concentrations were also low, ranging from 0.01 to 0.03 mg per 100 g, with the highest value in APO. Oxalates are known to hinder calcium absorption by forming insoluble calcium-oxalate complexes.[56] However, the minimal levels recorded in all formulations suggest negligible nutritional concern, as trace oxalate quantities are common in vegetables and generally well tolerated.[57] The results further confirm the destructive effect of extrusion processing on oxalate stability, contributing to improved mineral bioavailability.

Trypsin inhibitor activity was low across all samples (0.01–0.02 mg per 100 g), with AP exhibiting the highest value. Legumes are recognized sources of trypsin inhibitors, and their inclusion in composite blends may account for this observation.[13] Nonetheless, the low values observed confirm the ability of extrusion to inactivate protease inhibitors effectively, thereby enhancing protein digestibility. The results were notably lower than 2.97–4.93 mg per 100 g reported by Adeyanju *et al.* for wheat–acha–pigeon pea blends.[58]

3.4 *In vitro* starch digestibility of acha-based extruded snacks

Table 5 presents the *in vitro* starch digestibility characteristics of the acha-based extruded snacks. The total starch content varied significantly ($p < 0.05$) among the samples, with A exhibiting the highest value (85.94%) and APC showing the

Table 5 *In vitro* starch digestibility of acha-based extruded snacks[a]

Sample	Total starch (%)	Resistant starch (%)	Rapidly digested starch (%)	Slowly digested starch (%)	Predicted GI	Starch digestive index (SDI)
A	$85.94^{a} \pm 0.06$	$14.06^{d} \pm 0.06$	$99.55^{a} \pm 0.30$	$0.45^{d} \pm 0.30$	$55.12^{a} \pm 0.00$	$1.21^{a} \pm 0.01$
AP	$78.13^{b} \pm 0.34$	$21.87^{b} \pm 0.34$	$92.77^{b} \pm 0.30$	$7.23^{b} \pm 0.30$	$55.12^{a} \pm 0.00$	$1.18^{b} \pm 0.01$
APC	$72.14^{d} \pm 0.33$	$27.87^{a} \pm 0.33$	$81.44^{d} \pm 0.64$	$8.57^{a} \pm 0.64$	$41.62^{c} \pm 0.39$	$1.14^{c} \pm 0.01$
APO	$74.00^{c} \pm 0.16$	$16.01^{c} \pm 0.16$	$84.83^{c} \pm 0.22$	$5.18^{c} \pm 0.22$	$43.66^{b} \pm 0.45$	$1.15^{c} \pm 0.00$

[a] Values are means ± standard deviations of 3 replicates. Means in the same column with same superscripts are not significantly ($p > 0.05$) different. A = acha snack, APC = acha–peanut–carrot snack, APO = acha–peanut–orange-fleshed sweet potato snack, CHO = carbohydrate.

lowest (72.14%). The AP and APO snacks recorded intermediate values of 78.13% and 74.00%, respectively. The observed decrease (≈9–16%) in total starch with the inclusion of peanut, carrot, and orange-fleshed sweet potato (OFSP) flours can be attributed to a dilution effect, as non-starchy components such as protein, fibre, and fat increased proportionally within the blends (Table 2). This observation corroborates the findings of Noraidah *et al.*, who reported similar reductions in total starch (83.17–48.83%) in wheat-based composite flours following fortification with non-cereal ingredients.[59]

Resistant starch (RS) contents ranged from 14.06% in A to 27.87% in APC, indicating a significant ($p < 0.05$) increase in indigestible starch fractions (≈98%) with the addition of carrot flour, which promotes starch retrogradation and restricts enzymatic hydrolysis. Intermediate values were observed for AP (21.87%) and APO (16.01%), further demonstrating the role of fibre-rich composite ingredients in modulating starch digestibility. Resistant starch is known to resist enzymatic digestion in the small intestine, undergo fermentation in the colon, and yield short-chain fatty acids beneficial for gut health, glycaemic control, and colon cancer prevention.[60,61]

Rapidly digested starch (RDS) values followed an inverse trend, decreasing from 99.55% in A to 81.44% in APC. The high RDS in the control sample reflects the predominance of readily hydrolysable starch granules, while the incorporation of carrot and OFSP markedly reduced RDS, likely due to enhanced fibre–starch interactions and partial gelatinization during extrusion. The moderate RDS values in AP (92.77%) and APO (84.83%) suggest improved starch stability, which may be beneficial for moderating postprandial glycaemic response. The observed values were slightly higher than those (29.26–72.16%) reported by Bayomy *et al.* for extruded functional snacks from waste rice and whey milk.[62]

Slowly digested starch (SDS) values ranged from 0.45% in A to 8.57% in APC, indicating a significant improvement in starch fractions that release glucose gradually. The high SDS in APC is desirable for promoting sustained energy release and stabilizing blood glucose levels. The intermediate values for AP (7.23%) and APO (5.18%) further suggest that the inclusion of vegetable flours enhances starch fractions with slower digestibility, possibly due to increased amylose content and structural rearrangement of starch during extrusion.[63,64]

This shift in starch fractions is reflected in the reduction of glycaemic index by ≈25% in APC, indicating improved glycaemic response potential. Predicted glycaemic index (GI) values ranged from 41.62 in APC to 55.12 in A and AP, classifying all the snacks as low-GI foods.[65] The lower GI of APC and APO corresponds with their higher RS and SDS fractions, supporting their potential to attenuate postprandial glucose spikes. Low-GI foods are associated with improved glycaemic regulation, reduced insulin demand, and decreased risk of metabolic disorders, including obesity, cardiovascular disease, and type 2 diabetes.[66]

The starch digestibility index (SDI), which integrates the overall rate of starch hydrolysis, was highest in A (1.21) and AP (1.18), indicating higher digestibility. In contrast, APC (1.14) and APO (1.15) exhibited significantly ($p < 0.05$) lower SDI values of approximately 6%, aligning with their higher fibre, ash, and β-carotene contents, and reflecting slower starch breakdown and potential health benefits related to glycaemic moderation. These findings are consistent with previous reports which established that formulations rich in resistant and slowly digested starch typically exhibit reduced SDI and glycaemic response.[67]

3.5 Sensory characteristics of acha-based extruded snacks

Sensory evaluation is a fundamental aspect of food product development and quality improvement, providing insight into consumer perception, preference, and potential market acceptance. Table 6 presents the mean sensory scores for the acha-based extruded snacks, indicating significant ($p < 0.05$) variations across the evaluated attributes.

Aroma scores differed markedly among samples, with APC receiving the highest rating (8.10), followed closely by AP (8.00). The control (A) recorded a slightly lower score of 7.85, while APO exhibited the least aroma intensity (7.65). The enhanced aroma in the carrot-enriched sample (≈3% increase) relative to the control likely reflects the presence of volatile compounds and carotenoid-derived aldehydes inherent in carrots, which contribute a sweet, earthy, and mildly spicy note that becomes more pronounced upon heating.[68] These results highlight the positive influence of carrot inclusion on aroma enhancement during extrusion cooking.

Appearance scores, on the other hand, showed a gradual decline with composite flour inclusion. The control snack (A) displayed the highest score (7.75), whereas APC and APO showed lower scores of 6.40 and 6.35, respectively, translating to approximately 17–18% decline. The reduced visual appeal of the vegetable-fortified snacks could be linked to colour

Table 6 Sensory characteristics of acha-based extruded snacks[a]

Sample	Aroma	Appearance	Taste	Mouthfeel	Crispiness	Overall acceptability
A	$7.85^{b} \pm 0.73$	$7.75^{a} \pm 0.72$	$7.00^{c} \pm 0.81$	$7.65^{a} \pm 0.44$	$7.85^{a} \pm 0.60$	$7.95^{a} \pm 0.67$
AP	$8.00^{ab} \pm 0.50$	$7.60^{b} \pm 0.62$	$7.15^{b} \pm 0.64$	$7.45^{b} \pm 0.60$	$7.60^{b} \pm 0.47$	$7.65^{b} \pm 0.60$
APC	$8.10^{a} \pm 0.76$	$6.40^{c} \pm 0.41$	$7.25^{a} \pm 0.75$	$7.40^{b} \pm 0.89$	$7.55^{b} \pm 0.41$	$8.00^{a} \pm 0.72$
APO	$7.65^{c} \pm 0.82$	$6.35^{c} \pm 0.64$	$7.10^{b} \pm 0.88$	$7.50^{b} \pm 0.72$	$7.65^{b} \pm 0.69$	$7.55^{b} \pm 0.51$

[a] Values are means ± standard deviations of 20 replicates. Means in the same column with same superscripts are not significantly ($p > 0.05$) different. A = acha snack, APC = acha–peanut–carrot snack, APO = acha–peanut–orange-fleshed sweet potato snack, CHO = carbohydrate.

heterogeneity and structural variations resulting from the incorporation of fibre-rich carrot and OFSP flours, which alter product diameter, surface gloss, and uniformity. Panelists appeared to prefer the uniform colour and appearance of the 100% acha snack, consistent with the findings of Sanya *et al.*, who observed similar declines in visual preference following the addition of high-fibre vegetable ingredients to maize–sorghum extruded product.[69]

Taste evaluation revealed that carrot inclusion improved flavour perception and palatability of APC by approximately ≈4% relative to the control. This enhancement can be attributed to the natural sweetness and umami compounds in carrots, including glutamic acid and free amino acids, which act as flavour enhancers.[70] The control snack (A) had the lowest score (7.00), suggesting that, while acceptable, its flavour profile was relatively plain compared to the enriched variants.

Mouthfeel, which encompasses the tactile sensations perceived during mastication, also showed differences among the samples. The control snack (A) exhibited the best mouthfeel (7.65), followed by AP (7.45). APC and APO scored slightly lower (7.40 and 7.50, respectively), indicating that the inclusion of vegetable flours had minimal impact on texture perception. The results are comparable to those of Yadav *et al.*, who reported similar effects in vegetable-enriched wheat-pearl millet pasta.[71] The minor decline in mouthfeel may result from the higher fibre and moisture retention capacities of the added ingredients, which slightly modify the product's structural crispness.[72]

Crispiness was highest in A (7.85), followed by AP (7.60), while APC and APO scored marginally lower (7.55 and 7.65, respectively). The reduced crispiness (≈3–4%) in the composite snacks may be attributed to the moisture and fibre content of carrot and OFSP, which affect air cell formation and porosity during extrusion, leading to a denser texture. Similar findings were reported by Inyang and Nwabueze for acha-green banana biscuits, where fibre addition reduced crispiness but enhanced nutritional value.[38]

Overall acceptability ratings revealed that APC achieved the highest score (8.00), followed closely by A (7.95). The AP and APO samples were also well received, with scores of 7.65 and 7.55, respectively, indicating general consumer acceptance of all formulations. The superior acceptance of APC may be linked to its balanced flavour, appealing aroma, and satisfactory textural attributes. This aligns with the findings of Ayo and Gidado, who reported that carrot inclusion significantly enhanced the sensory quality of acha-based products.[15] Similarly, Korkerd *et al.* observed improved consumer preference in extruded snacks enriched with nutrient-dense plant-based by-products such as germinated brown rice and mango peel fibre.[73]

4. Conclusion

This study has demonstrated that the incorporation of peanut meal, carrot, and orange-fleshed sweet potato (OFSP) flours into acha significantly improved the chemical and sensory qualities of the extruded snacks. The enriched samples showed higher protein, fat, ash, fibre, and energy contents with a corresponding reduction in carbohydrate levels. Among the formulations, the acha–peanut–carrot (APC) snack exhibited superior starch digestibility as well as highest mineral and β-carotene contents, while samples A and APO were richer in thiamine and vitamin C, respectively. The products contained low levels of anti-nutrients, confirming their safety and potential nutritional benefits. Sensory evaluation identified APC as the most preferred sample, underscoring its balance of nutrition and acceptability. Therefore, incorporation of legume and vegetable-based flours into acha presents a viable strategy for developing nutrient-dense, and safe snacks that can enhance dietary quality and promote food diversification. Future studies should assess *in vivo* protein quality and storage stability to validate the nutritional performance and commercial viability of the products.

Author contributions

Conceptualization, S. S.; methodology, V. B. S.; writing – original draft preparation, S. S.; writing – review and editing, M. O. E.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data used are provided in the manuscript.

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