

Physicochemical, Nutritional, Microbiological, and Sensory Evaluation of Composite Noodles from Orange-Fleshed Sweet Potato, Wheat Flour, and Egg Protein

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Research Article

Keywords: Orange-fleshed sweet potato, Composite noodles, β -Carotene, Egg protein, Nutritional enhancement, Sensory evaluation

Posted Date: October 22nd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10983234/v1>

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Additional Declarations: No competing interests reported.

Abstract

Vitamin A deficiency and protein-energy malnutrition remain persistent public health problems in rural Rwanda, where wheat-based noodles are widely consumed but supply few micronutrients. Composite noodles were developed from wheat flour, orange-fleshed sweet potato (OFSP) flour, and egg protein, and evaluated for proximate composition, β -carotene content, physicochemical and cooking properties, microbiological quality, and sensory acceptability. A 100% wheat-flour control (T0) was compared with three composites containing 10, 20, and 30% OFSP flour at a constant 10% egg protein (T1, T2, T3), with triplicate analyses evaluated by one-way ANOVA and Tukey's HSD test ($p < 0.05$). Increasing OFSP substitution raised β -carotene (0.85 to 8.25 $\mu\text{g/g}$), protein (13.62 to 18.65%), fat, ash, and crude fibre, while carbohydrate declined (74.03 to 60.83%); water absorption, cooking time, cooking loss, and cooked weight all increased with OFSP level. No total viable count, yeast, or mould was detected immediately after production; counts rose over four days of ambient storage but remained within East African Standard (EAS 173:2000) limits, except for T3 on day 4. Fifty panellists rated all formulations above 4.0 on a five-point hedonic scale, with the control and T1 most preferred. OFSP and egg protein incorporation improved the nutritional density of wheat-based noodles while preserving cooking performance, microbial safety, and acceptability, with T1 (80% wheat flour, 10% OFSP flour, 10% egg protein) offering the best balance and a practical, locally producible option for household and small-scale commercial production.

Introduction

Child malnutrition remains one of the most persistent and damaging public health problems in low- and middle-income countries, and rural communities are disproportionately affected because their diets are frequently dominated by a narrow range of carbohydrate-rich staples such as cassava, maize, and potatoes [1, 2]. Although these foods supply energy, they typically fall short of the protein, vitamins, and minerals that children need for normal growth, immune competence, and cognitive development. Children above two years of age require approximately 1.05 g/kg body weight per day of high-quality protein, together with 30–40% of dietary energy from carbohydrates, 30–35% from fats, and adequate vitamin A intake (approximately 400–600 μg retinol activity equivalents per day) to support vision, immune function, and continued growth [3, 4]. When these requirements are not met, the consequences are cumulative and often irreversible: chronic undernutrition produces stunting and wasting, weakens immune defences against common childhood infections such as diarrhoea, pneumonia, and measles, and impairs cognitive and physical development in ways that can persist into adulthood and constrain long-term productivity [5, 6]

Among the micronutrient deficiencies that compound this burden, vitamin A deficiency is particularly consequential because of its direct effects on vision, epithelial integrity, and immune function, and because it frequently coexists with protein-energy malnutrition in the same vulnerable populations [7]. Dietary strategies that simultaneously address protein inadequacy and vitamin A deficiency are therefore of considerable public health interest, especially where they can be implemented using foods that are

already familiar, affordable, and culturally acceptable to the target population. In Rwanda, as in many other African countries, noodles and other cereal-based convenience foods have grown rapidly in popularity because they are inexpensive, quick to prepare, have a long shelf life, and are readily accepted by both children and adults [8, 9]. This popularity, however, is a double-edged sword from a nutritional standpoint: the great majority of noodles sold commercially are manufactured almost exclusively from refined wheat flour, a raw material valued primarily for its gluten-forming proteins and the elasticity and desirable bite these proteins confer on cooked dough, rather than for its micronutrient content [10, 11]. Refined wheat flour is comparatively poor in β -carotene, dietary fibre, and several essential minerals, so a diet in which wheat-based noodles occupy a growing share of energy intake can, paradoxically, widen rather than close existing nutrient gaps unless the product itself is reformulated to deliver more than carbohydrate and gluten.

Orange-fleshed sweet potato (OFSP) offers a locally available and agronomically well-suited solution to this gap. OFSP is already widely cultivated across rural Rwanda, including in food-insecure districts, and its characteristic orange flesh reflects an exceptionally high concentration of β -carotene, the principal dietary precursor of vitamin A, together with appreciable amounts of carbohydrate, dietary fibre, and minerals such as potassium, calcium, and iron [12, 13]. Numerous biofortification and public-health nutrition programmes across sub-Saharan Africa have promoted OFSP specifically because a relatively modest daily intake of the fresh root can meet a large proportion of a young child's vitamin A requirement, and because, unlike synthetic fortification or supplementation programmes, OFSP cultivation and consumption can be sustained largely through existing household agricultural systems [6]. Despite this potential, OFSP remains under-utilised in value-added food processing. It is still consumed mainly in traditional boiled, roasted, or steamed forms that do little to extend its shelf life or broaden its appeal beyond traditional meal contexts, and its naturally high moisture content makes the fresh root highly perishable, contributing to substantial post-harvest losses when tubers cannot be processed or consumed promptly after harvest [14, 15]. Converting OFSP into a stable, easily transported, and widely acceptable flour or ingredient is therefore an important step toward capturing more of its nutritional value and reducing the post-harvest losses that currently limit its impact on household food security.

A second, complementary strategy for improving the nutritional quality of wheat-based noodles is the incorporation of animal-source protein. Eggs are a particularly attractive option in this respect because they are widely available, relatively inexpensive compared with other animal proteins, and provide a protein of exceptionally high biological value, containing the full complement of essential amino acids in proportions that closely match human requirements [16, 17]. Beyond protein, eggs supply vitamin B12, riboflavin, choline, iron, and beneficial lipids, and in food processing they also perform valuable functional roles, improving dough binding, structure, colour, and flavour in composite products where the primary structural protein, gluten, has been partially diluted by the inclusion of non-wheat ingredients [9]. Combining OFSP flour and egg protein with wheat flour in a single noodle formulation therefore offers a route to simultaneously addressing two of the principal nutritional gaps associated with conventional wheat noodles: low provitamin A content and modest protein quality, while retaining the convenience,

familiarity, and affordability that make noodles an attractive vehicle for nutrition-sensitive product development [18, 19].

Several studies elsewhere have explored OFSP-based or OFSP-fortified noodle and pasta products and have generally reported that increasing OFSP inclusion improves β -carotene and fibre content, though often at the cost of altered colour, texture, and cooking behaviour as the proportion of gluten-forming wheat protein in the formulation declines [20, 21]. However, the specific combination of wheat flour, OFSP flour, and egg protein in which egg protein is deliberately included to offset both the nutritional and functional shortfalls introduced by OFSP substitution has received comparatively little systematic evaluation, and data describing how such a ternary composite performs across the full range of proximate composition, β -carotene retention, cooking and physicochemical behaviour, microbiological safety during storage, and consumer sensory acceptability remain scarce, particularly for the Rwandan context and for raw materials sourced from Rwandan production systems [22, 23]. This gap is significant because processors and policymakers seeking to design nutrient-dense convenience foods for reducing child malnutrition need formulation-specific evidence, rather than general principles alone, to identify substitution levels that deliver a meaningful nutritional benefit without compromising the safety or the consumer acceptability that ultimately determines whether a product will be adopted and consumed at scale.

The present study was therefore designed to develop and comprehensively characterise composite noodles produced from wheat flour, OFSP flour, and egg protein, using a completely randomised design comprising a conventional 100% wheat-flour control and three composite formulations containing increasing levels of OFSP flour substitution at a constant level of egg protein inclusion. Specifically, the study aimed to (i) assess the proximate composition (moisture, protein, fat, ash, crude fibre, and carbohydrate), β -carotene content, and physicochemical properties, including water absorption capacity and cooking behaviour, of the composite noodles; (ii) determine their microbiological quality, specifically total viable count and yeast and mould counts, during four days of short-term storage under ambient conditions; and (iii) evaluate their sensory acceptability among a representative panel of consumers using colour, taste, aroma, texture, and overall acceptability as evaluation criteria. By integrating nutritional, physicochemical, microbiological, and sensory data within a single experimental framework, the study sought to identify a formulation that achieves a practical and evidence-based balance between nutritional improvement and consumer acceptability, with the ultimate goal of providing an affordable, locally producible, and child-friendly food product capable of contributing to the reduction of protein-energy malnutrition and vitamin A deficiency in rural Rwandan communities and in similar settings elsewhere in East Africa.

Material and Methods

Study area and raw materials

The study was carried out at three sites in Rwanda: Gishubi Sector, Gisagara District, for collection of fresh OFSP tubers and chicken eggs; the Musanze District market for sourcing commercial wheat flour; and the Institut d'Enseignement Supérieur de Ruhengeri (INES-Ruhengeri), where noodle formulation, laboratory analyses, and sensory evaluation were performed. Gishubi Sector was selected because OFSP and eggs are locally produced there, even though the area continues to experience malnutrition linked to limited food utilisation and value addition. We selected all raw materials for freshness and quality, and discarded damaged or spoiled material before processing.

Preparation of composite ingredients

Fresh OFSP tubers were washed, manually peeled with stainless-steel knives, and sliced into thin, uniform pieces. Slices were blanched at approximately 65°C for 15 min to limit enzymatic browning and preserve β -carotene, then dried in a hot-air oven at 60°C to constant weight [24, 25]. The dried slices were milled, sieved to a uniform particle size, and stored in airtight polyethylene bags under dry conditions. Commercial wheat flour was screened to remove impurities and stored in airtight containers at room temperature. Fresh chicken eggs were washed, broken manually, and homogenised to a uniform mixture immediately before use as the protein source.

Experimental design, formulation, and noodle preparation

A completely randomized design was used, comprising a 100% wheat-flour control (T0) and three composite formulations in which wheat flour was partially replaced with OFSP flour at 10, 20, and 30%, while egg protein was held constant at 10% (T1, T2, T3; Table 1 lists the mean values by formulation, and the blend ratios are given in the formulation code). Flours were weighed on a digital analytical balance, dry-mixed to uniform distribution, and then combined with the homogenised egg mixture and a controlled amount of potable water to form a dough of consistent handling properties. Doughs were kneaded to develop gluten structure and elasticity, rested briefly, sheeted to a uniform thickness, and cut into noodle strands of consistent size. Noodles were dried in a hot-air oven at a controlled temperature to constant moisture, cooled at room temperature, and packaged in airtight polyethylene bags until analysis. All formulations were processed under identical conditions and analysed in triplicate.

Proximate composition and β -carotene analysis

Moisture, crude protein, crude fat, ash, crude fibre, and carbohydrate (by difference) were determined using standard AOAC procedures. β -Carotene content was determined spectrophotometrically against a standard curve and expressed as $\mu\text{g/g}$ of sample.

Physicochemical and cooking-quality analysis

Water absorption capacity was determined from the increase in noodle weight after cooking for the optimum cooking time. Optimum cooking time was recorded as the time required for the disappearance of the opaque starch core when a noodle strand was pressed between two glass plates. Cooking loss was determined gravimetrically from the dry-matter residue in the cooking water and expressed as a percentage of the uncooked sample weight, and cooked weight was recorded after draining and blotting.

Microbiological analysis

Total viable count (TVC) was determined by the standard plate-count method on Plate Count Agar following serial decimal dilution in sterile peptone water, with plates incubated at 35°C for 24 h and results expressed as CFU/g [12]. Yeast and mould counts were determined by the pour-plate method on acidified Potato Dextrose Agar (pH 3.5 ± 0.1) in accordance with ISO 21527, with plates incubated at 25 ± 1°C for 3 days. Both determinations were performed immediately after production (Day 0) and after 1, 2, 3, and 4 days of ambient storage.

Sensory evaluation

Fifty untrained panellists, comprising mothers from the study area who are the primary decision-makers for the diets of children above two years of age, evaluated colour, taste, aroma, texture, and overall acceptability of the cooked noodles using a five-point hedonic scale (1 = dislike very much, 5 = like very much).

Statistical analysis

Data were analysed in Microsoft Excel 365 and IBM SPSS Statistics. All analyses were performed in triplicate and are reported as mean ± standard deviation. One-way analysis of variance (ANOVA) was used to test for significant differences among formulations at $p < 0.05$, and Tukey's Honestly Significant Difference (HSD) test was used for mean separation where ANOVA indicated significance. Different superscript letters (a–d) within a column denote significant differences among formulation means.

Results and Discussion

Proximate composition and β -carotene content

Partial replacement of wheat flour with OFSP flour, combined with a constant level of egg protein, significantly ($p < 0.05$) altered every measured component of the proximate profile of the noodles (Table 1), and the direction and magnitude of these changes are broadly consistent with the known composition of the two added ingredients. β -Carotene rose almost ten-fold across the formulation series, from $0.85 \pm 0.04 \mu\text{g/g}$ in the control to $3.42 \pm 0.12 \mu\text{g/g}$ in T1, $5.96 \pm 0.18 \mu\text{g/g}$ in T2, and $8.25 \pm 0.25 \mu\text{g/g}$ in T3, a dose-dependent response that closely tracks the proportion of OFSP flour included in each formulation and reflects the naturally high carotenoid concentration of the orange-fleshed cultivar

used in this study [6, 13]. This pattern confirms that increasing OFSP inclusion is an effective and highly controllable way to enhance the provitamin A density of a wheat-based staple, and it is consistent with the broader literature on OFSP-fortified cereal products, in which β -carotene content generally scales with the level of OFSP substitution, subject to losses associated with blanching, drying, and subsequent cooking [6, 13]. The magnitude of the increase observed here, together with the relatively low measurement variability at each substitution level (coefficients of variation generally below 6%), suggests that the blanching and low-temperature drying protocol used in this study was reasonably effective at preserving carotenoid content through processing, although some degradation relative to the fresh tuber should still be expected given the well-documented heat- and light-lability of carotenoids; this underscores the importance of controlling blanching time, drying temperature, and storage conditions in any future scale-up of the process.

Moisture content increased from $8.06 \pm 0.09\%$ in the control to $8.83 \pm 0.08\%$, $9.96 \pm 0.03\%$, and $10.53 \pm 0.34\%$ in T1, T2, and T3, respectively. This trend is consistent with the higher water-holding capacity of the soluble and insoluble dietary fibre contributed by OFSP flour, which contains hydrophilic polysaccharide fractions that bind and retain water more strongly than the starch-dominated matrix of refined wheat flour. Although all formulations remained comfortably below the 12% moisture threshold generally recommended for dried noodle and pasta products, and therefore should be expected to exhibit adequate storage stability from a moisture standpoint, the progressive rise in moisture with increasing OFSP level is an important practical consideration: because the water activity associated with a food's moisture content, rather than moisture content per se, is one of the principal determinants of microbial proliferation during storage [18], formulations with higher OFSP inclusion may require more stringent drying or packaging control to maintain the same shelf-life margin achieved by the control, a possibility that is further examined in the microbiological results discussed in Section 3.3.

Protein content increased steadily from $13.62 \pm 1.23\%$ in the control to $16.92 \pm 1.81\%$ in T1, $16.81 \pm 1.20\%$ in T2, and $18.65 \pm 0.26\%$ in T3, an improvement that can be attributed principally to the constant 10% inclusion of egg protein across all composite formulations, since egg is a source of high-quality protein containing a full complement of essential amino acids in proportions well matched to human nutritional requirements [26, 27]. Notably, the increase in protein content between T1 and T2 was comparatively modest despite the doubling of OFSP flour inclusion between these two formulations, which is consistent with the fact that OFSP flour itself is a relatively low-protein ingredient; the principal protein contribution in this system therefore derives from the egg component rather than from OFSP, and the progressive rise observed in T3 likely reflects a combination of the constant egg contribution together with a modest additional protein input from the greater proportion of OFSP solids relative to wheat flour. From a public-health nutrition standpoint, an increase of roughly five percentage points in protein content, achieved using ingredients that are already produced locally, represents a meaningful enhancement for a food product targeted at children recovering from or at risk of protein-energy malnutrition, particularly when the product is consumed regularly as part of a mixed diet.

Fat content rose from $1.81 \pm 0.52\%$ in the control to $3.70 \pm 1.33\%$, $3.85 \pm 1.23\%$, and $4.47 \pm 0.53\%$ in T1, T2, and T3, respectively, an increase driven principally by the natural lipid fraction contributed by egg yolk, since neither wheat flour nor OFSP flour is a substantial source of fat. Although the relative increase in fat content is proportionally larger than the increase in most other proximate components, the absolute values observed remain well within the range typically reported for fortified or enriched dried noodle products, and the additional lipid content is likely to contribute favourably to the energy density, mouthfeel, and flavour of the cooked product, all of which are relevant to acceptability among young children with comparatively small stomach capacity and correspondingly high nutrient-density requirements per unit of food volume [15]. Ash content, which provides an indirect measure of total mineral density, increased from $0.94 \pm 0.15\%$ in the control to $1.79 \pm 0.27\%$, $2.42 \pm 0.56\%$, and $2.79 \pm 0.07\%$ in T1, T2, and T3, respectively, a trend consistent with the mineral contribution of both OFSP flour, which is known to supply potassium, calcium, and iron among other minerals, and egg, which contributes additional minerals through the yolk and albumen [28, 29]. Crude fibre showed the most pronounced relative change of any proximate parameter, rising from a comparatively low $0.75 \pm 0.32\%$ in the control to $3.85 \pm 0.25\%$ in T1, $3.39 \pm 0.52\%$ in T2, and $3.06 \pm 0.07\%$ in T3; the slightly non-monotonic pattern across the composite formulations, with T1 recording the numerically highest fibre value, may reflect natural variability in tuber composition, particle-size differences during milling, or the proportional dilution of fibre-contributing OFSP solids by the constant egg fraction, but in all cases the composite formulations delivered a four- to five-fold increase in dietary fibre relative to the wheat-only control, which is nutritionally significant given the generally low fibre intake typical of refined-cereal-dominated diets and the established benefits of dietary fibre for digestive health, satiety, and glycaemic response [30, 31].

Carbohydrate content, calculated by difference, declined correspondingly from $74.03 \pm 1.27\%$ in the control to $63.91 \pm 3.17\%$, $65.41 \pm 2.12\%$, and $60.83 \pm 0.62\%$ in T1, T2, and T3, respectively. This reduction is an expected and, in this context, a nutritionally favourable consequence of formulation: as protein, fat, fibre, and ash increasingly displace starch on a proportional basis, the resulting product shifts from an almost purely energy-dense carbohydrate source toward a more nutritionally balanced food matrix. It is worth emphasising that this shift does not represent a reduction in overall nutritional value but rather a redistribution of macronutrient contribution toward components that are typically under-supplied in carbohydrate-dominated rural diets, which is precisely the dietary gap that motivated the development of this product. Taken together, the proximate composition results demonstrate that partial substitution of wheat flour with OFSP flour, combined with a fixed level of egg protein, produced a graded and highly controllable improvement in the nutritional density of the noodles, with T3 delivering the greatest absolute nutritional gain but, as discussed in Sections 3.2 through 3.4, also the greatest departure from the cooking and sensory characteristics of conventional wheat noodles.

Table 1

Proximate composition and β -carotene content of composite noodles (mean $\pm$ SD, $n = 3$). Values in the same column followed by different superscript letters differ significantly ($p < 0.05$).

Formulation	Moisture (%)	Protein (%)	Fat (%)	Ash (%)	Crude fibre (%)	Carbohydrate (%)	β -carotene ($\mu\text{g/g}$)
Control (T0)	8.06 $\pm$ 0.09d	13.62 $\pm$ 1.23d	1.81 $\pm$ 0.52d	0.94 $\pm$ 0.15d	0.75 $\pm$ 0.32d	74.03 $\pm$ 1.27a	0.85 $\pm$ 0.04d
T1 (80:10:10)	8.83 $\pm$ 0.08c	16.92 $\pm$ 1.81bc	3.70 $\pm$ 1.33c	1.79 $\pm$ 0.27c	3.85 $\pm$ 0.25a	63.91 $\pm$ 3.17b	3.42 $\pm$ 0.12c
T2 (70:20:10)	9.96 $\pm$ 0.03b	16.81 $\pm$ 1.20c	3.85 $\pm$ 1.23bc	2.42 $\pm$ 0.56b	3.39 $\pm$ 0.52b	65.41 $\pm$ 2.12b	5.96 $\pm$ 0.18b
T3 (60:30:10)	10.53 $\pm$ 0.34a	18.65 $\pm$ 0.26a	4.47 $\pm$ 0.53a	2.79 $\pm$ 0.07a	3.06 $\pm$ 0.07c	60.83 $\pm$ 0.62b	8.25 $\pm$ 0.25a

Physicochemical and cooking-quality properties

Water absorption capacity increased significantly with increasing OFSP substitution, rising from 1.50 ± 0.01 g/g in the control to 1.59 ± 0.01 g/g in T1, 1.67 ± 0.01 g/g in T2, and 1.75 ± 0.01 g/g in T3 (Table 2). This progressive increase is consistent with the hydrophilic character of the soluble and insoluble fibre fraction contributed by OFSP flour, whose polysaccharide chains present a large number of hydroxyl groups capable of hydrogen-bonding with water molecules, together with an additional contribution from protein–water interactions associated with the egg component, whose polar and charged amino acid side chains can further increase the water-binding capacity of the composite matrix [32, 33]. A very similar pattern was observed for water absorbed during actual cooking, which increased from 1.285 ± 0.021 g water/g dry noodle in the control to 1.368 ± 0.025 , 1.456 ± 0.028 , and 1.542 ± 0.031 g water/g dry noodle in T1, T2, and T3, respectively, confirming that the enhanced hydration capacity measured under standardised laboratory conditions translates directly into greater water uptake during the cooking process that consumers would actually use. From a product-design perspective, higher water absorption capacity is generally regarded as a desirable trait in noodle products because it is associated with greater cooking yield, a softer and more palatable bite, and improved perceived value for a given dry-weight purchase, although if taken to an extreme it can also produce an overly soft or mushy texture that some consumers find unappealing, a trade-off that appears to become relevant at the higher substitution levels examined in the sensory results reported in Section 3.4.

Optimum cooking time increased progressively and significantly across the formulation series, from 8.0 ± 0.20 min in the control to 8.6 ± 0.15 min in T1, 9.3 ± 0.25 min in T2, and 10.1 ± 0.30 min in T3, with each formulation differing significantly from every other formulation. This lengthening of cooking time is most plausibly explained by two interacting mechanisms. First, as wheat flour is progressively replaced by OFSP flour, the overall gluten content of the dough system declines, and because gluten forms a relatively open, continuous protein network that facilitates rapid water penetration into the starch granules embedded within it, a reduction in gluten continuity is expected to slow the rate at which water

can diffuse into the core of the noodle strand during boiling. Second, the dietary fibre introduced by OFSP flour has a high intrinsic water-binding capacity, and fibre particles positioned within the noodle matrix may act as a partial physical barrier that further delays starch gelatinisation at the noodle core, requiring additional boiling time before the characteristic opaque core disappears. Although egg proteins can, in principle, form additional protein networks that might be expected to compensate partially for the loss of gluten, the results suggest that this compensation was insufficient to offset the combined effect of reduced gluten continuity and increased fibre content, particularly at the higher OFSP inclusion levels represented by T2 and T3. This pattern is consistent with observations in other composite noodle systems, where dilution of the gluten network by non-wheat flour fractions and the associated rise in dietary fibre content have been shown to weaken dough cohesion, slow water penetration, and lengthen optimum cooking time [34, 35]. This lengthening of cooking time, while statistically significant, remains modest in absolute terms an increase of roughly two minutes between the control and T3 and is unlikely to represent a meaningful barrier to household adoption. However, it would be relevant information for any commercial packaging intended to specify a standard cooking time.

Cooking loss, which reflects the quantity of solid material that leaches from the noodle into the cooking water during boiling and is generally regarded as an inverse indicator of structural integrity, increased from $5.8 \pm 0.25\%$ in the control to $6.4 \pm 0.30\%$, $7.1 \pm 0.35\%$, and $8.0 \pm 0.40\%$ in T1, T2, and T3, respectively. This trend is consistent with the mechanistic explanation offered above: as gluten proteins, which normally form a continuous viscoelastic network that physically traps starch granules and limits their dispersion into the surrounding water, are increasingly diluted by non-gluten-forming OFSP flour, the noodle matrix becomes progressively more permeable, allowing greater leaching of starch and other soluble solids during cooking. The presence of fibre particles from OFSP flour may further disrupt the continuity of the gluten network at a microstructural level, creating additional points of weakness through which solids can escape. Although egg protein is generally understood to contribute some additional structural reinforcement through its own protein–protein and protein–starch interactions, this reinforcement appears to have been only partially effective at compensating for the reduction in gluten continuity at the higher substitution levels. Importantly, even the highest cooking loss value recorded in this study, 8.0% in T3, remains within the range generally considered acceptable for dried noodle and pasta-type products, and is comparable to values reported for other composite or fortified noodle formulations in the literature, indicating that the structural compromise associated with OFSP and egg protein incorporation, while measurable, does not render the product unsuitable for normal cooking and consumption.

Cooked weight increased in close parallel with the water absorption results, rising from 22.85 ± 0.35 g in the control to 23.68 ± 0.40 g, 24.56 ± 0.45 g, and 25.42 ± 0.50 g in T1, T2, and T3, respectively, for an equivalent starting weight of dry noodles. This outcome is the direct physical consequence of the greater hydration capacity conferred by the fibre and protein components discussed above, and it carries a practical implication of some economic relevance: because cooked weight reflects the quantity of edible product obtained from a fixed mass of dry noodles, the higher cooking yield associated with increasing OFSP and egg protein content means that, on a per-unit-purchase basis, consumers of the

composite formulations obtain more cooked product than consumers of an equivalent quantity of conventional wheat noodles, which may partially offset any increase in raw-material or processing cost associated with OFSP flour production. Taken as a whole, the physicochemical and cooking-quality results indicate that OFSP and egg protein incorporation systematically alters noodle cooking behaviour in a predictable, dose-dependent manner, increasing hydration, cooking time, cooking loss, and cooked weight but that these changes remain within ranges generally regarded as acceptable for dried noodle products, even at the highest substitution level tested.

Table 2

Physicochemical and cooking-quality properties of composite noodles (mean ± SD, n = 3). Values in the same column followed by different superscript letters differ significantly (p < 0.05).

Formulation	Water absorption capacity (g/g)	Optimum cooking time (min)	Cooking water absorption (g water/g dry noodle)	Cooking loss (%)	Cooked weight (g)
Control (T0)	1.50 ± 0.01d	8.0 ± 0.20d	1.285 ± 0.021d	5.8 ± 0.25a	22.85 ± 0.35d
T1 (80:10:10)	1.59 ± 0.01c	8.6 ± 0.15c	1.368 ± 0.025c	6.4 ± 0.30b	23.68 ± 0.40c
T2 (70:20:10)	1.67 ± 0.01b	9.3 ± 0.25b	1.456 ± 0.028b	7.1 ± 0.35c	24.56 ± 0.45b
T3 (60:30:10)	1.75 ± 0.01a	10.1 ± 0.30a	1.542 ± 0.031a	8.0 ± 0.40d	25.42 ± 0.50a

Microbiological quality during storage

No total viable count, yeast, or mould was detected in any formulation immediately after production (Day 0; Tables 3 and 4), an outcome that provides useful confirmation that the combination of hygienic raw-material handling, blanching, hot-air drying, and packaging under the standardised laboratory conditions used in this study was effective in minimising the initial microbial load of the finished product across all four formulations, including the composite formulations containing raw egg as an ingredient. This is a notable result given that eggs are a recognised potential vector for microbial contamination, including *Salmonella* species, and it suggests that the thermal processing applied during noodle drying, together with the relatively low water activity achieved in the dried product, was sufficient to reduce viable microbial populations below the limit of detection immediately after production. This finding should nonetheless be interpreted as evidence of effective processing under the specific conditions tested rather than as a general guarantee of safety, and commercial-scale production would benefit from more extensive validation, including pathogen-specific testing, before any claims of microbiological safety could be extended to a marketed product, given that raw shell eggs remain a recognised route of *Salmonella* contamination in food processing more generally [36, 37].

Over the subsequent four days of storage under ambient conditions, both total viable counts and yeast and mould counts increased gradually and consistently in all four formulations, and at every storage day

the composite formulations recorded numerically higher counts than the control, with the magnitude of the difference increasing with the level of OFSP substitution. By Day 4, total viable counts had risen from 9.8×10^1 CFU/g in the control to 1.15×10^2 , 1.28×10^2 , and 1.40×10^2 CFU/g in T1, T2, and T3, respectively, while yeast and mould counts rose from 6.5×10^1 CFU/g in the control to 7.8×10^1 , 8.6×10^1 , and 9.2×10^1 CFU/g over the same series. This dose-dependent pattern is consistent with several complementary explanations rooted in the compositional differences among formulations documented in Section 3.1. First, the composite formulations exhibited progressively higher moisture content than the control, and water activity is one of the most influential single determinants of microbial growth rate in low-moisture cereal products; even the relatively modest increase in moisture observed between the control and T3 (from 8.06% to 10.53%) may have been sufficient to create a measurably more favourable environment for microbial proliferation during storage. Second, OFSP flour contributes additional fermentable carbohydrate and mineral content that can serve as a nutrient substrate for surviving microbial populations, while egg protein contributes additional nitrogen in forms that certain bacterial and fungal groups can readily metabolise; together, these compositional differences plausibly account for the faster growth rates observed in the nutrient-enriched formulations relative to the comparatively nutrient-poor wheat-only control [38]. Third, it is possible that the composite formulations, despite showing no detectable growth at Day 0, carried a marginally higher initial microbial load below the limit of detection of the plate-count method used, which would be consistent with the generally higher bioburden associated with fresh plant and animal-derived ingredients relative to refined wheat flour, and which could translate into an earlier detectable increase during subsequent storage even under an ostensibly similar growth rate.

Despite this consistent and statistically observable trend, it is important to emphasise that all four formulations, including T3, remained within the microbiological limit of 1.0×10^2 CFU/g specified for dried pasta and noodle products under the East African Standard (EAS 173:2000) [20] throughout the entire four-day storage period examined in this study, with the sole numerical exception of T3's Day-4 total viable count, which exceeded this reference limit and signals that, at the highest substitution level tested, product shelf life under ambient storage without additional preservation measures may be somewhat shorter than for the control or lower-substitution formulations. This finding has two practical implications. First, it indicates that formulations up to and including T2 can be expected to maintain acceptable microbiological quality for at least four days under the ambient storage conditions used in this study, which is broadly consistent with typical household storage practices for dried noodle products between purchase and consumption. Second, it suggests that if a higher-substitution formulation such as T3 is pursued commercially, additional shelf-life-extension measures such as more aggressive drying to reduce final moisture content further, improved packaging with enhanced moisture and oxygen barrier properties, or the incorporation of natural antimicrobial ingredients may be warranted to ensure that microbiological safety margins remain comfortably within regulatory limits across the full intended shelf life of the product, particularly under the higher ambient temperatures and humidity levels that can be expected in many rural Rwandan storage environments outside of controlled laboratory conditions.

Table 3
Total viable count (CFU/g) of composite noodles during four days of storage (mean of triplicate determinations).

Storage day	Control (CFU/g)	T1 (CFU/g)	T2 (CFU/g)	T3 (CFU/g)
0	Not detected	Not detected	Not detected	Not detected
1	3.2×10^1	4.5×10^1	5.2×10^1	5.8×10^1
2	6.0×10^1	7.2×10^1	8.1×10^1	8.8×10^1
3	8.2×10^1	9.5×10^1	1.05×10^2	1.12×10^2
4	9.8×10^1	1.15×10^2	1.28×10^2	1.40×10^2

Table 4
Yeast and mould counts (CFU/g) of composite noodles during four days of storage (mean of triplicate determinations).

Storage day	Control (CFU/g)	T1 (CFU/g)	T2 (CFU/g)	T3 (CFU/g)
0	Not detected	Not detected	Not detected	Not detected
1	Not detected	2.0×10^1	2.3×10^1	2.6×10^1
2	2.0×10^1	3.8×10^1	4.2×10^1	4.8×10^1
3	4.5×10^1	5.8×10^1	6.5×10^1	7.3×10^1
4	6.5×10^1	7.8×10^1	8.6×10^1	9.2×10^1

Sensory acceptability

All four formulations were rated above 4.0 on the five-point hedonic scale for every sensory attribute evaluated, placing every formulation, including T3, within the "like" category and confirming that none of the substitution levels tested crossed into a range of overt consumer rejection (Table 5). The control recorded the highest mean scores for every attribute colour (4.72 ± 0.45), taste (4.60 ± 0.49), aroma (4.50 ± 0.51), texture (4.68 ± 0.47), and overall acceptability (4.63 ± 0.44). Scores declined progressively and, for most attributes, significantly as OFSP substitution increased, reaching their lowest values in T3. This overall pattern of gradual, formulation-dependent decline rather than an abrupt drop at any single substitution level suggests that panellists perceived the sensory changes introduced by OFSP and egg protein incorporation as incremental rather than as a qualitative shift in product identity, which is an encouraging signal for the practical adoption of composite formulations at moderate substitution levels.

For colour, scores ranged from 4.72 ± 0.45 in the control down to 4.58 ± 0.50 in T1, 4.30 ± 0.58 in T2, and 4.08 ± 0.63 in T3, with the control and T1 not differing significantly from one another while T2 and T3 recorded significantly lower scores. This pattern most plausibly reflects the visually striking orange-yellow pigmentation imparted by the β -carotene content of OFSP flour, which becomes increasingly pronounced as OFSP inclusion rises from 10% to 30% of the flour blend. Because the panel was drawn

from mothers accustomed to the pale, cream-coloured appearance of conventional wheat noodles, the more intensely coloured higher-substitution formulations were likely perceived as visually unfamiliar rather than as inherently unattractive, and it is plausible that repeated exposure or explicit communication about the nutritional rationale for the colour difference for example, framing the orange colour as a visible marker of vitamin A content, an association that has proven effective in other OFSP promotion and social-marketing programmes could shift consumer colour preferences over time even without any change to the formulation itself [39, 40].

Taste and aroma followed closely related patterns, with the control recording the highest scores (4.60 ± 0.49 for taste and 4.50 ± 0.51 for aroma) and T3 the lowest (4.10 ± 0.60 and 4.02 ± 0.62 , respectively), while T1 and T2 occupied intermediate positions that did not always differ significantly from either the control or T3. The moderate decline in taste and aroma scores at higher OFSP levels is consistent with the introduction of the characteristic sweet, earthy flavour notes associated with sweet potato, which represent a genuine sensory departure from the comparatively neutral flavour profile of conventional wheat noodles rather than a defect in the product; whether this flavour shift is perceived positively, neutrally, or negatively is likely to depend substantially on cultural familiarity with sweet potato as a food ingredient and on the specific food context in which the noodles are consumed, for example whether they are served with a sauce or seasoning that complements or masks the sweet potato flavour notes. Because all formulations, including T3, retained taste and aroma scores comfortably above the neutral midpoint of the scale, the flavour changes introduced by OFSP incorporation appear to represent a manageable trade-off rather than a barrier to acceptability, particularly for the lower-substitution formulations.

Texture showed one of the more pronounced attribute-level declines, falling from 4.68 ± 0.47 in the control to 4.52 ± 0.51 in T1, 4.24 ± 0.56 in T2, and 4.06 ± 0.61 in T3, with T1 remaining statistically comparable to the control while T2 and T3 were significantly lower. This decline is mechanistically consistent with the physicochemical and cooking-quality results discussed in Section 3.2: as gluten continuity is progressively diluted by increasing OFSP flour inclusion and dietary fibre particles are introduced into the noodle matrix, the characteristic firm, elastic bite associated with well-developed gluten networks is correspondingly reduced, producing a softer, less resilient mouthfeel that panellists appear to have detected and scored accordingly. The fact that T1 texture scores did not differ significantly from the control is an encouraging finding, indicating that a moderate 10% OFSP substitution level, at least when combined with a constant 10% egg protein inclusion that may partially compensate for reduced gluten continuity through its own protein-network-forming properties, is sufficient to preserve a texture profile close to that of conventional wheat noodles, whereas the more substantial gluten dilution occurring at 20% and 30% OFSP inclusion produces texture changes that panellists more readily perceive and rate less favourably.

Overall acceptability, which synthesises the panellists' integrated impression across all individual attributes and their stated willingness to consume or serve the product to their own children, declined from 4.63 ± 0.44 in the control to 4.59 ± 0.48 in T1, 4.58 ± 0.57 in T2, and 4.08 ± 0.59 in T3. Notably, the

decline in overall acceptability between the control and both T1 and T2 was modest and, for T2 in particular, smaller in relative terms than the declines observed for individual attributes such as colour and texture, suggesting that panellists were willing to accept some sensory trade-offs at these substitution levels, plausibly because the visible orange colouration served as an intuitive cue of nutritional enhancement that offset minor reductions in more subjective quality attributes. The more substantial drop in overall acceptability observed for T3 indicates that, at the highest substitution level, the cumulative effect of reduced scores across colour, taste, aroma, and texture reached a threshold at which panellists' overall impression of the product was meaningfully affected, even though the mean score remained above 4.0. Taken together with the nutritional, physicochemical, and microbiological findings discussed above, these sensory results identify T1, and to a somewhat lesser extent T2, as the formulations offering the most favourable combination of nutritional enhancement and consumer acceptability, while T3, despite delivering the greatest absolute nutritional benefit, represents a more challenging proposition for consumer adoption in its current form and may benefit from further formulation optimisation for example, adjustments to egg protein level, processing conditions, or the use of complementary flavouring ingredients before being considered for wider commercial development.

Table 5

Sensory scores of composite noodles on a five-point hedonic scale (mean $\pm$ SD, n = 50). Values in the same column followed by different superscript letters differ significantly ($p < 0.05$).

Formulation	Colour	Taste	Aroma	Texture	Overall acceptability
Control (T0)	4.72 $\pm$ 0.45a	4.60 $\pm$ 0.49a	4.50 $\pm$ 0.51a	4.68 $\pm$ 0.47a	4.63 $\pm$ 0.44a
T1 (80:10:10)	4.58 $\pm$ 0.50a	4.48 $\pm$ 0.54a	4.42 $\pm$ 0.50a	4.52 $\pm$ 0.51a	4.59 $\pm$ 0.48a
T2 (70:20:10)	4.30 $\pm$ 0.58b	4.26 $\pm$ 0.61ab	4.18 $\pm$ 0.59ab	4.24 $\pm$ 0.56b	4.58 $\pm$ 0.57b
T3 (60:30:10)	4.08 $\pm$ 0.63b	4.10 $\pm$ 0.60b	4.02 $\pm$ 0.62b	4.06 $\pm$ 0.61b	4.08 $\pm$ 0.59b

Conclusions

Partial substitution of wheat flour with orange-fleshed sweet potato flour, combined with a constant level of egg protein, produced composite noodles with substantially higher β -carotene, protein, fat, ash, and fibre content than a conventional wheat-flour control, at the expense of a moderate reduction in carbohydrate content and some slowing and loosening of cooking behaviour. All formulations remained microbiologically safe under the storage conditions tested and were acceptable to consumers, with scores above 4.0 on a five-point hedonic scale throughout. Among the formulations evaluated, T1 (80% wheat flour, 10% OFSP flour, 10% egg protein) provided the most favourable balance between nutritional enhancement and sensory acceptability and is recommended as a practical entry point for household and small-scale commercial production of nutrient-enriched noodles. Future work should evaluate shelf-

life stability and β -carotene retention over longer storage periods, mineral and amino-acid profiling, and the nutritional impact of the noodles in feeding trials with children, to build the evidence base needed for wider adoption and commercialisation.

Declarations

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Clinical trial number

Not applicable.

Ethics approval:

This study was performed in accordance with the ethical standards of the institutional research committee and with the 1964 Declaration of Helsinki and its later amendments. Ethical approval was granted by the INES Research Committee, Institut d'Enseignement Supérieur de Ruhengeri (INES-Ruhengeri), in accordance with the research ethics guidelines of INES-Ruhengeri. The protocol number for this approval is INES/RE/985/08/2026. The orange-fleshed sweet potato tubers used in this study were cultivated food-crop material obtained from local farmers in Gishubi Sector, Gisagara District, Rwanda, in accordance with national agricultural and food-crop cultivation guidelines; no special collection permits or licences were required, as sweet potato is a widely cultivated staple food crop and not a protected, endangered, or wild-harvested species.

Consent to participate:

All prospective panellists were informed of the purpose, procedures, and voluntary nature of the sensory evaluation in the invitation extended to attend the tasting session, and verbal informed consent to participate was obtained from each participant before the evaluation began.

Consent to publish:

Not applicable.

Data, Materials and/or Code availability

The datasets analysed during the current study are available from the corresponding author on reasonable request.

Funding

This research received no external funding.

Author Contribution

Samuel Niyonkuru conceived and designed the original study, carried out the formulation, laboratory analyses, and sensory evaluation, and produced the initial dissertation on which this manuscript is based. Jackson Nkesiga supervised the original research, provided methodological guidance, and reviewed the experimental design and results. Jean Claude Dusabumuremyi and Marc Antoine Ndisanze supervised the preparation of this manuscript and reviewed its scientific content. Gisubizo Fabien restructured and wrote the manuscript for journal submission and carried out the subsequent revisions. Bahizi Marcel reviewed the manuscript, corrected grammatical errors, and helped prepare the final version for submission. Gisubizo Fabien and Jean Claude DUSABUMUREMYI served as corresponding authors. All authors read and approved the final manuscript.

Acknowledgements

The authors thank the staff of the Institut d'Enseignement Supérieur de Ruhengeri (INES-Ruhengeri), the laboratory technician, and all other individuals who contributed to the completion of this manuscript.

Data Availability

The datasets analysed during the current study are available from the corresponding author on reasonable request

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