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Soy-Groundnut Suya Meat Analogue Compared with Beef Control: A Nutritional, Phytochemical and Quality Evaluation

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Abstract: Growing demand for sustainable, affordable, and nutritionally adequate plant-based proteins has intensified interest in meat analogues as viable alternatives to animal-source foods. This study investigated the use of complementary legume proteins from soybean (*Glycine max*) and groundnut (*Arachis hypogaea*) in producing a culturally relevant suya-type meat analogue. Three soy-groundnut suya meat analogues (SGMS1: 50:50%; SGMS2: 60:40%; SGMS3: 70:30%) were formulated and evaluated against a 100% beef suya control (MS) for proximate and mineral composition (AOAC, 2023), vitamin content (HPLC), phytochemical profile (spectrophotometry), textural attributes (texture profile analysis), CIELab colour parameters, and sensory acceptability (9-point hedonic scale). Protein content increased significantly ($p < 0.05$) with soy-groundnut inclusion, peaking at 33.61 mg/100g in SGMS3 versus 24.23 mg/100g in MS, while crude fat declined from 13.51 to 7.59 mg/100g. SGMS2 recorded the highest concentrations of magnesium, potassium, phosphorus, calcium, and iron, as well as total phenolics (164.37 mg/100g). SGMS3 showed the highest niacin, pyridoxine, flavonoid, and zinc values. Textural parameters increased progressively with soy inclusion. Sensory acceptability scores ranged from 5.90 to 6.20 for the analogues versus 8.10 for the control. Soy-groundnut meat analogues improved nutritional quality over conventional beef suya, with SGMS2 emerging as the most balanced formulation. Targeted sensory optimization is required before commercial adoption.

Keywords: plant-based protein; meat analogue; suya; soybean; groundnut; proximate composition; texture profile analysis; phytochemicals; sensory evaluation

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1. Introduction

Global food systems face increased pressure to deliver nutritionally adequate, affordable, and environmentally sustainable protein at scale. The world population is projected to reach 9.7 billion by 2050 [1]. This trajectory is projected to intensify protein demand when the environmental costs of conventional livestock production, such as greenhouse gas emissions, land degradation, and freshwater depletion, become untenable [2, 3]. These dual pressures have catalyzed sustained scientific and commercial interest in plant-based meat analogues. Meat analogues are structured products designed to replicate the nutritional and sensory characteristics of animal-derived meat from legumes, cereals, or fungal feedstocks [3].

While early formulations relied predominantly on textured soy protein or wheat gluten, research into plant-based meat analogues has expanded considerably over the past decade. Contemporary products utilize diverse protein blends, novel processing modalities such as high-moisture extrusion and shear-cell technology, and functional

ingredient combinations. These are engineered to recreate the texture, colour, juiciness, and flavour of meat [4, 5]. Soybean (*Glycine max*), with its near-complete amino acid profile and a protein digestibility-corrected amino acid score (PDCAAS) of 1.00, remains the dominant protein ingredient in commercial analogues [6]. However, there is a growing consensus that single-legume products can exhibit amino acid deficiencies. Soy is notably limiting in methionine and cysteine, while groundnut is limiting for sulphur-containing amino acids. It therefore becomes necessary to blend complementary legume proteins to achieve nutritional adequacy [7, 8].

Soybeans contribute 40-50% protein, functional isoflavones, and dietary fibre. Groundnuts provide 22-30% protein alongside niacin, tocopherols, resveratrol, and flavonoids [9, 10, 11]. The soybean-groundnut dyad represents a strategically underexplored frontier in food material science, despite its nutritional synergy and regional abundance. This study addresses a critical knowledge gap; it pioneers the integration of these complementary legumes into a structured, culturally specific meat analogue: Suya. While existing research focuses on single-source proteins, this work uniquely leverages the high-protein density of soy alongside the rich bioactive profile of groundnut. Systematically evaluating this novel composite matrix within the "Suya" framework provides the first comprehensive evidence that this indigenous, cost-effective combination can replicate the complex textural and nutritional profiles of animal-derived proteins.

Suya is a traditional Nigerian spiced, grilled meat product consumed widely across West Africa. It represents a culturally significant protein delivery vehicle and a potential plant-based alternative to the population. However, no comprehensive published study has systematically examined how variations of soy-to-groundnut substitution level influence the full spectrum of nutritional composition, phytochemical load, textural attributes, colorimetric properties, and sensory acceptability within a single experimental framework.

To bridge the gap between traditional West African cuisine and sustainable food science, this study engineered soy-groundnut suya meat analogues. We transitioned from animal to plant protein using three strategic substitution levels 50%, 60%, and 70% soybean designed to optimize the soy-to-groundnut amino acid complementarity identified in existing literature. These ratios prioritize the balance between soy's structural integrity and groundnut's essential fatty acids. To validate this transition, we benchmarked the analogues against a conventional beef control, scrutinizing their nutritional density, bioactive phytochemical loads, and micro-textural properties. Trained sensory panels ultimately assessed whether these innovative, legume-based matrices could successfully replicate the iconic "Suya" experience.

2. Materials and Methods

2.1 Raw Materials and Preparation

Soybeans (*Glycine max*), groundnuts (*Arachis hypogaea*), and all ancillary ingredients: carboxymethylcellulose (CMC), dried mushroom, soy sauce, coconut oil, beetroot powder, vegetable oil, yaji spice, ginger, garlic, curry, and salt, were sourced from certified dealers in local markets at Ose-Onitsha and Eke-Awka, Anambra State, Nigeria. All chemical reagents were of analytical grade (Sigma-Aldrich, Germany). To ensure consistency and control protein denaturation, precise thermal parameters were implemented. Soybeans underwent a 12-hour dehydration at 40°C—a temperate threshold specifically chosen to preserve protein solubility and enzymatic activity before the high-heat phase. Subsequent toasting occurred at 140°C for 15 minutes in a forced-air oven (Model DHG-9053A) to induce controlled Maillard reactions for flavor development. Groundnuts were blanched at 85°C for 3 minutes to inactivate lipoxygenase and facilitate manual dehulling, followed by a 6-hour dehydration at 40°C. These standardized time-temperature profiles minimize batch-to-batch variability, ensuring a uniform protein matrix across all analogue formulations.

2.2 Formulation and Production of Suya Analogues

This study engineered a culturally relevant "Suya" meat analogue by strategically blending soybean and groundnut to maximize nutritional synergy. Utilizing three specific substitution levels (50:50, 60:40, and 70:30), the research targeted the "amino acid gap" between these legumes, aiming for a complete protein profile comparable to beef. Findings revealed that the 70% soy formulation surpassed the control in protein density, while the 60% soy blend emerged as the mineral-optimal formulation. Despite these nutritional victories, an acceptability gap remains, as sensory panels favored the traditional beef control, highlighting the need for further refinement in flavor and texture. The formulation on a 1 kg batch basis is presented in Table 1. Each formulation was blended to a homogeneous mixture, pressed under a weighted cheesecloth to form a dense sliceable block, shaped into thin strips, marinated in vegetable oil and yaji spice, and grilled at 150°C for dehydration and flavour development. Standardizing the batch to 1 kg ensures formulation precision, while 150°C grilling facilitates essential Maillard browning and moisture reduction. Products were cooled and stored in airtight, labelled pouches.

Table 1. Formulation of Soy-Groundnut Meat Analogue-1 kg Batch

Food Samples	SG1 (50:50)	SG2 (60:40)	SG3 (70:30)
A. Protein Base			
Soybeans(g)	300	360	420
Groundnut(g)	300	240	180
Protein base subtotal (g)	600	600	600
B. Binding agent			
Carboxyl methyl cellulose (CMC) (g)	20	20	20
Coconut oil(ml)	75	75	75
C. Color and Moisture agent			
Beet root powder(g)	75	75	75
Soy sauce(mi)	75	75	75
D. Flavor and Seasoning			
Dried Mushroom powder (g)	35	35	35
Ginger(g)	5	5	5
Garlic(g)	5	5	5
Yaji spice(g)	100	100	100
Salt(g)	5	5	5
Curry powder(g)	5	5	5

Keys: SG1= 50%Soybeans, 50% Groundnut; SG2=60% Soybeans, 40% Groundnut; SG3=70% Soybeans, 30% Groundnut

2.3 Proximate Composition

Moisture (oven drying, 105°C), crude protein (Kjeldahl, $N \times 6.25$), crude fat (Soxhlet extraction, petroleum ether), crude fibre (acid-alkali digestion), and total ash (muffle furnace, 550°C) were determined according to AOAC official methods [12]. Total available carbohydrate was calculated by difference. All analyses were performed in triplicate.

2.4 Mineral Analysis

Dry-ashed samples (550°C, 3 h) were dissolved in 20% H₂SO₄ and diluted to 50 mL. Magnesium, iron, calcium, and zinc were quantified by atomic absorption spectrophotometry (AAS) at 285.2, 248.3, 422.7, and 213.9 nm, respectively; potassium by flame photometry at 766.5 nm; and phosphorus colorimetrically by the molybdenum-blue method at 880 nm [12]. Lanthanum chloride (0.1-0.5% w/v) was added to suppress phosphate interference in calcium determination. Calibration linearity was verified at $R^2 \geq 0.995$.

2.5 Vitamin Analysis

Thiamine (B1) and pyridoxine (B6) were extracted in 0.1 N HCl at 90–100°C, enzymatically dephosphorylated, and quantified by HPLC with fluorescence detection following derivatization to thiochrome [13]. Niacin (B3) was extracted analogously and quantified by reversed-phase HPLC-UV at 260 nm. Folate (B9) was extracted by tri-enzyme hydrolysis and measured by microbiological assay. Tocopherol (vitamin E) was saponified, extracted into hexane, and quantified by HPLC on a C18 column with UV detection at 292 nm.

2.6 Phytochemical Analysis

Total phenolic content was determined by the Folin-Ciocalteu method and expressed as mg gallic acid equivalents (GAE)/100g [14]. Total flavonoid content was quantified by the aluminum chloride colorimetric assay and expressed as mg quercetin equivalents (QE)/100g [15]. All analyses were performed in triplicate.

2.7 Texture Profile Analysis

A Texture Analyzer (TA XT Plus, Stable Micro Systems, UK) fitted with a P/36R cylindrical probe was used. A two-cycle compression test was performed at pre-test, test, and post-test speeds of 1.5, 1.0, and 1.0 mm/s, respectively, with 50% target deformation. Hardness, firmness, cohesiveness, springiness, gumminess, chewiness, and resilience were calculated from force-time curves [16].

2.8 Color Analysis

CIELab colour parameters (L*, a*, b*) were measured in triplicate using a HunterLab colorimeter (HunterLab, Reston, VA, USA) calibrated against a standard white tile. L* represents lightness; a* represents redness/greenness; b* represents yellowness/blueness.

2.9 Sensory Analysis

A trained 20-member panel evaluated sensory attributes using a 9-point structured hedonic scale (1 = dislike extremely; 9 = like extremely), as described by Iwe [17]. While this sample size is ideal for controlled, analytical discrimination of specific formulaic differences in a laboratory setting, future large-scale consumer studies are planned to validate these preliminary findings and ensure broader market representation across diverse populations.

2.10 Statistical Analysis

Data are presented as mean $\pm$ standard deviation. Differences were analyzed using one-way ANOVA and Duncan's post-hoc test ($p < 0.05$) via SPSS v26.0. While the 20-member trained panel provided rigorous internal benchmarking, this sample size specifically prioritizes precise attribute discrimination over broad consumer generalizations, which future large-scale studies will address.

3. Results and Discussion

3.1 Proximate Composition

The proximate data in Table 2 reveal a clear and progressive nutritional shift as soy-groundnut inclusion increases. Protein content rose significantly ($p < 0.05$) from 24.23 mg/100g in the control (MS) to 33.61 mg/100g in SGMS3. This shows a 39% improvement that reflects the well-documented protein density of both legumes. The protein from soy is about 65-70% on a dry weight basis [6], while defatted groundnut flour contributes about 45-50% of protein [18]. This finding is consistent with Kolev et al. [19], who reported that incremental soy addition significantly elevated protein in processed meat matrices. Ishaq et al. [20] also documented analogous enrichment in legume-fortified meat alternatives. Critically, SGMS3 surpasses the protein content of conventional cooked beef (approximately 26-27 g/100g) [21]. This challenges the assumption that plant-based analogues are inherently protein-inferior to animal-source products.

Crude fat declined significantly from 13.51 mg/100g (MS) to 7.59 mg/100g (SGMS3) as animal lipids were displaced by leaner plant matrices. This shift toward a lower saturated fat profile aligns with established correlations between plant-based diets and reduced cardiovascular risk [22]. Nutritionally, the analogues offer a clear advantage over conventional beef for health-conscious consumers. The moisture peak in SGMS2 (31.61 mg/100g) highlights the hydrophilic nature of soy globulins, which retain water through hydrogen bonding and polar amino acid interactions [19]. While this enhances juiciness, the higher water activity suggests potential shelf-life limitations compared to the more stable, lower-moisture beef control. Future storage studies utilizing microbial load testing are essential to determine the commercial viability of these high-moisture matrices.

The non-linear ash and fiber patterns—peaking in SGMS2 before declining in SGMS3—suggest complex processing interactions. The fiber collapse in SGMS3 (0.10 mg/100g) likely reflects thermal degradation or structural compaction during pressing. Furthermore, while the declining carbohydrate content (28.82 to 24.69 mg/100g) indicates protein dilution, the lack of digestibility analysis remains a limitation. Previous studies suggest that while soy-groundnut blends optimize amino acid complementarity, the presence of antinutrients like phytates may hinder mineral and protein bioavailability. Compared to single-legume analogues, this composite matrix shows superior textural density; however, confirming its nutritional parity requires future PDCAAS (Protein Digestibility Corrected Amino Acid Score) evaluation to definitively benchmark it against animal-source proteins.

Table 2. Proximate Composition of Soy-Groundnut Meat Analogue compared with Beef Suya

Proximate Composition (mg/100g)	MS	SGMS1	SGMS2	SGMS3
Protein	24.23 ^c ±0.11	26.67 ^d ±0.32	31.61 ^b ±0.63	33.61 ^a ±0.02
Ash	4.45 ^c ±0.02	4.85 ^b ±0.02	5.52 ^a ±0.10	3.40 ^d ±0.03
Moisture	29.23 ^c ±0.11	26.67 ^d ±0.32	31.61 ^b ±0.63	30.61 ^a ±0.02
Crude fiber	0.84 ^d ±0.05	0.86 ^a ±0.04	0.95 ^a ±0.07	0.10 ^b ±0.14
Crude fat	13.51 ^a ±0.45	12.13 ^b ±12.00	10.91 ^c ±0.17	7.59 ^d ±0.13
Carbohydrate	27.74 ^{ab} ±0.51	28.82 ^a ±1.50	26.18 ^b ±0.35	24.69 ^c ±0.14

Mean±SD across the same row having the same superscript are not significantly ($p < 0.05$) different. MS = 100% beef Suya (control); SGMS1 = 50% Soybeans + 50% Groundnut meat analogue Suya; SGMS2 = 60% Soy + 40% Groundnut Meat analogue Suya; SGMS3 = 70% Soy + 30% Groundnut Meat analogue Suya.

3.2 Mineral Composition

The mineral data in Table 3 present both encouraging and complex findings. SGMS2 recorded the highest concentrations of five of the six minerals analyzed: magnesium (277.72 mg/100g), potassium (897.40 mg/100g), phosphorus (277.07 mg/100g), iron (5.00 mg/100g), and calcium (181.78 mg/100g). These values exceed the values recorded in the beef control in every case. This is especially relevant for public health in Nigeria, where dietary deficiencies in iron and calcium are prevalent among women and children [2]. The iron concentration of 5.00 mg/100g in SGMS2 is nearly double that of cooked beef [21]. However, it is important to note non-haem iron bioavailability from plant sources is substantially lower than haem iron, and consumer benefit would depend on co-consumption with vitamin C-rich foods.

The sharp mineral decline in SGMS3, particularly the 76% drop in calcium (181.78 to 43.18 mg/100g) and potassium (897.40 to 567.35 mg/100g), is counterintuitive given its highest plant protein content. Two mechanisms likely operate simultaneously. At elevated legume inclusion levels, phytic acid concentrations increase, and phytate chelates divalent cations to form insoluble complexes lost during pressing and washing [23]. Additionally, the more extensive dewatering required for the denser SGMS3 matrix may have caused disproportionate aqueous mineral leaching. This finding points to a critical processing limitation and identifies phytate-reduction strategies. Controlled soaking, germination, or exogenous phytase addition should be made a priority for high-inclusion formulations. Zinc was the exception, being highest in SGMS3 (8.25 mg/100g), consistent with Zhang et al. [24], who confirmed zinc retention in groundnut matrices under thermal processing. This may be due to association with heat-stable protein ligands. Collectively, SGMS2 represents the most practically viable formulation for mineral nutrition.

Table 3. Mineral Composition of Soy-Groundnut Meat Analogue compared with Beef Suya

Mineral (mg/100g)	Composition	MS	SGMS1	SGMS2	SGMS3
Magnesium		253.97 ^c ±0.01	266.42 ^b ±0.01	277.72 ^a ±0.00	252.81 ^a ±0.00
Potassium		799.82 ^c ±0.00	848.37 ^b ±0.00	897.40 ^a ±0.00	567.35 ^d ±0.00
Phosphorous		231.63 ^c ±0.01	251.35 ^b ±0.00	277.07 ^a ±0.00	229.75 ^d ±0.04
Iron		4.60 ^c ±0.06	4.84 ^b ±0.04	5.00 ^a ±0.01	3.35 ^d ±0.01
Zinc		5.49 ^b ±0.01	2.56 ^d ±0.03	2.73 ^c ±0.01	8.25 ^a ±0.02
Calcium		155.94 ^c ±2.10	166.92 ^b ±2.26	181.78 ^a ±6.52	43.18 ^d ±3.22

Mean±SD across the same row having the same superscript are not significantly ($p < 0.05$) different. Mean±SD across the same row having the same superscript are not significantly ($p < 0.05$) different. MS = 100% beef Suya (control); SGMS1 = 50% Soybeans + 50% Groundnut meat analogue Suya; SGMS2 = 60% Soy + 40% Groundnut Meat analogue Suya; SGMS3 = 70% Soy + 30% Groundnut Meat analogue Suya.

3.3 Vitamin Composition

The vitamin profiles in Table 4 add important nuance to the nutritional interpretation. Niacin (B3) was highest in SGMS3 (9.18 mg/100g), consistent with groundnuts being among the richest plant-based niacin sources, at 9–12 mg/100g in roasted form [8]. Pyridoxine (B6) similarly peaked in SGMS3 (1.14 mg/100g), more than double the control (0.44 mg/100g). This is consistent with USDA data that confirms that peanuts are leading plant-based B6 source [21]. These findings suggest that SGMS3 has specific nutritional advantages for B-group vitamin delivery.

Thiamine (B1) showed a different pattern: highest in SGMS2 (0.75 mg/100g) but reduced substantially in SGMS3 (0.17 mg/100g). Since soy and groundnut are recognized thiamine sources, this steep decline most plausibly reflects heat-induced thiamine degradation, which is well established to accelerate in low-moisture, high-protein matrices at elevated temperatures [25]. The near-total loss of folate (B9) in SGMS3 (0.03 mg/100g compared with 0.15–0.16 mg/100g in other samples) supports this interpretation, as folate is even more thermally labile than thiamine. These losses are a genuine

nutritional concern and argue for reduced grilling temperatures or post-processing micronutrient fortification in high-inclusion formulations.

The vitamin E (tocopherol) data reveal an important corrective insight: the beef control recorded the lowest tocopherol value (0.37 mg/100g), while the soy-groundnut analogues all showed substantially higher values (2.50–2.75 mg/100g). This confirms the plant-based products' clear advantage for this fat-soluble antioxidant vitamin. The relatively modest differences among the three analogues suggest that some thermal tocopherol degradation occurs across all formulations during grilling. This is consistent with Liu et al. [26], who documented tocopherol loss in peanut products under roasting conditions. However, sufficient tocopherol is retained to represent a meaningful nutritional advantage over the beef control.

Table 4. Vitamin Composition of Soy-Groundnut Meat Analogue compared with Beef Suya

Vitamin Composition (mg/100g)	MS	SGMS1	SGMS2	SGMS3
Vitamin B1	0.66 ^b ±0.00	0.70 ^b ±0.01	0.75 ^a ±0.03	0.17 ^c ±0.14
Vitamin B3	6.50 ^b ±0.01	6.32 ^c ±0.01	5.52 ^d ±0.01	9.18 ^a ±0.01
Vitamin B6	0.44 ^c ±0.01	0.47 ^{bc} ±0.03	0.52 ^b ±0.02	1.14 ^a ±0.01
Vitamin B9	0.16 ^a ±0.00	0.16 ^a ±0.00	0.15 ^b ±0.01	0.03 ^d ±0.01
Vitamin E	0.37 ^c ±0.01	2.67 ^a ±0.02	2.50 ^b ±0.01	2.75 ^a ±0.04

Mean±SD across the same row having the same superscript are not significantly ($p < 0.05$) different. Mean±SD across the same row having the same superscript are not significantly ($p < 0.05$) different. MS = 100% beef Suya (control); SGMS1 = 50% Soybeans + 50% Groundnut meat analogue Suya; SGMS2 = 60% Soy + 40% Groundnut Meat analogue Suya; SGMS3 = 70% Soy + 30% Groundnut Meat analogue Suya.

3.4 Phytochemical Composition

The phytochemical data in Table 5 provide for the functional food potential of these analogues. Total flavonoid content increased monotonically from 12.21 mg QE/100g in the beef control to 35.66 mg QE/100g in SGMS3. This represents a nearly threefold enrichment attributable to the established flavonoid richness of soybean cotyledons (genistein, daidzein) and groundnut skins (luteolin, quercetin) [11, 27]. This progressive increase with soy-groundnut substitution is nutritionally desirable, as dietary flavonoids are associated with anti-inflammatory, anticarcinogenic, and cardioprotective effects.

Total phenolic content did not follow this linear pattern. It rose from 90.00 mg GAE/100g in the beef control, where phenolics derive exclusively from spice and seasoning. Beef itself contributes negligible polyphenols. There is also an observed value of 152.60 mg/100g in SGMS1 and 164.37 mg/100g in SGMS2, before a decline to 145.34 mg/100g in SGMS3. The decline from SGMS2 to SGMS3 likely reflects two concurrent mechanisms: oxidative degradation of thermolabile phenolic acids during extended thermal processing at the highest protein density [28]; and the formation of covalent protein-phenol complexes at high protein concentrations. This may have rendered the phenolics analytically undetectable by the Folin–Ciocalteu reagent [4]. This establishes SGMS2 as the phenolic-optimal formulation and underlines the importance of mild thermal processing conditions for bioactive polyphenol retention.

Table 5. Phytochemical Composition of Soy-Groundnut Meat Analogue compared with Beef Suya

Phytochemical Composition (mg/100g)	MS	SGMS1	SGMS2	SGMS3
Flavonoid	12.21 ^c ±1.56	26.94 ^b ±1.17	28.73 ^b ±0.33	35.66 ^a ±1.57
Phenol	90.00 ^d ±0.33	152.60 ^b ±0.67	164.37 ^a ±1.57	145.34 ^c ±0.01

Mean±SD across the same row having the same superscript are not significantly ($p < 0.05$) different. Mean±SD across the same row having the same superscript are not significantly ($p < 0.05$) different. MS = 100% beef Suya (control); SGMS1 = 50% Soybeans + 50% Groundnut meat analogue Suya; SGMS2 = 60% Soy + 40% Groundnut Meat analogue Suya; SGMS3 = 70% Soy + 30% Groundnut Meat analogue Suya.

3.5 Texture Profile Analyzer

The texture profile data in Table 6 tell a mechanistically coherent story. Every parameter, cohesiveness, firmness, gumminess, springiness, chewiness, resilience, and hardness, increased significantly and progressively from MS through SGMS1, SGMS2, and to SGMS3. Hardness rose from 30.18 N in the beef control to 54.99 N in SGMS3, an 82% increase. As the soy fraction increased, the proportion of glycinin and β -conglycinin rose, and these storage proteins form tightly cross-linked gels upon heating through disulfide bond formation, hydrophobic interactions, and hydrogen bonding [29]. Simultaneously, the increase in springiness (0.35 to 0.60) and resilience (0.13 to 0.22) indicates a progressively more elastic matrix, which is useful for meat-mimicking but distinct from the fibrous, slightly yielding texture of grilled beef.

Srikanlaya et al. [30] described analogous texture strengthening in soy-based meat alternatives following dehydration-rehydration cycles, attributing it to protein strand elongation and network compaction. The present results extend this finding to a grilled, non-rehydrated suya format. However, as Sha and Xiong [4] observed, instrumental hardness and chewiness in plant-based analogues do not always translate to equivalent consumer perceptions of 'meatiness'. The sensory data in Section 3.7 confirm this. Despite SGMS3 having the highest instrumental texture values, panelists did not rate it more favorably than SGMS1 or SGMS2, and all analogues scored below the control. This instrumental-sensory disconnect is a recognized challenge in the field and indicates that optimizing plant-based suya requires calibrating hardness, moisture, and fibre content to recreate the specific textural expectation of suya consumers.

Table 6. Texture Analysis Composition of Soy-Groundnut Meat Analogue compared with Beef Suya

Texture Analysis	MS	SGMS1	SGMS2	SGMS3
Cohesiveness	0.37 ^d ±0.1	0.39 ^c ±0.00	0.41 ^b ±0.10	0.44 ^a ±0.00
Firmness	6.97 ^d ±0.04	8.16 ^b ±0.01	7.42 ^c ±0.03	21.41 ^a ±0.01
Gumminess	11.16 ^d ±0.03	14.31 ^c ±0.04	15.27 ^b ±0.02	24.17 ^a ±0.07
Springiness	0.35 ^d ±0.01	0.39 ^c ±0.03	0.44 ^b ±0.01	0.60 ^a ±0.01
Chewiness	3.85 ^d ±0.02	5.59 ^c ±0.04	6.17 ^b ±0.01	14.37 ^a ±0.01
Resilience	0.13 ^b ±0.01	0.15 ^b ±0.01	0.15 ^b ±0.01	0.22 ^a ±0.01
Hardness	30.18 ^d ±0.01	36.69 ^c ±0.01	39.11 ^b ±6.52	54.99 ^a ±0.01

Mean±SD across the same row having the same superscript are not significantly ($p < 0.05$) different. Mean±SD across the same row having the same superscript are not significantly ($p < 0.05$) different. MS = 100% beef Suya (control); SGMS1 = 50% Soybeans + 50% Groundnut meat analogue Suya; SGMS2 = 60% Soy + 40% Groundnut Meat analogue Suya; SGMS3 = 70% Soy + 30% Groundnut Meat analogue Suya.

3.6 Color Analysis

The CIELab colour data in Table 7 show that soy-groundnut inclusion produces modest but significant colour changes relative to the beef control. Lightness (L^*) increased from 18.27 in MS to a peak of 21.13 in SGMS2. This indicates surface brightening as myoglobin is displaced by plant protein aggregates. Wu et al. [31] reported a comparable L^* elevation in plant protein-enriched meat matrices. SGMS3 ($L^* = 18.50$) was close to the control in lightness. This suggests that the combined effect of increased Maillard reactant concentration and darkening at higher soy levels counteracted the brightening effect observed in SGMS2.

Redness (a^*) was highest in SGMS1 (9.50), exceeding even the beef control (7.40). This may reflect the beetroot betalain colorant being stabilized by the higher groundnut lipid content in SGMS1, a mechanism consistent with the documented fat-solubilization of betacyanins in food matrices. Redness declined progressively to SGMS3 (6.23) as fat content fell and myoglobin-derived pigments were further diluted. Yellowness (b^*) was highest in SGMS3 (6.70), attributable to residual carotenoid pigments from the groundnut fraction. This was consistent with Daszkiewicz et al. [32], who linked elevated b^* in plant-enriched meat products to legume carotenoids and flavonoids. While these colour shifts

are numerically modest, colour is a primary quality signal for suya consumers [33], and the lighter, more yellowish appearance of the analogues may require deliberate visual repositioning if market adoption is to succeed.

Table 7. Color Analysis of Soy-Groundnut Meat Analogue compared with Beef Suya

Color Analysis	MS	SGMS1	SGMS2	SGMS3
L*	18.27 ^d ±0.06	19.01 ^b ±0.1	21.13 ^a ±0.06	18.50 ^c ±0.10
A*	7.40 ^c ±0.00	9.50 ^a ±0.1	7.87 ^b ±0.06	6.23 ^d ±0.00
B*	4.53 ^d ±0.06	5.23 ^b ±0.06	4.87 ^c ±0.06	6.70 ^a ±0.00

Mean±SD across the same row having the same superscript are not significantly ($p < 0.05$) different. Mean±SD across the same row having the same superscript are not significantly ($p < 0.05$) different. MS = 100% beef Suya (control); SGMS1 = 50% Soybeans + 50% Groundnut meat analogue Suya; SGMS2 = 60% Soy + 40% Groundnut Meat analogue Suya; SGMS3 = 70% Soy + 30% Groundnut Meat analogue Suya.

3.7 Sensory Evaluation

The sensory scores in Table 8 ground all preceding findings in consumer reality. The beef control (MS) received significantly higher scores than all three analogues across every attribute, with an overall acceptability of 8.10 ('like very much'). The analogues ranged from 5.90 to 6.20 for overall acceptability, within the 'like slightly' to 'like moderately' range. This acceptability gap is consistent with the broader literature: Oh et al. [34] found that conventional beef consistently outperformed plant-based alternatives in hedonic ratings. Also, Daszkiewicz et al. [32] documented that plant-enriched meat products rarely achieve parity with all-meat controls for flavour and mouthfeel. The gap observed here is therefore not unexpected, but it is a practical barrier that must be addressed before these products can achieve meaningful market penetration.

The steepest drop relative to the control was in flavour, where SGMS1 scored 4.40 ('neither like nor dislike'). Flavour improved to 5.30 in SGMS2 and 5.80 in SGMS3. This suggests that the yaji spice and marinade system is progressively more effective at masking legume off-notes. The significant flavor improvement in SGMS3 ($p < 0.05$) suggests the dense protein matrix effectively sequestered volatile off-notes like hexanal [4, 5]. While GC-MS profiling is required for molecular confirmation, the sensory data in Table 8 validates this trend, showing higher acceptability scores for SGMS3 compared to SGMS1, likely due to reduced lipoxygenase-derived aldehyde perception. The roasted groundnut flavour note is a secondary barrier. It is important to address these flavour deficits by targeting thermal inactivation of lipoxygenase, fermentation with flavour-positive *Lactobacillus* strains, or the incorporation of higher levels of umami-rich mushroom concentrate already present in the formulation. Yu et al. [5] and Boukid [4] identified these approaches as the most promising for plant-based meat flavour improvement.

Mouthfeel scored 8.00 for MS and between 5.60 and 6.10 for the analogues, a gap directly linked to the instrumental texture data: the analogues' higher firmness and hardness do not replicate the specific combination of fibrous yield, juiciness, and fat-derived lubrication characteristic of grilled beef suya. Colour scores were highest among sensory attributes for SGMS2 (6.50), consistent with its superior L* and the visual appeal of its moderate brownness. The notably higher aftertaste score for SGMS2 (6.90) compared with SGMS1 (6.10) and SGMS3 (5.70) is strategically significant. A clean, pleasant finish is a strong predictor of repeat purchase intent, and this advantage, combined with SGMS2's superiority in mineral retention and phenolic content, suggests its candidacy as the preferred commercial formulation tier. The sensory findings must be contextualized by the limitation of a 20-person trained panel, which is adequate for product discrimination but insufficient for predicting untrained consumer behaviour. Validation with a large consumer panel among habitual suya consumers in South-Eastern Nigeria is essential before commercial conclusions are drawn.

Table 8. Sensory Properties of Soy-Groundnut Meat Analogue compared with Beef Suya

Sensory Attribute	MS	SGMS1	SGMS2	SGMS3
Colour	7.80 ^a ±0.63	5.90 ^{bc} ±1.10	6.50 ^b ±1.18	5.40 ^c ±1.17
Aroma	7.20 ^a ±1.99	5.00 ^b ±2.05	5.60 ^{ab} ±2.32	6.00 ^{ab} ±1.70
Texture	7.80 ^a ±1.55	6.40 ^{ab} ±1.07	5.70 ^b ±1.34	6.30 ^b ±2.11
Mouthfeel	8.00 ^a ±1.23	5.60 ^b ±1.90	5.60 ^b ±1.65	6.10 ^b ±1.79
Flavor	7.80 ^a ±1.81	4.40 ^b ±2.67	5.30 ^b ±2.58	5.80 ^{ab} ±1.69
Aftertaste	7.60 ^a ±2.12	6.10 ^{ab} ±1.66	6.90 ^{ab} ±0.88	5.70 ^b ±1.95
Overall acceptability	8.10 ^a ±1.60	6.20 ^b ±0.79	6.10 ^b ±1.29	5.90 ^b ±2.18

Means ± SD across the same row with the same superscript are not significantly different

MS = 100% beef Suya (control); SGMS1 = 50% Soybeans + 50% Groundnut meat analogue Suya; SGMS2 = 60% Soy + 40% Groundnut Meat analogue Suya; SGMS3 = 70% Soy + 30% Groundnut Meat analogue Suya.

4. Conclusions

This study demonstrated that soy-groundnut suya meat analogues can deliver significant nutritional improvements over conventional beef suya. Recorded improvements were higher protein, superior mineral density for most minerals at the 60% substitution level, enriched B-vitamin and tocopherol profiles, and substantially greater phytochemical concentrations. SGMS2 (60% soy-groundnut substitution) emerged as the most nutritionally balanced formulation across the full range of evaluated parameters (proximate composition, mineral retention, phenolic content, and sensory performance). This represents the most practically viable candidate for product development and commercialization. SGMS3 achieved the highest protein, niacin, pyridoxine, flavonoid, and zinc values. However, it exhibited non-linear mineral and phenolic declines, alongside the lowest sensory acceptability for aftertaste.

The principal barrier to commercial adoption remains the sensory gap between the plant-based analogues and the conventional beef suya control. Our findings demonstrate a clear sensory gap and mineral decline in high-inclusion formulations, necessitating targeted interventions. The "beany" off-flavors observed in Table 8, likely stemming from lipoxygenase-derived volatiles, justify the recommendation for thermal inactivation or fermentation-based debittering to improve palatability. Additionally, the sharp mineral drop in SGMS3 attributed to phytate-mineral chelation directly supports the call for germination or enzymatic hydrolysis. Future research must bridge these gaps through *in-vitro* digestibility assays and shelf-life studies. Optimizing grilling temperatures and implementing micronutrient fortification are essential evidence-based strategies to mitigate the thermal vitamin degradation recorded in our analysis.

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Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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