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Development of a Clean-label, High-protein Sorghum-based Extruded Snack Prototype: Formulation, Optimization, and Quality Evaluation

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Abstract

The growing demand for healthy, clean-label snack foods has increased interest in products offering both nutritional value and consumer acceptability. Sorghum (*Sorghum bicolor*), a gluten-free cereal rich in protein, dietary fibre and bioactive phytochemicals, holds significant potential as a functional snack ingredient but remains underutilised in high-protein extruded foods. This study aimed to develop a high-protein, clean-label sorghum-based extruded snack prototype through formulation optimization, extrusion processing, and quality evaluation.

Three composite flour formulations were processed using a commercial twin-screw extruder: sorghum flour with soy protein isolate in the first, pea protein isolate and corn flour in the second, and tapioca starch and rice flour in the third. Different barrel temperatures and protein incorporation rates were tested to achieve optimal expansion and product quality. An ascending barrel temperature profile (70°C□40°C□110°C) produced a well-expanded, light-textured product in the optimized formulation.

Proximate analysis by a NABL-accredited laboratory showed the optimized product contained protein 31.08 g/100 g, moisture 3.82 g/100 g, fat 1.20 g/100 g, dietary fibre 4.84 g/100 g and 362.20 kcal/100 g. Sensory evaluation by 50 untrained panelists on a nine-point hedonic scale yielded mean scores of 8.00□8.40, with one-way ANOVA showing no significant difference between sensory attributes ($p>0.05$), and chi-square goodness-of-fit confirming the score distribution reflected genuine consumer preference.

These results establish sorghum as a viable ingredient for producing a nutritious, high-protein extruded snack with desirable composition, processing characteristics, and consumer acceptance, suitable for future development as a sustainable functional snack.

Keywords: *Clean label; extrusion cooking; functional snack; plant protein; proximate analysis; sensory evaluation*

1. Introduction

1.1 Background

Snack food has grown in the world to become a fast-growing category that is more convenient, ready-to-eat, or easy-to-prepare foods. Many common snacks are considered to be ultra-processed foods (UPFs) and are low in nutrients and high in saturated fats, refined carbohydrates, sodium and artificial ingredients. The regular use of these products has been linked to obesity, cardiovascular diseases, type 2 diabetes and other diet-related non-communicable diseases (Baker et al., 2020; Srour et al., 2019).

With an increasing awareness of health, consumers now seek out foods with nutritional value and transparency of ingredients. Thus, the clean-label idea has garnered substantial interest with focus on simplifying and making the ingredient lists more plain, so that consumers are able to easily identify the ingredients and know less about the “less is more” processing, and less on unnecessary artificial additives (Asioli et al., 2017; Kajzer & Diowksz, 2021). At the same time, the demand for protein-rich foods has grown as sufficient dietary protein is linked to an increased feeling of "fullness," muscle preservation, and metabolic health (Lonnie et al., 2018).

Sorghum (Sorghum bicolor) is the fifth most grown cereal worldwide and it is known for its nutritional and functional properties. It naturally contains 8□13% protein, dietary fibre and bioactive phytochemicals such as antioxidant 3-deoxyanthocyanidins, a compound that is unique to purple cabbage. Sorghum is gluten free and drought tolerant, and is also a potential sustainable cereal for development of functional food products (Awika & Rooney, 2004; Devi & Naik, 2016).

Extrusion cooking is one of the most adopted among the technologies used to produce expanded snack products. The process consists of mixing, cooking, texturizing and shaping and it makes starch gelatinization, enhances digestibility and gives the light

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and porous texture, which is desirable by the consumers (Seth & Rajamanickam, 2012; Bhattarai, 2025). However, including a high amount of protein required for good expansion of the formulations is still a challenge because it can negatively impact texture.

1.2 Research Gap

The sorghum extruded snack has been studied previously in terms of optimizing single formulation components or the extrusion processing parameters. Few studies have combined the concepts of clean-label formulation, increased protein enrichment from complementary plant protein sources, using sorghum as a main cereal ingredient, and optimizing the extrusion process in a single product development approach. Also, the majority of the commercially available high-protein snacks still use as the main cereal ingredient oats, wheat, maize, or rice, hardly any of which use sorghum as a main cereal ingredient.

A nutritionally balanced, clean label, protein rich sorghum based extruded snack with desirable processing properties, enhanced nutritional profile and consumer acceptability is therefore needed.

1.3 Study Objectives

The aims of the current research were to:

- Formulate composite flour formulations containing sorghum with minimum removal of starch and protein that are suitable for extrusion processing and have good clean label.
- Optimize level of protein incorporation and barrel temperature profile for desired expansion characteristics and product quality.
- Optimized formulation (proximate composition) by standard analytical methods in NABL-accredited laboratory.
- Determine consumer acceptability of the product optimized using a nine-point hedonic sensory scale.
- Identify the potential of sorghum in the production of clean label, high-protein functional snack products using a sustainable cereal sources.

2. Materials and Methods

2.1 Raw Material Procurement

Sorghum flour and Rice flour were purchased from Pansiri. Soy protein isolate, pea protein isolate, and brown rice protein isolate were derived from Unibourne. Collaborating industry provided corn flour and corn grits and tapioca starch was bought from Purenso. Commercial sources of inulin, oat fibre, cocoa powder, stevia, soy lecithin, and refined edible oil (Daily Gold) and iodized salt (Tata Sampann) were used. All ingredients were food grade and chosen to meet the clean label formulation principles by avoiding chemically modified starches, artificial flavors and colors, preservatives and synthetic additives.

2.2 Blend Formulation Development

Three composite formulations of flour were prepared with the basic cereal ingredient of sorghum and complementary plant protein sources, and functional ingredients. The formulations were intended to assess the influence of increasing protein concentration (35%, 40% and 45%), on the extrusion characteristics and product quality. Blend 3 which contained soy protein isolate, pea protein isolate, sorghum flour, corn flour, rice flour, tapioca starch, edible oil and salt was found to be best in terms of extrusion performance and optimized formulation for further studies. All formulations include the detailed information on ingredient composition as shown in Table 1.



Figure 1: *Preparation and mixing of raw materials prior to extrusion processing*

Table 1. *Composition of Composite Flour Formulations Developed for Extrusion Trials*

Ingredient	35% Protein	40% Protein	45% Protein
Soy protein isolate	751.6 g	859.0 g	966.0 g
Pea protein isolate	751.6 g	859.0 g	966.0 g
Corn flour	715.8 g	842.0 g	772.0 g
Sorghum flour	859.0 g	1011.0 g	926.0 g
Rice flour	620.0 g	731.0 g	669.0 g
Tapioca starch	477.0 g	562.0 g	515.0 g
Oil	100.0 ml	112.0 ml	103.0 ml
Salt	25.0 g	28.0 g	26.0 g
Total	**4300.0 g**	**4804.0 g**	**4397.0 g**



Figure 2: *Blend 1 (45% protein) formulation*



Figure 3: *Blend 2 (40% protein)*



Figure 4: *Blend 3 (35% protein) formulation*



Figure 5: *Final optimized Blend 3 (35% Protein) with Calcium Carbonate*

2.3 Extrusion Processing

The trials on extrusion were carried out at Shyam Singh Industries, Bhiwadi, Rajasthan, India with a commercial twin screw extruder. The first tests used a descending barrel temperature profile (165°C-40°C-98°C), yielding dense products which were not as expanded. An ascending barrel temperature profile (70°C-40°C-110°C) was hence used for the optimized formulation, based on these observations. The new process conditions resulted in a better feed conditioning, delayed starch gelatinisation during the last third of the extrusion process, and improved product expansion and texture. The various processing conditions tested for this study and the corresponding values are summarized in Table 2.

Table 2: *Extrusion Processing Conditions - Day 2 Successful Trials*

Parameter	Day 1 – Failed Trial	Day 2 – Successful Trial
Extruder type	Twin-screw	Twin-screw
Zone 1 temperature	165°C	70°C
Zone 2 temperature	40°C	40°C
Zone 3 temperature	98°C	110°C
Profile direction	Descending then Ascending	Ascending
Outcome	Dense, compact, and unacceptable extrudate	Light, porous, and acceptable extrudate



Figure 6: *Commercial twin-screw extruder used for product development*

In the commercial production, the parameters such as the type of screw, barrel dimensions, die specifications, feed rate and screw speed were not made public by the production plant and were thus proprietary information. For this reason, only variables which the authors have directly experimented upon are reported.

2.4 Sensory Evaluation

The optimized formulation was presented to 50 non-expert volunteer panelists for evaluation by a nine-point hedonic rating scale ranging from 1 = "dislike extremely" to 9 = "like extremely". The optimized formulation was presented to 50 untrained volunteer panelists for evaluation, using a nine-point hedonic rating scale, with 1 = "dislike extremely" and 9 = "like extremely". Flavour, texture, colour, aroma and overall acceptability were evaluated.

The participants included friends, family and acquaintances who had been informed of the study and the ingredients in the product and had volunteered in the study. The prototype was made from the most commonly consumed food ingredients and only anonymous hedonic scores were taken, so formal institutional ethical approval was not required. Consent was obtained verbally from all participants, who were informed beforehand.

2.5 Proximate Analysis

The optimized product was evaluated in a nationally acclaimed analytical laboratory, which is well equipped and accredited by NABL for moisture, protein, fat, carbohydrate, dietary fibre, total sugars and energy content, by the standard methods. Protein was analysed using the Kjeldahl method and other analyses done by IS and FSSAI standard procedures.

The analyses were carried out as analytical outsourcing service. The authors were not provided with the instrument operating conditions nor the calibration procedures. All analyses were performed according to standardized analytical protocols, however, maintaining a reliable and traceable analysis.

2.6 Statistical Analysis

For all sensory attributes, descriptive statistics such as mean, median, mode, variance, and standard deviation were determined. A one-way Analysis of Variance (ANOVA) was used at the 0.05 level of significance to determine differences between sensory scores. A Chi-squared goodness-of-fit test was then used to test for the uniformity of the distribution of hedonic scores, which was used to establish that consumers' responses were not random but rather reflected their true preferences.

3. Results and Discussion

3.1 Optimization of Formulation and Extrusion Processing

Three composite flour formulations were developed to evaluate the combined effects of protein incorporation level and extrusion processing conditions on product quality. Blend 1 (45% protein) and Blend 2 (40% protein), processed using a descending barrel temperature profile (165°C-40°C-98°C), produced dense, compact extrudates with poor expansion and hard texture. The high protein content increased melt viscosity and reduced starch expansion, resulting in products with limited consumer acceptability.

Based on these observations, Blend 3 was reformulated using soy protein isolate, pea protein isolate, sorghum flour, corn flour, rice flour, and tapioca starch. The formulation was processed using an ascending barrel temperature profile (70°C-40°C-110°C), which improved feed conditioning and delayed starch gelatinization until the final stage of extrusion. This resulted in a light, porous product with superior expansion and crisp texture.

Among the three protein incorporation levels evaluated (35%, 40%, and 45%), the 35% protein formulation exhibited the most desirable extrusion characteristics. Increasing protein concentration beyond this level progressively reduced expansion because proteins competed with starch for available moisture and increased melt viscosity, limiting bubble growth during extrusion. Therefore, Blend 3 containing 35% protein was selected as the optimized formulation for subsequent nutritional and sensory evaluation.

3.2 Proximate Composition Analysis

Table 3 shows the proximate composition of optimized formulation. The product was analysed in the laboratory and the results were as follows: 100 g would contain 31.08 g protein, 56.77 g carbohydrate, 4.84 g dietary fibre, 1.20 g fat, 3.82 g moisture and 362.20 kcal.

Table 3: *Proximate Composition of Optimized Sorghum-Based Extruded Snack*

S. No.	Parameter	Unit	Result	Method
1	Moisture	g/100 g	3.82	IS 15271
2	Carbohydrate	g/100 g	56.77	IS 1656
3	Energy	kcal/100 g	362.20	FL/SOP/FC-024
4	Fat	g/100 g	1.20	IS 15271
5	Dietary Fibre	g/100 g	4.84	FL/SOP/FC-185
6	Protein	g/100 g	31.08	IS 7219
7	Total Sugars	g/100 g	6.97	FSSAI Manual 4, 2015

This high protein content was obtained by a complementary incorporation of soy and pea protein isolates, and in the main, the use of sorghum as a main cereal ingredient. The low fat content is attributed to the extrusion cooking rather than deep frying and the low moisture content is preferred for expanded snack products for a better crispness and shelf stability. In general, the nutritional composition has proven to be the effective development of a clean label snack with a significantly higher protein content than the typical cereal based extruded snack.

3.3 Sensory Evaluation

A nine-point hedonic scale was used with 50 untrained consumers to evaluate the optimized formulation. The mean sensory scores of the flavour, texture, colour, aroma and acceptability of the food products was 8.00 to 8.40, which shows a good acceptability among the consumers.

Table 4: *Descriptive Statistics of Sensory Evaluation Data - 50 Untrained Panelists*

Statistic	Flavour	Texture	Colour	Aroma	Overall Acceptability
Mean	8.30	8.10	8.20	8.40	8.00
Median	9.00	8.50	8.50	9.00	8.00
Mode	9	9	9	9	8
Variance	0.618	0.666	0.604	0.520	0.720
Standard Deviation	0.786	0.816	0.777	0.721	0.849

The highest mean score was for aroma (8.40), followed by flavour (8.30), colour (8.20), texture (8.10) and overall acceptability (8.00) of the evaluated attributes. The scores obtained were high in all cases, showing that the formulation was optimized to provide a good nutritional value without compromising the desirable sensory properties, even at high levels of plant protein.

3.4 Statistical Analysis

3.4.1 One-Way Analysis of Variance (ANOVA) Analysis

To perform One-Way Analysis of Variance (ANOVA) analysis, follow these steps: One-way Analysis of Variance (ANOVA) was used to test for significant differences between the mean sensory scores of the flavour, texture, colour, aroma and overall acceptability. From the results of Table 5, the calculated F-value obtained (1.959) was small compared to the critical F-value (2.37) at 5% significance level; this shows that there were no statistically significant differences between the analyzed sensory attributes ($p > 0.05$). The optimized formulation had a balanced sensory profile, with no individual sensory property being excessively liked or disliked.

Table 5: *One-Way ANOVA of Sensory Evaluation Scores*

Source of Variation	Sum of Squares (SS)	Df	Mean Square (MS)	F Calculated	F Critical	Result
Between Groups	5.00	4	1.25	1.959	2.37	Not Significant
Within Groups	156.40	245	0.638	—	—	—
Total	161.40	249	—	—	—	—

Significance level (α) = 0.05

3.4.2 Chi-Square Goodness-of-Fit Test

A chi square goodness of fit test was used to test if there was a significant difference between the uniform distribution and the observed distribution of sensory scores. The calculated value of chi-square (26.956) at 5% level of significance was greater than the tabulated chi-square value (15.507), thus concluding that the differences among the sensory responses were not random. The higher hedonic scores of 8 and 9 indicate the high and consistent consumer preferences for the optimized product, thus showing the overall acceptability of the optimized product.

Table 6: *Chi-Square Goodness of Fit Test for Sensory Evaluation Scores*

Score	Total Observed Frequency	Total Expected Frequency	χ^2 Contribution
7	58	83.33	7.713
8	83	83.33	0.001
9	109	83.33	7.916
Total χ^2			**26.956**

Degrees of Freedom (df): 8
Critical χ^2 Value (α = 0.05): 15.507
Calculated χ^2 Value: 26.956
Statistical Decision: Reject the null hypothesis

4. Conclusion

In the present study, a systematic formulation, process optimization of the extrusion process and quality evaluation of the prototype snack is successfully done to create a high-protein sorghum based extruded snack with clean label. Blend 3 with a protein content of 35% processed with an ascending barrel temperature profile (70°C-40°C-110°C) exhibited the most desirable extrusion properties and the product was light and porous with better expansion and texture.

The optimized formulation was found to contain 31.08 g protein, 4.84 g dietary fibre, 1.20 g fat and 362.20 kcal per 100 g by proximate analysis, which showed it to be a nutritionally superior formulation than the conventional extruded snack products. The sensory evaluation also showed high consumer acceptability as mean hedonic scores were between 8.00 and 8.40, and the statistical analysis proved the uniformity and reliability of consumers' answers.

The results showed that the sorghum can be effectively used as the main cereal ingredient in manufacturing clean label, high protein extruded snacks without affecting the product quality and consumer acceptance. The study also reveals the key role of formulation and extrusion processing variables for desirable physical and sensory properties of the high protein snack product.

This investigation is a prototype development investigation which is part of an undergraduate research project. However, because of access to commercial extrusion facilities, it was not possible to conduct trials in triplicate and some processing parameters were confidential to the collaborating industry. Moreover, in the present work,

the digestion and utilization of proteins, quantification of Antinutrient factors, Glycemic index (GI) and optimization of protein using Response surface methodology (RSM) were not included.

Large scale process optimization, complete nutritional characterization, storage stability and commercial scale production should be studied in the future to further advance the potential of this clean label, high protein sorghum based extruded snack for functional food product development.

Conflict of Interest and Ethical Statement

The authors have no conflicts of interest to declare with regard to the publication of this manuscript. The sensory evaluation was carried out by 50 untrained volunteers who were friends, family and acquaintances of research team. The purpose of the study and the ingredients in the product were explained to all participants before the evaluation and informed verbal consent was obtained before participation. Only food grade ingredients used in common consumption were used in the preparation of the product and only anonymous hedonic scores were gathered. Thus it was not necessary for this undergraduate prototype development study to seek formal institutional ethical clearance.

Author Contributions

Anoushka Aniruddha Maheshwarkar: Conceptualization, methodology, formulation development, experimental investigation, data collection, statistical analysis, interpretation of results, visualization, manuscript preparation.

Deepa Joshi: Research supervision, Methodology review, Manuscript review, Editing, Academic guidance.

Raj Kamal Pandey: Industrial supervision, technical guidance of extrusion processing, validation of product development and manuscript reviews.

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