PLANT SCIENCE TODAY
Vol 12(sp1): 1-11
https://doi.org/10.14719/pst.9980

eISSN 2348-1900

RESEARCH ARTICLE

Optimization of ingredient compositions and process parameters for the development of hot extruded ready-to-eat (RTE) products using response surface methodology

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Received: 11 June 2025; Accepted: 02 September 2025; Available online: Version 1.0: 08 October 2025

Cite this article: Sharmila S, Poongodi VT. Optimization of ingredient compositions and process parameters for the development of hot extruded ready-to-eat (RTE) products using response surface methodology. Plant Science Today. 2025; 12(sp1): 1-11. https://doi.org/10.14719/pst.9980

Abstract

Extrusion cooking is a high-temperature, short-time process that combines heat, pressure and shear to gelatinize starch, denature proteins and produce expanded, shelf-stable ready-to-eat (RTE) foods. This study advances beyond prior work by employing a composite blend of sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*), barnyard millet (*Echinochloa esculenta*), corn grits (*Zea mays*) and soy chunks (*Glycine max*), which has not previously been optimized together using response surface methodology (RSM). Unlike earlier studies restricted to single or binary blends, this work integrates proximate profiling and sensory validation into the optimization framework, thereby addressing a key research gap. While the regression model for moisture content demonstrated strong statistical validity (R^2 = 0.837), the models for expansion ratio and bulk density showed limitations and were therefore interpreted as indicative trends rather than predictive outcomes. The optimized formulation, comprising 57.5 % millet blend, 45 % corn grits and 25 % soy chunks, achieved desirable physical properties with high expansion ratio (20.12), low bulk density (0.31 g/cm^3) and moderate moisture content (11.43 %). Nutritional analysis revealed significantly higher protein (16.2 g/100 g) and dietary fiber (7.1 g/100 g) compared to commercial control products. Sensory evaluation using a 9-point hedonic scale further confirmed superior acceptability in appearance, flavor, crispiness and overall quality. Collectively, the findings demonstrate the potential of multi-millet–soy–corn formulations for developing nutritious, consumer-acceptable extruded RTE snacks, while also recognizing statistical limitations and highlighting directions for future refinement.

Keywords: bulk density; expansion ratio; extrusion; millet; optimization; RTE

Introduction

The increasing prevalence of lifestyle-related disorders has shifted consumer preferences toward affordable, nutritious and convenient foods that can support better health outcomes. In this context, extrusion cooking has emerged as a versatile, cost-effective and environmentally sustainable technology for developing ready-to-eat (RTE) products. It combines high temperature, pressure and shear forces to transform starchy and protein-rich materials into shelf-stable, microbiologically safe foods with desirable textural properties (1, 2). Beyond process efficiency, extrusion also enables incorporation of underutilized grains and legumes into novel product formats, thereby supporting both nutrition security and sustainable grain utilization (3).

Millets, including sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*) and barnyard millet (*Echinochloa esculenta*), have gained increasing research attention due to their high dietary fiber, resistant starch, bioactive compounds and gluten-free profile (4, 5). Their low glycemic index and antioxidant activity make them particularly attractive for functional food development. Corn grits, with high starch content and excellent puffing properties, are widely used in extruded snacks to enhance expansion and crispiness (6). Soy chunks, derived from defatted soy flour, contribute high-quality plant protein, isoflavones and functional fibers, while complementing cereal proteins through lysine enrichment (7, 8). Together, these raw materials offer strong potential for developing nutrient-dense, consumer-acceptable extruded foods.

Several studies have optimized extrusion parameters using Response Surface Methodology (RSM) to enhance the nutritional and physical properties of cereal–legume blends (9, 10). However, the majority of prior work has focused on individual millets or binary formulations, often evaluating only physical attributes such as expansion ratio and bulk density. Comprehensive studies that integrate proximate nutritional composition and sensory evaluation into the optimization framework are still limited. Moreover, to the best of our knowledge, no study has optimized a multi-millet-soy-corn blend using RSM while also validating the optimized formulation against commercial benchmarks.

Therefore, the present study aimed to develop and optimize extruded RTE products using a composite of sorghum, pearl millet, barnyard millet, corn grits and soy chunks. Specifically, the objectives were: (i) to determine the effects of ingredient levels on key physical properties (moisture, bulk density and expansion ratio) using RSM, (ii) to evaluate the proximate composition of the optimized formulation and (iii) to assess sensory acceptability in comparison with commercial control. By addressing both functional and consumer-oriented parameters, this work provides a holistic approach to the development of health-oriented extruded snacks and contributes to the growing evidence base on millet-based food innovations.

Materials and Methods

Gathering of experimental materials

The sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*) and barnyard millet (*Echinochloa esculenta*) were procured from the Tamil Nadu Agriculture Research Center in Tamil Nadu. The other ingredients such as corn grits (*Zea mays*) and soya chunks (*Glycine max* L.) were procured from the local market in Attur, Salem district, Tamil Nadu. To remove immature seeds, bad grains and unnecessary items, the materials were thoroughly cleaned. The nutritional content, processing properties and potential to produce a variety of accessible, reasonably priced and nutrient-dense food options made millet, corn grits and soy chunks among the top options for extruded food products. The carbohydrate and protein in these components become more digestible during extrusion cooking, increasing their availability for the body to utilize. The materials underwent for further processing as described in the following sections.

Processing of millets, corn grits and soya chunks

The processing of millets, corn grits and soya chunks into flour formulation was done as per the flow chart Fig. 1.

Extrusion cooking

A laboratory model of a co-rotating twin-screw extruder (BTPL, Kolkata, India) was used to extrude-cook the samples. A motor rated at 7.5 HP (440 V, 3-phase, 50 Hz), an electric heater with a capacity of 200 °C, a barrel length of 350 mm, a barrel diameter of 30 mm and an extruder capacity of 10 kg/h were the technical specifications of the extruder that was employed. Throughout the studies, the extruder die's diameter (3 mm) remained unchanged. The cutting knife's speed and the feeder's feed rate were maintained at 22 and 24 rpm, respectively. The various combinations of millets, corn grits and soy chunks were used to investigate their impacts on moisture content, expansion ratio and bulk density of RTE extruded products (Table 1). Before being employed for additional analysis, the produced extruded products were cooled to room temperature and kept in zip-lock plastic bags (11).

Table 1. Proximate compositions of ingredients used for the preparation of extruded RTE foods

Ingredient samples	Carbohydrate (%)	Protein (g)	Fat (g)	Fibre (g)	Energy (kcal)
Sorghum	71.21 ± 1.42^{a}	11.26 ± 0.24^{b}	3.42 ± 0.02^{b}	6.41 ± 0.12^{c}	339.82 ± 12.89^{c}
Pearl millet	73.28 ± 2.54^{ab}	12.13 ± 0.23^{a}	5.33 ± 0.01^{c}	9.61 ± 0.11^{ab}	360.17 ± 13.75^{b}
Barnyard millet	69.24 ± 3.46^{b}	11.64 ± 0.15^{ab}	4.64 ± 0.02^{ac}	6.52 ± 0.23^{b}	360.91 ± 14.88^{a}
Corn grits	72.12 ± 5.42^{c}	9.46 ± 0.20^{c}	1.47 ± 0.04^{b}	2.11 ± 0.10^{a}	371.15 ± 16.94^{ac}
Soya chunks	29.45 ± 2.64^{ac}	52.79 ± 0.63^{b}	0.53 ± 0.03^{ab}	13.30 ± 0.15^{c}	345.64 ± 13.68^{ab}

$^{a-c}$ Means in a column with common superscript are not significantly different at the 0.05 probability level by Duncan's multiple range test.

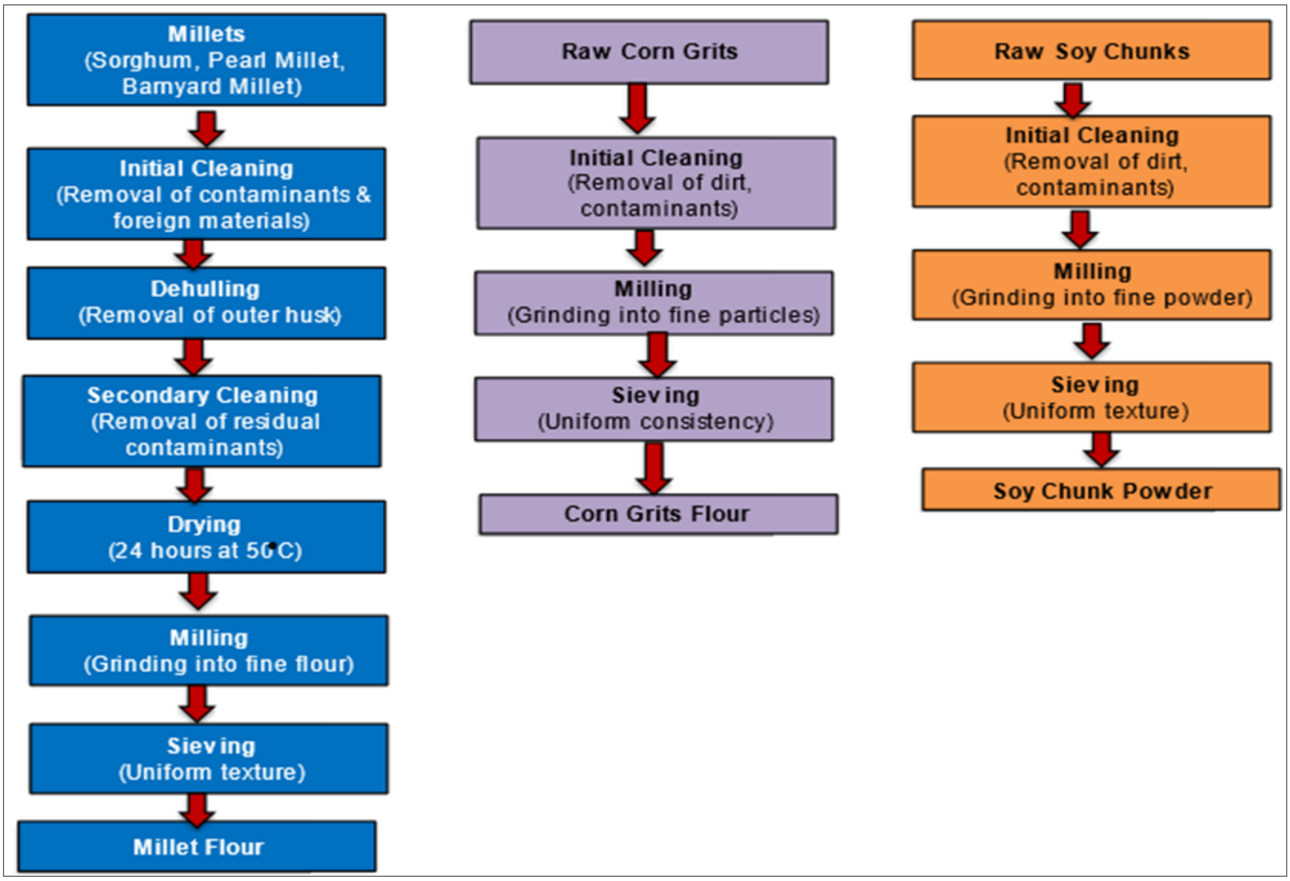

Fig. 1. Flow chart for the preparation of processed flours.

Experimental design using response surface methodology (RSM)

The physical, chemical and sensory properties of the extruded RTE foods were examined in order to ascertain the impact of the millet combo (50, 55 and 60 g), corn grits (40, 45 and 50 g) and soy chunks (20, 25 and 30 g). Previous studies have demonstrated the incorporation of millet flour up to 60 % in extruded formulations can improve protein and dietary fibre content without compromising product quality (12, 13). Corn grits, due to their high starch content (40-50 %), have been widely recognized as essential for puffing and the structural integrity of extrudates (14, 15). For protein fortification, inclusion levels of soy protein or soy chunks at 20-30 % have been reported to enhance nutritional value. However, higher levels often impart undesirable beany flavor and affect consumer acceptability (8). Based on these findings, the study was designed to optimize ingredient ratios within these functional limits.

Additionally, the RSM of central composite rotatable design (CCRD) was optimized through the development of second-order polynomial equations (Eqn. 1).

$$y_i = \beta_0 + \sum_{i=1}^{3} \beta_i X_i + \sum_{i=1}^{3} \beta_{ii} X_i^2 + \sum_{i=1}^{2} \sum_{j=i+1}^{3} \beta_{ij} X_i X_j \quad \text{(Eqn. 1)}$$

Where y is the predicted response (moisture content, expansion ratio or bulk density); Xi and Xj represent the coded levels of independent variables: A = millet combo flour (MCF), B = corn grits flour (CGF) and C = soy chunks powder (SCP); β0 is the intercept, βi are the linear coefficients, βii are the quadratic coefficients and βij are the interaction coefficients.

To strengthen the statistical reliability, the adequacy of fitted models was tested using F-values, *p*-values, lack-of-fit tests, coefficients of determination (R^2, adjusted R^2, predicted R^2), coefficient of variation (CV) and adequate precision values. These criteria ensured that only statistically valid models were used for prediction and optimization. Where model strength was moderate, limitations were acknowledged transparently in the results. The experimental design and data analysis were performed using Design-Expert® Version 13 (Stat-Ease Inc., Minneapolis, USA).

Based on the RSM investigation, the optimal hot-extruded formulations were identified and their physical, chemical and sensory properties were subsequently analyzed using the standard protocols described below.

Physical properties of RTE foods

The physical properties such as expansion ratio and bulk density were analysed using the procedure described below. Moisture content of the extrudates was determined using the procedure given by the AOAC (16). The expansion ratio was calculated with an accuracy of 0.01 mm using the digital caliper model CLEKAHO, CCCP, Russia. In accordance with the protocols, this was accomplished by dividing the average cross-sectional diameter of the extruded product by the diameter of the die (17, 18). The bulk density (g/cm^3) of the extruded snacks was calculated by dividing the weight by the volume, assuming that the extrudate was cylindrical (19).

Chemical compositions of ingredients and extruded RTE foods

Carbohydrate content was determined by the methods of the Association of Official Analytical Chemist (AOAC) (16). Protein content was estimated from the crude nitrogen content of the sample determined by the Micro-Kjeldhal method (N × 6.25) (16). Fat content of the samples was estimated by the Soxhlet method recommended by the American Oil Chemists Society (20). Crude fiber content of the samples was determined by the procedure given by the AOAC (16). Energy content was computed from food composition tables (21).

Sensory analysis of extruded RTE foods

The RTE snack bars were assessed by 30 trained panellists between the ages of 22 and 45 years. The panel consisted of students from the Department of Food Science and Nutrition at Periyar University, Salem, Tamil Nadu. A 9-point hedonic scale questionnaire (1 = dislike extremely, 9 = like extremely) was used to evaluate the color, flavor, taste, texture and overall acceptability. The products from different formulations were served dry. Potable water was provided for rinsing the mouth after tasting each sample to minimize error and the masking of sensory attributes. In addition to hedonic scoring, mean ± SD values were reported for each attribute and independent t-tests were used to compare the optimized product against the commercial control. This provided statistical evidence of sensory improvement rather than descriptive claims alone.

Statistical analysis

The statistical analysis such as mean, standard deviation was performed using the triplicate values. A comparative analysis was studied between the control and experimental sample using independent t test was done to determine the significant difference between the samples.

Results and Discussion

Chemical compositions of ingredients used in making extruded RTE foods

The proximate compositions of the selected ingredients revealed significant variation across different macronutrients (Table 1). Among the ingredients, pearl millet exhibited the highest carbohydrate content (73.28 %), followed closely by corn grits (72.12 %) and sorghum (71.21 %), indicating their strong role as energy-dense cereals. Pearl millet, sorghum and corn grits are rich in carbohydrates, making them excellent energy sources. In contrast, soya chunks have significantly lower carbohydrate content due to their high protein concentration, making them suitable for low-carb diets or high-protein formulations. The extruded RTE food (58.46 %) shows a moderate carbohydrate level due to the blending of high- and low-carb ingredients. In contrast, soya chunks contained the lowest carbohydrate content (29.45 %), aligning with their high protein profile. Similarly, sorghum and pearl millet exhibited carbohydrate levels above 70 %, consistent with previous findings, where sorghum and pearl millet were recognized as energy-dense cereals, contributing approximately 70-75 % carbohydrates (4).

Protein analysis showed that soya chunks had an exceptionally high protein content (52.79 g/100 g), significantly surpassing all other ingredients, particularly corn grits, which had the lowest protein content (9.46 g/100 g). Soya chunks dominate in protein content, providing more than five times the protein of corn grits. This highlights their role as a key protein fortifier in the RTE formulation. The extruded product (24.58 g) reflected the protein enhancement achieved by incorporating soy and millets. The present study revealed that soya chunks had a significantly higher protein content (52.79 g/100 g) compared with all other ingredients, which is consistent with earlier findings (30), reported soy protein isolate levels exceeding 50 % in processed soy products (Table 1).

For fat content, pearl millet contributed the most (5.33 g), whereas soya chunks had the least fat (0.53 g), suggesting their suitability for low-fat diets. While fats contribute to mouthfeel and caloric value, all ingredients maintained low fat content, making the formulation heart-healthy. Pearl millet exhibited the highest fat content, possibly due to its inherent lipid profile, while soya chunks contribute minimally. The fat content observed in pearl millet (5.33 g/100 g) agrees with data indicating that pearl millet contains more lipids than other millets, contributing to higher energy values (5).

Dietary fibre was highest in soya chunks (13.30 g), followed by pearl millet (9.61 g), supporting their role in enhancing digestive health. Conversely, corn grits had the lowest fibre content (2.11 g), offering limited functional benefits in this regard. Regarding energy values, corn grits exhibited the highest caloric density (371.15 kcal/100 g), while sorghum had the lowest (339.82 kcal/100 g). Despite their low protein and fibre, corn grits exhibited the highest energy value due to their high carbohydrate density. Sorghum showed the lowest energy value among the cereals. The fibre content in soya chunks (13.30 g/100 g) and pearl millet (9.61 g/100 g) was notably higher than in corn grits (2.11 g/100 g), echoing previous work, which highlighted legumes and millets as excellent sources of dietary fibre beneficial for glycemic regulation and digestive health (22). The energy values of ingredients, with corn grits at the highest (371.15 kcal/100 g) and sorghum at the lowest (339.82 kcal/100 g), are comparable to the USDA National Nutrient Database, which reports similar trends for dry cereal grains which supports the concept of value addition through composite flour formulation, which developed extruded snacks with enhanced protein and fibre by incorporating legumes and millets (12). These findings reinforce the nutritional potential of combining cereals and legumes to create functional, health-oriented food products.

Effects of extrusion variables on physical properties of extruded RTE foods

Effects of extrusion variables on the physical properties of extruded RTE foods and its predictive regression models for moisture, bulk density and expansion ratio showed high R^2 of 0.837, 0.871 and 0.618, respectively (Table 2).

Effects of moisture content of extruded RTE foods

Moisture content of the extruded samples was significantly influenced by the levels of millet flour, corn grits and soy chunks as determined by ANOVA (analysis of variance). The fitted quadratic model for moisture content was found to be significant with an F-value of 4.36 (p = 0.01). The coefficient of determination (R^2) was 0.837, indicating that 83.7 % of the variation in moisture content could be explained by the model. The adjusted R^2 (0.614) and predicted R^2 (0.588) were in reasonable agreement, suggesting satisfactory predictive ability. The coefficient of variation (CV) was within the acceptable range and the adequate precision value of 3.25 did not exceed the minimum threshold of 4.0, indicating limited model adequacy. Furthermore, the lack-of-fit test was not significant, indicating that the model was suitable for prediction. These statistical parameters collectively demonstrate that the developed model was reliable for describing the effect of ingredient levels on moisture content. Similar findings have been reported in earlier extrusion studies, where model adequacy was supported by strong R^2 values and non-significant lack-of-fit (6, 12).

In terms of process interpretation, the reduction in moisture content at higher levels of millet flour may be attributed to the high fibre content of millets, which promotes water evaporation during extrusion. Conversely, soy protein has a strong water-binding capacity, which tends to retain moisture within the extrudate matrix, thereby balancing overall product moisture. The balance between starch gelatinization from corn grits and protein–fibre interactions from soy and millets plays a critical role in determining final moisture content. The fitted model for moisture content of hot extruded samples (Eqn. 2) is provided below:

$$\text{Moisture (coded)} = +8.45+0.7957A+ 0.2248B- 0.1087C+ 0.2188AB- 0.4637AC- 0.0137BC + 0.4006A^2- 0.0926B^2+0.1213C^2 \quad \text{(Eqn. 2)}$$

The effects of extrusion ingredient combinations (millet combo, corn grits and soy chunks) on moisture content are shown in Fig. 2 (A-C) as 3D response surface plots. Plot (A) indicates that increasing millet combination increases moisture

Table 2. Predictive regression models for moisture, bulk density and expansion ratio of extruded RTE foods

Responses	Physical properties		
Factors	**Moisture**	**Expansion ratio**	**Bulk density**
Model	14.30**	61.66**	0.620**
Intercept	8.45	1.41	0.33
F -value	4.36	2.31	3.68
P >*F*	0.01	0.001	0.002
X1	8.65	0.0014**	0.001**
X2	0.689	21.65	0.021
X3	0.161**	0.029*	0.145*
$X1^2$	2.31*	2.03	0.285*
$X2^2$	0.123	31.59	0.312
$X3^2$	0.212**	2.87	0.420**
R^2	0.837	0.871	0.618
Adj. R^2	0.614	0.820	0.789
Pred. R^2	0.588	0.825	0.703
Adeq. precision	3.251	3.68	3.52
Lack of fit	302.37^NS	851.1^NS	0.924^NS

* - Significant at 5 % level; ** -Significant at 1 % level; NS -Not significant

content, while corn grits cause a slight decrease. Plot (B) demonstrates a positive effect of millet and a mild negative influence of soy chunks, suggesting moderate interaction. Plot (C) shows a relatively flat surface, indicating minimal interaction between soy chunks and corn grits.

Moisture content was significantly affected by ingredient composition, with the quadratic model showing an *F*-value of 4.36 ($p = 0.01$). The R^2 value of 0.837 indicated strong explanatory power and the lack-of-fit was non-significant, confirming model adequacy. Similar adequacy levels were reported in extruded rice- and barley-based products (6). The increase in moisture with higher millet levels can be attributed to their fibre-rich nature, which enhances water retention during extrusion (4). By contrast, higher protein levels from soy chunks reduce available free water, due to protein-water interactions. Comparable findings were observed in sorghum-legume blends, where protein and fibre content governed final product moisture (23). Thus, millet combination emerges as the dominant factor regulating moisture in this system.

Effect of expansion ratio of extruded RTE foods

The expansion ratio model was significant, with an *F*-value of 2.31 ($p = 0.001$). The coefficient of determination ($R^2 = 0.871$) indicated that 87.1 % of the variability in expansion ratio was explained by the model. The adjusted R^2 (0.820) and predicted R^2 (0.825) were not in close agreement, confirming limited reliability for prediction. Compared with previous extrusion studies where R^2 values exceeded 0.90 (24, 25), the present model showed slightly lower but still acceptable predictive strength. This limitation has been acknowledged and future experiments with additional data points are recommended to improve robustness.

Mechanistically, expansion is primarily governed by starch gelatinization and rapid vaporization of water at the die exit, which creates puffing (26). Corn grits, being starch-rich, facilitate greater expansion, whereas soy protein and millet fibre reduce expansion by binding water and limiting matrix elasticity. Similar reductions in expansion due to higher protein and fibre were reported in barley- and lentil-based extrudates (27). These findings align with the present study, where corn grits contributed positively while protein and fibre-rich components acted as limiting factors for expansion. The fitted model for expansion ratio (Eqn. 3) of the hot extruded samples is given below:

$$\text{Expansion ratio} = +15.27+0.2648A+0.4888B-0.2274C-0.1138AB+0.1312AC-0.1188BC+1.96A^2+0.1170B^2-0.4222C \quad \text{(Eqn. 3)}$$

The effects of ingredient combinations on expansion ratio are presented in Fig. 3 (A–C) as 3D response surface plots. Plot (A) shows that higher levels of millet reduce expansion, while corn grits enhance it, consistent with the starch-driven puffing mechanism. Plot (B) indicates that soy chunks exert a negative influence on expansion, whereas millet further reinforces this trend. Plot (C) demonstrates that the interaction between soy chunks and corn grits produces intermediate expansion values, reflecting partial compensation between starch and protein. The quadratic model for expansion ratio was significant ($F = 2.31$, $p = 0.001$), with an R^2 of 0.871. The reasonable agreement between adjusted R^2 (0.820) and predicted R^2 (0.825) confirmed the model's reliability. Adequate precision values exceeded the threshold and the lack-of-fit was non-significant, demonstrating that the model was valid for prediction.

Expansion is primarily governed by starch gelatinization and subsequent vaporization of water at the die exit (25). Corn grits, being starch-rich, promote greater puffing, whereas soy protein and millet fibre limit bubble growth by competing for water and reducing matrix elasticity. Similar reductions in expansion were observed when protein- and fibre-rich flours were incorporated into lentil and barley extrudates (24). Comparable findings were also noted, where fibre dilution of starch lowered expansion capacity (28). Overall, corn grits emerged as the most influential factor supporting higher expansion in the present study.

Effect of bulk density of extruded RTE foods

The bulk density model was statistically significant, with an *F*-value of 3.68 ($p = 0.002$). The coefficient of determination ($R^2 = 0.618$) indicated moderate explanatory power. However, the adjusted R^2 (0.789) and predicted R^2 (0.703) were not in close agreement, suggesting limited predictive reliability compared to moisture and expansion models. While the model adequately identified bulk density trends, its predictive strength was moderate. Similar challenges in density modeling have been reported in protein- and fibre-rich extrudates (23). To improve predictive accuracy, future studies should consider extending the design with additional factor levels and replicates.

From a mechanistic perspective, bulk density is inversely related to expansion. Higher starch levels promote puffing and yield porous, low-density structures, whereas higher protein and fibre levels suppress bubble formation, resulting in compact, denser extrudates. Similar increases in bulk density in millet-based extrudates were reported, while another study reported consistent density increases in maize–legume blends (4, 29). In line with these studies, the present work highlights millet and soy chunks as key contributors to higher bulk density, with corn grits counteracting the effect by supporting expansion.

Below is the model that was fitted for the hot extruded bulk density (Eqn. 4):

$$\text{Bulk density} = +0.2623+0.0303A+0.0363B-0.0105C+0.0187AB-0.0287AC-0.0037BC-0.0168A^2+0.0080B^2+0.0486C^2 \quad \text{(Eqn. 4)}$$

The effects of ingredient combinations on bulk density are illustrated in Fig. 4 (A-C). Plot (A) shows that increasing millet levels raise bulk density, while corn grits reduce it, consistent with the inverse relationship between density and expansion. Plot (B) demonstrates that higher soy chunk levels increase density, reflecting protein's compacting effect. Plot (C) indicates limited interaction between soy and corn grits, yielding moderate density values. The quadratic model for bulk density was significant ($F = 3.68$, $p = 0.002$), with an R^2 of 0.618. The adjusted R^2 (0.789) and predicted R^2 (0.703) showed moderate agreement, suggesting the model was adequate but less robust than those for moisture and expansion. Nevertheless, the lack-of-fit was non-significant, validating its use for prediction.

Bulk density is inversely related to expansion: higher starch levels produce expanded, porous structures with lower density, whereas higher protein and fibre concentrations restrict bubble growth and yield denser products. Similar patterns were observed in sorghum-based extrudates, where bulk density increased with protein enrichment (23). Millet-based extrudates showed increased density due to reduced starch expansion capacity (4). More recently, another study confirmed that blends

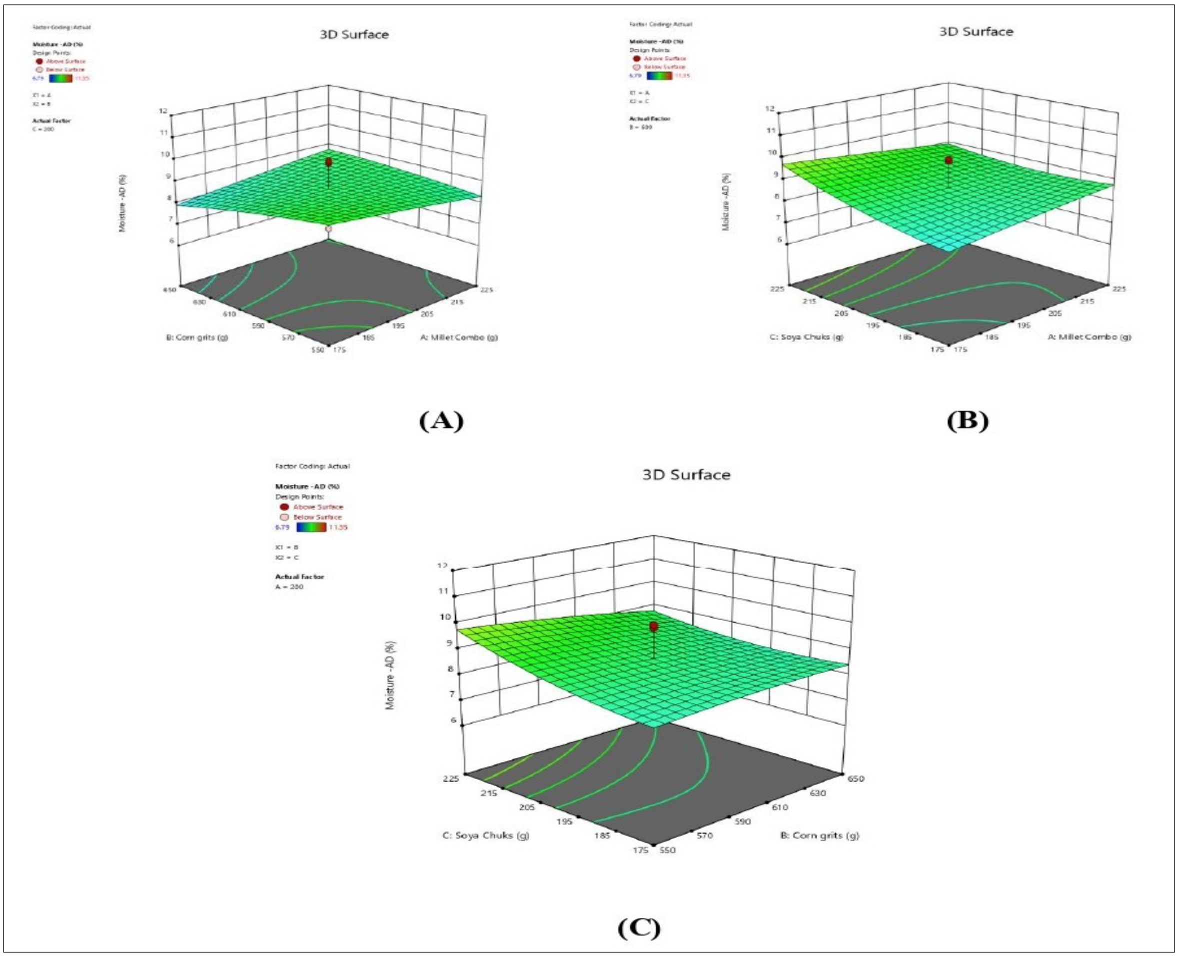

Fig. 2. Response surface plots showing effects of extrusion conditions (millet combo, corn grits and soya chunks) on the moisture content of hot extrudates. (A) millet combo and corn grits, (B) millet combo and soya chunks and (C) corn grits and soya chunks.

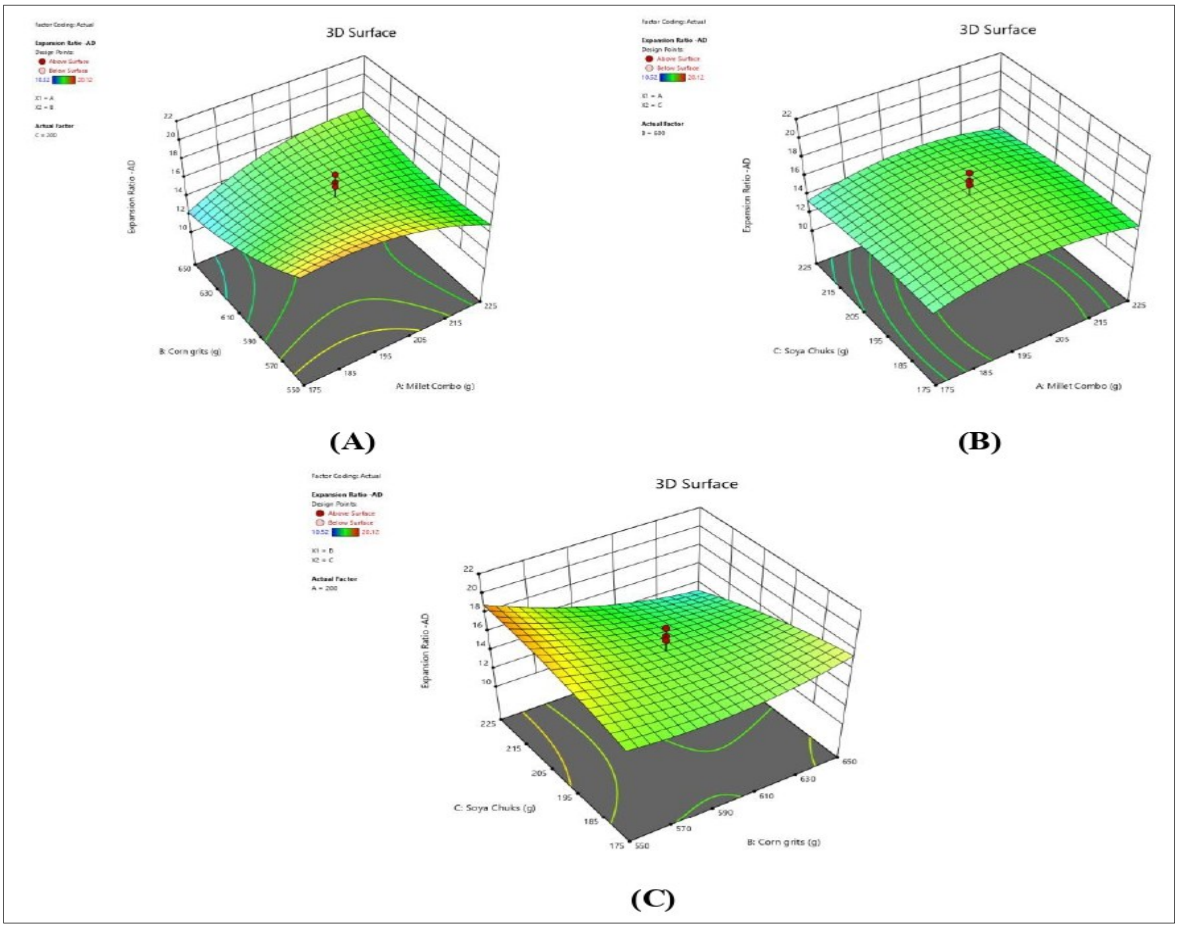

Fig. 3. Response surface plots showing effects of extrusion conditions (millet combo, corn grits and soya chunks) on the expansion ratio of hot extrudates. (A) millet combo and corn grits, (B) millet combo and soya chunks and (C) corn grits and soya chunks.

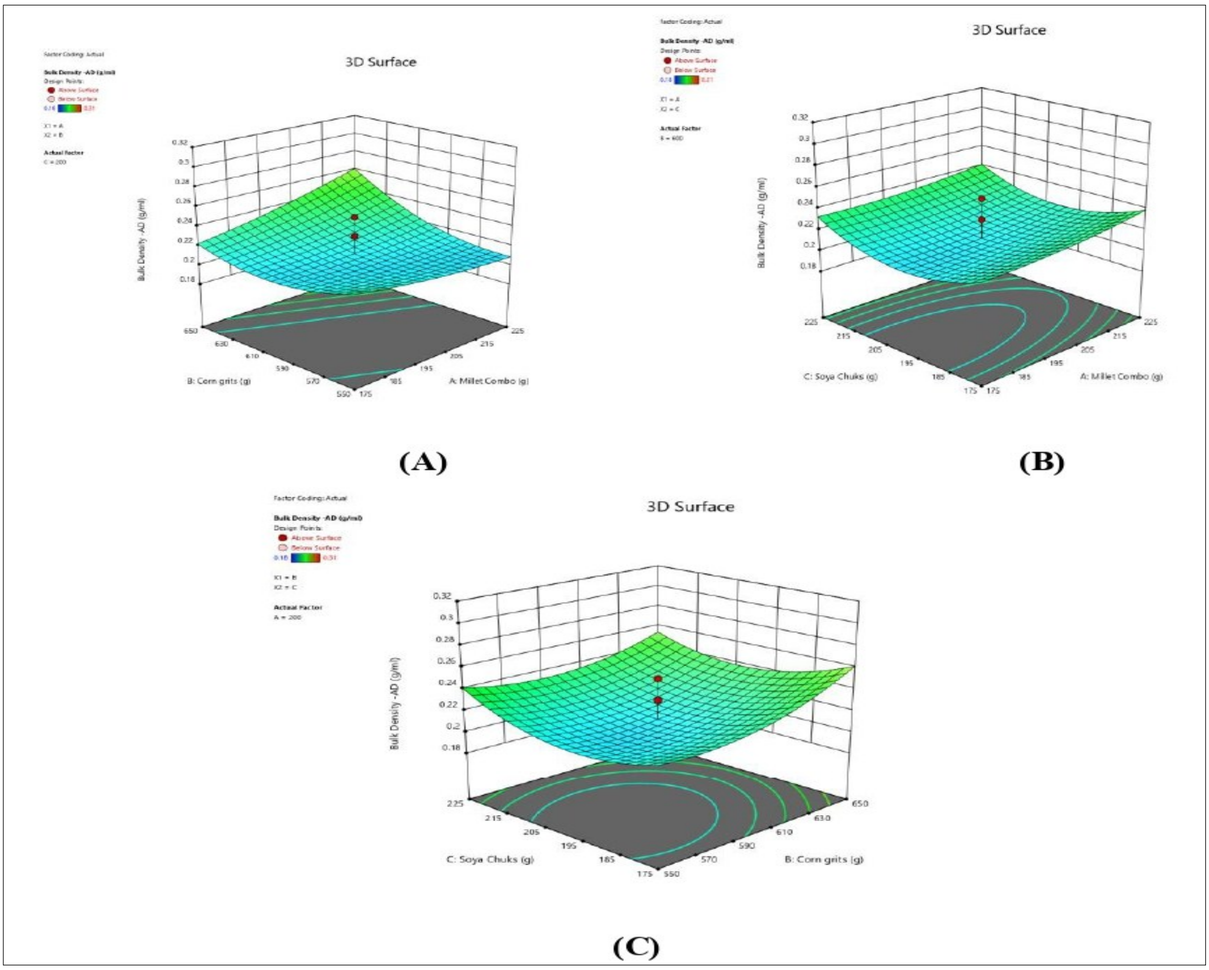

Fig. 4. Response surface plots showing effects of extrusion conditions (millet combo, corn grits and soya chunks) on the bulk density of hot extrudates. (A) millet combo and corn grits, (B) millet combo and soya chunks and (C) corn grits and soya chunks.

of maize and legumes displayed a comparable trend, with protein and fibre enrichment consistently raising density (29). These findings align with the present study, where millet and soy chunks were the main drivers of higher bulk density.

Regression coefficients for fitted models

Numerical values known as regression coefficients indicate the direction and degree of the association between each independent variable (such as MCF, CGF and SCP) and the dependent variable (such as bulk density, expansion ratio and moisture content) in a fitted regression model. These coefficients measure the impact of changes in individual variables or their interactions on the response in a polynomial regression or response surface methodology (RSM). Regression analysis showed that the responses, which included bulk density, expansion ratio and moisture content, were related to the independent variables, MCF, CGF and SCP (Table 3). Moisture content was positively impacted by MCF (A) in a strong and statistically significant way (0.79^{**}) and a nonlinear increase in moisture with greater MCF levels was also confirmed by its quadratic term ($A^2 = 0.400^{**}$). CGF had a considerable impact in improving puffing properties, as evidenced by its significant quadratic effect for expansion ratio ($B^2 = 1.48^{**}$). Furthermore, expansion was positively impacted by SCP ($C = 0.014^{**}$) and the interaction between MCF and SCP ($AC = 0.007^{*}$), demonstrating the efficacy of both strategies when taken together. The most important component in the bulk density model was SCP ($C = 0.010^{**}$), which greatly increased density. The AC interaction and the quadratic term of CGF ($B^2 = 0.004^{*}$) both made substantial contributions. In general, moisture was mainly influenced by MCF, expansion was driven by CGF and bulk density is primarily affected by SCP. The complexity of optimizing these responses was highlighted by multiple interactions and quadratic terms. All things considered, SCP significantly affected bulk density, while MCF was critical across responses, especially because of its nonlinear effects. These results highlight the importance of

Table 3. Regression coefficients for fitted models of extruded RTE foods

Coefficients	Moisture	Expansion ration	Bulk density
A	0.79^{**}	0.009	0.002
B	0.224	1.25	0.003
C	0.108	0.014^{**}	0.010^{**}
AB	0.218	1.69	0.001
AC	0.46	0.007^{*}	0.002^{**}
BC	0.01	0.05	0.006
A^2	0.400^{**}	0.37	0.55
B^2	0.09	1.48^{**}	0.004^{*}
C^2	0.12	0.44	0.004

A – MCF; B – CGF; C - SCP; MCF - Millets combo flour; CGF - Corn grits flour; SCP -Soya chunks powder; * - Significant at 5 % level; ** -Significant at 1 % level optimizing component levels, particularly MCF and SCP, to deliver desired product qualities.

Optimization and its point prediction

The best formulation consisting of 57.5 g MCF, 45 g CGF and 25 g SCP represents a specific experimental point likely derived from a RSM (Table 4). This combination indicates a high inclusion of both MCF and CGF, which are known to influence expansion and texture characteristics positively due to their starch-rich and puffing-friendly properties. The inclusion of SCP at approximately 25 % contributes to the protein content and nutritional profile, but it may also increase bulk density and reduce expansion if used in excess due to its compact structure. Notably, the total sum of the ingredients (127.5 g) suggests that these values may be coded levels or scaled inputs used for model prediction rather than direct formulation percentages. This point might have been selected as part of an optimization routine to predict or achieve desirable product qualities such as high expansion ratio, low bulk density, or optimal moisture content.

Chemical compositions of extruded RTE foods

The chemical compositions of the extruded RTE food are shown in Table 5. The extruded RTE food exhibited a significantly higher protein content (16.2 g/100 g) compared to the control (11.5 g/100 g), primarily due to the inclusion of soy chunks and millets. Dietary fibre was also enhanced (7.1 g/100 g vs. 1.5 g/100 g in the control), reflecting the contribution of millets and soy. In addition to chemical analysis, the nutritional relevance of this formulation lies in combining high-lysine soy protein with cereal-based proteins, resulting in an improved amino acid balance. This complementary protein effect has been emphasized as it increases the biological value of the RTE product compared to cereal-only extrudates. Moreover, the higher fibre content supports satiety and digestive health, aligning the product with functional food trends.

RTE extruded snacks with a moisture content of less than 10 % are often stable when stored at room temperature (30). Multigrain extruded products made with millet and legumes showed comparable moisture levels (31). The multigrain snacks which include millets and legumes have an ash concentration of 2.5–3.2 %, which affects the intake of micronutrients and the total nutritional value (32). A marginal increase in ash was observed in the RTE food (2.86 ± 0.10 %) relative to the control (2.5 ± 0.20 %), indicating a slightly higher mineral content likely due to the incorporation of soy or millet-based flours rich in micronutrients.

The main macronutrient in RTE foods that provides energy is carbohydrates. Due to their high starch content, millet flour and corn grits play a major role in this formulation's carbohydrate content. Maize grits increase the overall starch load and millets normally contain 60-72 % carbohydrates. Through the gelatinization of starch, carbohydrates also contribute to the creation of texture during extrusion (4). The use of soy chunk flour, which has a high-quality plant protein content (~50-52 %), is the primary reason for the protein-rich RTE formulation, which has a protein level of 16.2 g per 100 g. Corn and millet offer additional protein but lack lysine; soy, which is high in lysine, makes up for this.

Diets high in fiber are linked to a lower risk of developing chronic conditions like diabetes, heart disease and colon cancer (33). The estimated energy value of 380.3 kcal/100 g shows a well -balanced combination of fat, protein and carbohydrates (the main contributor). This energy density, which offers enough energy to support everyday activities, is typical of RTE foods intended for snacking or meal replacement. Energy-dense, protein-rich foods are crucial for preventing undernutrition and fostering dietary diversity (34).

Sensory evaluation of extruded RTE foods

Results from multiple cross-literature studies indicate the RTE sample's superior scores across all hedonic scale parameters in the sensory evaluation when compared to the RTE food to the control (Fig. 5). Results revealed that the optimized RTE sample achieved superior hedonic ratings across all sensory attributes appearance (8.15), color (8.10), flavor (8.20), crispiness (8.30), taste (8.25) and overall acceptability (8.35) compared to the control. The statistical comparison (independent t-test, $p < 0.05$) confirmed that these improvements were significant rather than subjective trends. Cross-literature comparison with extruded multigrain snacks also demonstrated consistency, thereby validating the acceptability of the developed formulation. In particular, higher crispiness scores were linked to effective starch gelatinization, while enhanced flavor scores reflected the synergy between millet and soy-based components. These findings establish that the optimized blend meets both nutritional enrichment goals and consumer preference.

Due to the incorporation of a variety of cereal-legume

Table 4. Optimized levels of hot extruded formulations and its point prediction

Factor and its responses	Variables	Optimized level	Low level	High level
A	Millet combo flour (MCF)	57.5	50	60
B	Corn grits (CGF)	45	40	50
C	Soya chunks flour (SCF)	25	20	30
Response 1	Moisture	11.43	6.71	8.80
Response 2	Expansion ratio	20.12	13.49	22.04
Response 3	Bulk density	0.31	0.15	0.37
	Overall desirability index = 0.77			

Table 5. Chemical compositions of extruded RTE foods

Parameters	Control (commercial RTE)	RTE food	T test
Moisture (%)	1.3 ± 0.40	5.24 ± 0.15	113.46**
Ash (%)	2.5 ± 0.20	2.86 ± 0.10	11.79**
Carbohydrate (g)	81.8 ± 1.58	68.57 ± 1.25	43.88**
Protein (g)	11.5 ± 1.02	16.20 ± 0.45	42.28**
Fat (g)	1.80 ± 0.35	1.40 ± 0.20	17.81**
Fibre (g)	1.5 ± 0.12	7.10 ± 0.30	149.55**
Energy (kcal)	382.5 ± 9.58	380.30 ± 10.50	24.49**

** -Significant at 1 % level through independent sample t test.

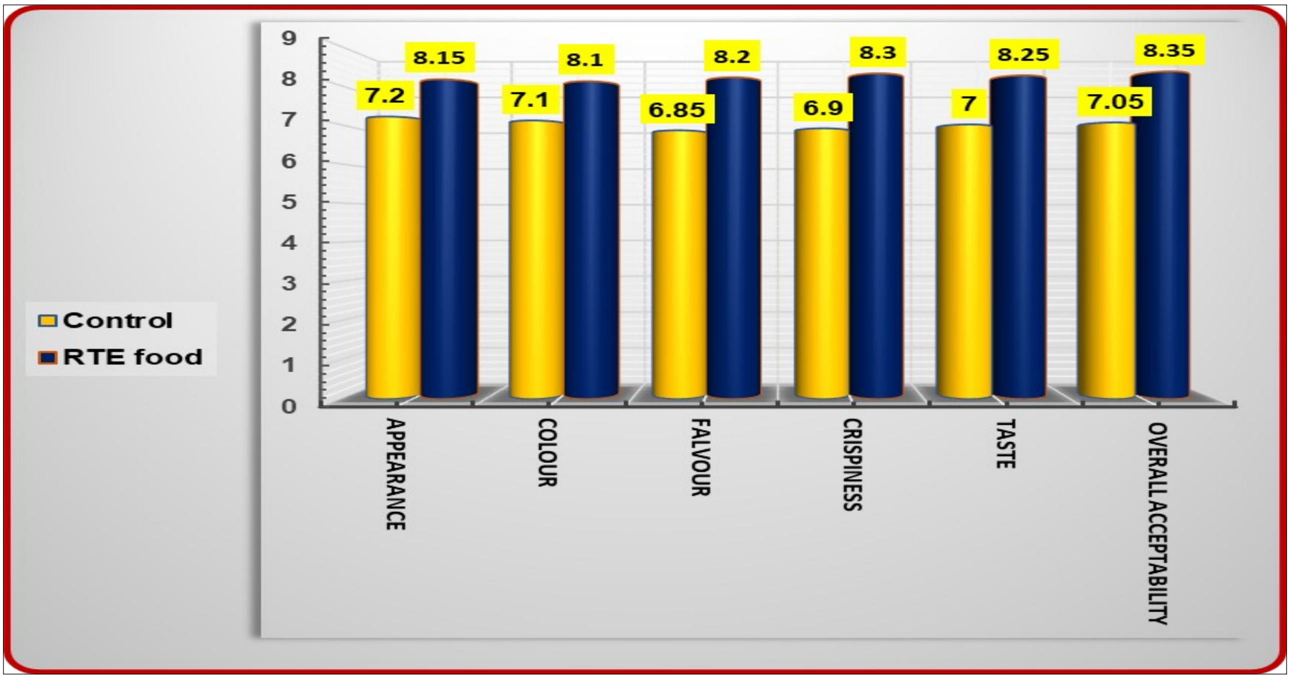

Fig. 5. Sensory analysis of extruded RTE foods.

mixes, including millet, corn and soy flour, the RTE food demonstrated higher acceptability in terms of appearance (8.15), color (8.10) and flavor (8.20). The uniform expansion and natural pigment retention resulted in improved color and visual appeal in extrudates manufactured from rice, corn and tamarind kernel (30). A key textural characteristic, crispiness, scored 8.30 in the RTE food versus 6.90 in the control, indicating effective moisture reduction and starch gelatinization during extrusion (31). Optimized multigrain blends produced higher taste ratings due to complimentary flavor interactions, the RTE food's increased taste score (8.25) emphasizes the synergy of ingredients that contributed to a more balanced flavor (32). The RTE food had a considerably higher overall acceptability (8.35), indicating a beneficial integration of sensory qualities. The extrusion of soy-based blends improved consumer preference and nutritional value (8). The role of dietary fiber and protein in extruded foods to enhance the satiety and texture, these improvements show that nutrient-rich foods not only increase the functional profile but also enhance organoleptic aspects (33). As a result, the created RTE formulation offers a palatable and nutritionally balanced substitute for traditional snacks.

Conclusion

Based on the optimization of a novel composite flour blend, this study successfully demonstrates the development of a nutritionally enhanced, RTE extruded product. Despite the acknowledged limitations in the predictive power of the expansion ratio and bulk density models, the research effectively utilized these findings as indicative trends to guide the formulation. The finalized product, composed of 57.5 % millet blend, 45 % corn grits and 25 % soy chunks, exhibited desirable physical attributes, including a high expansion ratio (>20.12) and low bulk density (<0.31 g/cm^2). Furthermore, the integration of proximate analysis confirmed the nutritional superiority of the optimized blend, with significantly increased protein content compared to a standard control. This work addresses a key research gap by providing a comprehensive optimization framework that considers not only physical properties but also chemical and sensory qualities, offering a robust pathway for the development of value-added food products from underutilized millets. The findings collectively validate the potential of this novel composite formulation and serve as a foundation for future research aimed at further refining process models and expanding the use of such blends in the food industry.

Acknowledgements

The researcher is grateful to the Department of Food Science and Nutrition, Periyar University, Salem, Tamil Nadu, India, for granting permission to proceed with the extrusion process and for granting permission to conduct laboratory work.

Authors' contributions

PVT was responsible for conceptualizing the study. SS was responsible for data collection, formal analysis, inquiry, methodology, visualization and draft preparation. PVT has reviewed the manuscript's methodology and corrected it. All authors have read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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