PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.14463

eISSN 2348-1900

RESEARCH ARTICLE

Valorisation of red gram (*Cajanus cajan* (L.) Huth) milling by-products into reconstituted dal analogues: Optimisation of extrusion cooking parameters

Rajender Gundu[1*], Ch V V Satyanarayana[2], Ch Someswara Rao[3], B Hari Babu[4] & B Anila Kumari[5]

[1]Department of Processing and Food Engineering, Professor Jayashankar Telangana Agricultural University (PJTAU), Hyderabad 500 030, Telangana, India

[2]Department of Food Engineering, Acharya N. G. Ranga Agricultural University (ANGRAU), Bapatla 522 101, Andhra Pradesh, India

[3]Department of Food Processing Technology, Acharya N. G. Ranga Agricultural University (ANGRAU), Bapatla 522 101, Andhra Pradesh, India

[4]Department of Farm Machinery and Power Engineering, Acharya N. G. Ranga Agricultural University (ANGRAU), Bapatla 522 101, Andhra Pradesh, India

[5]Department of Foods and Nutrition, Professor Jayashankar Telangana Agricultural University (PJTAU), Hyderabad 500 030, Telangana, India

*Correspondence email - rajender.agengg@gmail.com

Received: 08 March 2026; Accepted: 13 April 2026; Available online: Version 1.0: 04 May 2026

Cite this article: Rajender G, Satyanarayana ChVV, Someswara Rao Ch, Hari BB, Anila KB. Valorisation of red gram (*Cajanus cajan* (L.) Huth) milling by-products into reconstituted dal analogues: Optimisation of extrusion cooking parameters. Plant Science Today (Early Access). https://doi.org/10.14719/pst.14463

Abstract

The accumulation of milling by-products presents a significant challenge in pulse processing, necessitating sustainable valorisation strategies to support global food security. This study aimed to develop and optimise quick-cooking dal analogues from red gram (*Cajanus cajan*, var. PRG-176) brokens and fines using twin-screw extrusion technology. A four-factor, five-level central composite design (CCD) was employed to evaluate the impact of barrel temperature (171.46 °C), feed moisture (18.48 %), feed rate (60 kg/hr) and screw speed (220 rpm) on the functional and cooking quality of the analogues. Statistical analysis via response surface methodology (RSM) revealed that barrel temperature and feed moisture were the primary drivers of the starch-protein matrix (p <0.05). The integrity index, reflecting structural stability, ranged from 3.72 % to 18.60 % and was positively correlated with product hardness. Optimised analogues exhibited significantly shorter cooking times than natural pulses, with a strong correlation (r = 0.84) between hardness and cooking duration. Colour dynamics were governed by the Maillard reaction, where increased thermal intensity decreased lightness (L*) and increased redness (a*). A negative correlation between hardness and solids loss (r = -0.62) confirmed that a well-gelatinised matrix minimises nutrient leaching during hydrothermal treatment. The study demonstrates that pigeon pea milling by-products can be successfully upcycled into high-quality dal analogues that mimic the aesthetic and functional properties of natural tur dal. These findings provide a technical framework to produce value-added, plant-based protein alternatives that offer superior convenience and reduced energy consumption for the consumer market.

Keywords: cooking quality; dal analogues; pigeon pea; response surface methodology; valorisation

Introduction

Pulses, particularly red gram (*Cajanus cajan* (L.) Huth), are integral to global food security, serving as primary sources of vegetable protein, dietary fibre and essential minerals. However, conventional pulse milling remains an inefficient process, generating significant quantities of processing by-products in the form of "brokens" and "fines." These fractions, while nutritionally equivalent to whole grains, are often underutilised or relegated to low-value animal feed, leading to substantial economic losses and post-harvest inefficiencies (1). As global demand for plant-based proteins and sustainable food systems increases, the development of reconstituted dal analogues through extrusion technology offers a promising pathway for upcycling these milling side-streams into high-value, consumer-ready food products.

The valorisation of these milling fractions into "dal analogues"-reconstituted grains shaped to resemble natural pulses-presents a dual opportunity for food waste reduction and the creation of value-added functional foods. Traditional cooking of natural pulses is often time-consuming, requiring prolonged boiling or pressure cooking to achieve the desired texture, which can lead to significant nutrient degradation. In contrast, engineered analogues offer the advantage of "quick-cooking" properties due to the pre-gelatinisation of starch during processing (2).

Twin-screw extrusion technology has emerged as a superior method for developing these analogues. Unlike single-screw systems, the intermeshing co-rotating twin-screw extruder provides excellent mixing, high shear and precise control over residence time and thermal profiles (3). During extrusion, the high-temperature short-time (HTST) conditions facilitate the denaturation of proteins and the gelatinisation of starch, creating a stable, porous matrix that can be easily rehydrated. The quality of the final extrudate is a complex function of independent variables, including barrel temperature, feed moisture and mechanical shear (screw speed and feed rate) (4).

Despite the potential of extrusion, achieving the specific textural and functional characteristics that mimic the sensory profile of natural dal requires precise optimisation. Previous research has demonstrated that starch-rich legume matrices undergo specific rheological shifts during extrusion, yet the specific impact of high-capacity pilot-scale parameters on red gram by-products remains insufficiently characterised (5). Response surface methodology (RSM), specifically the central composite design (CCD), serves as an indispensable statistical tool for modeling these multi-variable interactions and identifying optimal processing windows (6).

Therefore, the objective of this study was to systematically evaluate the influence of extrusion process parameters on the functional, colour and cooking qualities of red gram dal analogues. By employing a CCD, this research sought to identify the optimal processing window that minimises cooking time while maximising the structural and sensory attributes of the reconstituted grains, thereby providing a technical framework for the industrial-scale upcycling of pulse milling by-products.

Materials and Methods

Materials

Red gram (*Cajanus cajan*, var. PRG-176) by-products (brokens and fines) procured from M/s. Our Food Pvt. Ltd, Kondapur, Telangana state and stored in HDPE bags under hygienic conditions, were milled into a fine flour and screened to achieve a targeted particle-size distribution. The fraction passing through a 150 µm sieve (BSS 100) was retained, while ultra-fine (<38 µm) and coarse (>180 µm) fractions were discarded to avoid agglomeration and textural inconsistencies, respectively (7). The formulation of the reconstituted analogues was supplemented with food-grade calcium chloride ($CaCl_2$), glycerol monostearate (GMS) and turmeric as a natural colourant.

Formulation and conditioning of the product

The base material, red gram flour, was blended with $CaCl_2$ (0.2 % w/w), glycerol monostearate (1.0 % w/w) and turmeric powder (0.2 % w/w) to produce the dal analogues (8, 9). To achieve the target moisture levels of 18–25 % (wet basis), the blends were conditioned by incorporating calculated volumes of distilled water via continuous spray-mixing. To ensure uniform moisture distribution and biochemical equilibration, samples were sealed in high-density polyethylene (HDPE) containers and tempered at 4 °C (overnight) (10). Prior to extrusion, the conditioned feed was equilibrated to ambient temperature of 3 hr to maintain thermal consistency.

Extrusion cooking parameters

Extrusion was conducted using a pilot-scale intermeshing co-rotating twin-screw extruder (M/s Best Engineering Technologies Pvt Ltd, Hyderabad, India) with a rated capacity of 175 kg/hr. The equipment features a five-zone barrel configuration: feeding, transition, cooking and two sequential metering zones. The screw assembly, measuring 1410.5 mm in length, utilised a descending pitch profile from the feed to the discharge section to facilitate progressive compression. Specific thermal profiles were maintained throughout the experimental trials, with the transition and second metering zones held constant at 90 °C and 120 °C, respectively. The temperature in the cooking zone and the first metering zone was varied systematically according to the experimental design, along with adjustments to feed moisture, feed rate and screw speed.

Post-extrusion processing

The extrudates were discharged through a 20-hole circular die (6 mm diameter) and immediately transferred to a five-pass continuous hot-air dryer. Drying was performed at 65 °C with a total retention time of 45 min (11). Following dehydration, the dal analogues were cooled on a wire-mesh conveyor for 2 min to achieve a stable storage moisture content of 5–6 % (w.b.). The final products were packaged in linear low-density polyethylene (LLDPE) bags and stored at room temperature for subsequent analytical evaluation.

Statistical design and optimisation

The experimental framework was structured using a four-factor, five-level central composite design (CCD) to evaluate the effects of independent process variables: barrel temperature (A), feed moisture (B), feed rate (C) and screw speed (D). Each variable was coded at 5 levels ($-\alpha$, -1, 0, +1, $+\alpha$), where $\alpha = 1.682$, as detailed in Table 1. This second-order design was implemented using Design-Expert software (v. 13.0, Stat-Ease, Minneapolis, MN, USA) to facilitate response surface modeling and process optimisation.

The CCD matrix comprised 21 distinct experimental runs, incorporating 8 factorial points (2^k), eight axial (star) points (2^k) and 5 replicates at the center point to estimate pure error and ensure model curvature (Table 2) (3). To mitigate systematic bias and prevent confounding of variables, the execution order of the trials was fully randomised. All experimental runs were performed in triplicate to ensure reproducibility. Statistical significance was evaluated via Analysis of Variance (ANOVA), with a confidence threshold established at $p<0.05$.

Determination of functional properties

Water absorption index and water solubility index

The water absorption index (WAI) and water solubility index (WSI) were determined according to the previously known protocol (12). A 0.5 g sample of ground analogue was suspended in 10 mL of distilled water, agitated and allowed to hydrate for 30 min. The suspension was subsequently centrifuged at 3000 rpm for 15 min. The supernatant was decanted into a tared Petri dish for WSI determination and the weight of the remaining hydrated sediment was recorded to calculate WAI (Eqn.1):

$$\text{WAI (g/g)} = \frac{\text{Weight of sediment, g}}{\text{Weight of initial sample, g}} \quad \text{(Eqn. 1)}$$

Table 1. Coded values of extrusion parameters in central composite rotatable design

Variable	Coded levels and actual values				
	-1.682 (-α)	-1	0	+1	+1.682 (+α)
Barrel temperature (°C)	101.25	120	147.5	175	193.75
Feed moisture (%)	15.6	18	21.5	25	27.4
Feed rate (kg/hr)	33.18	40	50	60	66.82
Screw speed (rpm)	60	100	160	220	260

Table 2. Central composite design of independent variables in coded and actual form for tur dal analogues

Exp. No.	Barrel temperature °C, (A)	Feed moisture %, (B)	Feed rate, kg/hr, (C)	Screw speed, rpm, (D)
T1	120 (-1)	25 (+1)	60 (+1)	220 (+1)
T2	147.5 (0)	21.5 (0)	50 (0)	160 (0)
T3	147.5 (0)	21.5 (0)	50 (0)	160 (0)
T4	147.5 (0)	21.50 (0)	50 (0)	160 (0)
T5	193.75 (+1.682)	21.5 (0)	50 (0)	160 (0)
T6	147.5 (0)	21.5 (0)	50 (0)	160 (0)
T7	175 (+1)	18 (-1)	60 (+1)	220 (+1)
T8	175 (+1)	18 (-1)	40 (-1)	220 (+1)
T9	147.5 (0)	21.5 (0)	33.18 (-1.682)	160 (0)
T10	147.5 (0)	21.5 (0)	50 (0)	260.91(+1.682)
T11	147.5 (0)	21.5 (0)	50 (0)	59.09 (-1.682)
T12	147.5 (0)	21.5 (0)	50 (0)	160 (0)
T13	120 (-1)	18 (-1)	40 (-1)	100 (-1)
T14	120 (-1)	25 (+1)	40 (-1)	220 (+1)
T15	175 (+1)	25 (+1)	60 (+1)	100 (-1)
T16	101.25 (-1.682)	21.5 (0)	50 (0)	160 (0)
T17	147.5 (0)	27.4(+1.682)	50 (0)	160 (0)
T18	175 (+1)	25 (+1)	40 (-1)	100 (-1)
T19	147.5 (0)	15.6 (-1.682)	50(0)	160 (0)
T20	120 (-1)	18(-1)	60(+1)	100 (-1)
T21	147.5 (0)	21.5(0)	66.82 (+1.682)	160 (0)

For WSI, the decanted supernatant evaporated to a constant weight in a drying oven. The index was calculated as the percentage of dry solids recovered from the supernatant (Eqn.2):

$$\text{WSI (g/g)} = \frac{\text{Weight of dissolved solids in the supernatant, g}}{\text{Weight of initial sample, g}} \quad \text{(Eqn. 2)}$$

Integrity index

The integrity index was determined following the methodology was previously described (13). A 5 g sample of dried dal analogue was steeped in 100 mL of distilled water for 30 min at 80 °C. The steeped samples were subsequently cooked in an autoclave at 121 °C for 15 min. Following the thermal treatment, the samples were briefly rinsed with tap water and homogenised in 100 mL of distilled water at 14450 rpm for 1 min. The resulting suspension was filtered through a muslin cloth and the retained solids were dried at 105 °C until a constant equilibrium weight was achieved. Measurements were performed in triplicate to ensure reproducibility. The integrity index was calculated using the following expression (Eqn.3):

$$\text{WSI (g/g)} = \frac{\text{Dry residue weight, g}}{\text{initial sample weight, g}} \times 100 \quad \text{(Eqn. 3)}$$

Colour

The colour analysis of the developed dal analogues was conducted using a Hunter Lab Colorimeter (Model: Colorflex EZ, Hunter Associates Laboratory, Reston, VA, USA). The instrument was calibrated prior to sample measurement using a standard green tile test. Chromaticity coordinates L*, a* and b* were determined in triplicate for each sample according to the hunter colour scale. In this system, the L* value denotes lightness (0 = black, 100 = white), the a* value signifies redness (+) or greenness (-) and the b* value indicates yellowness (+) or blueness (-). Samples were placed into a specialised cuvette and positioned in the measuring slot for data acquisition. The total color difference (ΔE), which quantifies the deviation in color between the developed analogue and the reference, was calculated using the following expression (Eqn.4) (14)

Where:

$$\Delta E = \sqrt{(L_i^* - L^*)^2 + (a_i^* - a^*)^2 + (b_i^* - b^*)^2} \quad \text{(Eqn. 4)}$$

- L*, a* and b* represent the chromatic values of the extruded dal analogues.
- L_i^*, a_i^* and b_i^* represent the reference values.

Cooking characteristics

Determination of cooking time

The cooking time of the dal analogues was determined according to the method described by Kuna et al. (15). A 10 g sample of the analogue was boiled in 70 mL of distilled water using a thermostatically controlled hot water bath. To determine the minimum cooking time, samples were withdrawn at 1 min intervals during the boiling process and evaluated for softness. The degree of cooking was assessed using the center-core method: a cooked grain was placed between 2 plexiglass plates and squeezed. The point at which the internal white core (indicating ungelatinised starch) completely disappeared and the sample reached a uniform softened mass, was recorded as the cooking time. All measurements were performed in triplicate to ensure statistical accuracy.

Determination of water absorption and cooking loss

The cooking characteristics, specifically water absorption and solids loss, were determined in accordance with the previously known procedures (15). A 10 g sample of the dal analogue was placed in a digestive tube and cooked in 70 mL of distilled water for its pre-determined optimal cooking time. Post-cooking, the excess water was carefully decanted and the weight of the cooked analogue was recorded. The percentage of water absorption was calculated using (Eqn. 5):

$$\text{Water absorption (\%)} = \frac{\text{Weight of cooked sample after decanting, g}}{\text{Weight of initial sample, g}} \times 100 \quad \text{(Eqn. 5)}$$

To determine the cooking loss (solids loss), the decanted water (gruel) was collected and dried in an oven at 135 °C until complete evaporation was achieved. The remaining dry residue, representing the solids leached during the cooking process, was weighed. The solids loss was calculated using (Eqn.6):

$$\text{Solids loss (\%)} = \frac{\text{Weight of dry solids dissolved I cooked water, g}}{\text{Weight of initial sample, g}} \times 100 \quad \text{(Eqn. 6)}$$

All measurements were conducted in triplicate to ensure statistical reliability.

Data analysis and modeling

Experimental data (Table 2) were subjected to multiple regression analysis using a second-order polynomial model. The relationship between independent variables and response attributes (WAI, WSI, integrity index, colour and cooking characteristics) was interpreted through coded variables. Response surface methodology (RSM) was employed to generate three-dimensional plots, allowing for the visualisation of interactions between process parameters while maintaining other factors constantly.

Results

The functional properties of the red gram analogues-comprising (WAI) and (WSI), integrity index, colour and cooking characteristics were evaluated across 21 experimental runs as specified by the RSM design (Table 3). Hardness results (a textural property) were considered from the previous work done by the current study's team (8).

Influence of process variables on functional properties

The interaction effects of barrel temperature (A), feed moisture content (B), feed rate (C) and screw speed (D) on the physical attributes were visualised through 3D response surface plots. Statistical analysis revealed that these parameters significantly influenced the quality of the dal analogues.

Influence on water absorption index

The WAI values for the red gram analogues ranged from 2.69 to 4.65 g/g (Table 3). The second-order polynomial model demonstrated high statistical adequacy (R^2= 0.995; Adj. R^2 = 0.985), with the predicted R^2(0.805) aligning well with the adjusted value. The ANOVA indicated that all independent process variables exerted a significant effect (p<0.05) on WAI. The regression equation in terms of coded factors is presented below (Eqn.7):

$$\text{WAI (g/g)} = 4.07-0.2022A+0.2884B-0.2238C+0.4519D+0.3631AB-0.1463AC+0.2021AD+0.0637BC-0.3384BD+0.0013CD+0.0239A^2-0.3102B^2+0.0274C^2-0.0574D^2 \quad \text{(Eqn. 7)}$$

Influence on water solubility index

The WSI values for the red gram analogues ranged from 0.096 to 0.260 g/g (Table 3). The second-order quadratic model demonstrated high statistical reliability (R^2 = 0.998; Adj. R^2 = 0.994), with a predicted R^2 (0.907) showing excellent agreement with the adjusted value. All independent variables-barrel temperature (A), feed moisture (B), feed rate (C) and screw speed (D)-were identified as significant factors (p<0.05). The regression equation in terms of coded factors is as follows (Eqn.8):

$$\text{WSI (g/g)} = 0.1656+0.0294A-0.0422B-0.0134C-0.0196D-0.0157AB-0.0031AC-0.0418AD-0.0039BC+0.0291BD-0.0054CD\ 0.0068A^2+0.0086B^2+0.0004C^2-0.0123D^2 \quad \text{(Eqn. 8)}$$

Influence on the integrity index and matrix formation

The integrity index values for the red gram analogues were found to vary from 3.72 to 18.60 % (Table 3). The lowest integrity index (3.72 %) was observed in treatment T20 (120 °C barrel temperature, 18 % feed moisture, 60 kg/hr feed rate and 100 rpm screw speed). The highest integrity index (18.60 %) was recorded in treatment T8 (175 °C barrel temperature, 18 % feed moisture, 40 kg/hr feed rate and 220 rpm screw speed). The ANOVA was employed to assess the variation of the integrity index as a function of the independent variables (Supplementary Table 1). The quadratic model was highly significant (p <0.05), with all independent variables showing a significant impact. The R^2 value of 0.998 indicates an excellent fit, with an adjusted R^2 of 0.995. The predicted R^2 (0.894) was in reasonable agreement with the adjusted value. The regression equation representing the integrity index in terms of coded factors is (Eqn.9):

$$\text{Integrity index} = 8.26+1.05A+1.10B-0.5331C+0.4162D-2.47AB-0.7488AC + 1.57AD + 0.9187BC\ 2.00BD+0.1188CD+0.7764A^2+0.9815B^2+0.7976C^2-0.8287D^2 \quad \text{(Eqn. 9)}$$

This variation in integrity is fundamentally governed by the development of the starch–protein matrix during extrusion. At

Table 3. Functional properties of developed tur dal analogues at different processing conditions

Treatment	Water absorption index (WAI)	Water solubility index (WSI)	Integrity index	Colour		
				L*	a*	b*
T1	3.81±0.05	0.133±0.003	10.63±0.15	55.22±1.49	7.03±0.52	38.83±1.28
T2	4.12 ±0.08	0.164±0.004	8.30±0.10	57.62±1.88	5.56±0.48	37.17±1.18
T3	4.02 ±0.13	0.165±0.003	8.33±0.31	57.54±0.66	5.45±0.36	37.24±1.18
T4	4.07±0.13	0.168±0.003	8.25±0.05	57.68±0.33	5.58±0.14	37.10±0.12
T5	3.78±0.05	0.195±0.005	12.10±0.21	47.60±1.33	7.64±0.53	30.63±0.25
T6	4.05±0.10	0.167±0.004	8.20±0.20	57.55±1.93	5.61±0.44	37.25±0.50
T7	3.49±0.03	0.136±0.004	14.33±0.15	54.61±0.69	6.52±0.18	39.77±0.61
T8	4.31±0.07	0.170±0.003	18.60±0.10	50.04±0.80	8.86±0.43	37.20±0.23
T9	4.56±0.06	0.191±0.004	11.17±0.15	49.96±1.19	9.16±0.35	32.66±1.17
T10	4.65±0.06	0.097±0.004	6.50±0.17	48.72±0.27	7.98±0.28	34.15±0.40
T11	3.13±0.03	0.163±0.003	5.10±0.10	61.38±1.83	3.22±0.46	37.27±1.18
T12	4.11±0.04	0.166±0.004	8.47±0.12	57.82±1.07	5.64±0.18	37.32±1.69
T13	3.57±0.08	0.160±0.004	5.47±0.12	66.72±0.37	1.96±0.13	43.55±0.69
T14	3.79±0.04	0.170±0.002	8.23±0.06	53.27±1.13	8.05±0.31	40.30±2.02
T15	3.61±0.03	0.146±0.004	9.23±0.12	58.84±0.81	4.39±0.48	39.35±0.36
T16	4.46±0.09	0.096±0.009	8.58±0.08	61.19±0.52	3.40±0.19	38.30±0.13
T17	3.66±0.05	0.118±0.003	12.77±0.25	44.63±0.52	10.39±0.04	27.39±0.98
T18	4.18±0.08	0.174±0.004	10.30±0.10	47.95±0.57	9.20±0.24	35.19±0.57
T19	2.69±0.04	0.260±0.018	9.07±0.06	55.10±0.16	7.70±0.21	40.46±0.43
T20	3.33±0.03	0.160±0.005	3.72±0.08	67.59±0.25	1.50±0.11	43.73±0.30
T21	3.70±0.05	0.141±0.003	9.63±0.15	54.67±1.78	4.48±0.59	33.22±0.68

optimal processing conditions, such as those seen in T8, the synergy of high thermal energy and mechanical shear facilitates extensive starch gelatinisation and protein denaturation. This creates a dense, continuous and well-integrated macromolecular network. Such a compact structure enhances both hardness and the integrity index, as the cross-linked matrix becomes more resistant to mechanical and hydrothermal breakdown.

Conversely, treatments like T20-characterised by inadequate thermal and mechanical input-result in an incomplete matrix development. This produces a weaker, more porous structure that is vulnerable to the cooking process. During hydrothermal treatment, this fragmented matrix allows for rapid water ingress and accelerated swelling, leading to higher solids loss and a lower integrity index. Consequently, the extrusion parameters do not merely change the physical dimensions of the analogue; they dictate the structural stability of the matrix, directly determining whether the final product is resistant or susceptible to disintegration during cooking.

Effect of process parameters on color (L*, a*, b*)

Lightness (L*): The L* values, representing lightness, varied from 44.63 to 67.59 (Table 3). The minimum L* (44.63) was recorded for treatment T17 (147.5 °C, 27.4 % moisture, 50 kg/hr feed rate, 160 rpm), while the maximum (67.59) was observed in T20 (120 °C, 18 % moisture, 60 kg/hr feed rate, 100 rpm). The ANOVA results (Supplementary Table 2) indicated that the linear model was significant (p <0.05) with an R^2 of 0.785. The regression equation 10 is:

$$L^* = 55.50-3.97A-3.02B+1.92C-3.61D \quad \text{(Eqn. 10)}$$

Redness (a*): The chromaticity coordinate a*, representing the redness of the analogues, varied from 1.5 to 10.39 (Table 3). The lowest a* value (1.5) was observed in treatment T20 (120 °C barrel temperature, 18 % feed moisture, 60 kg/hr feed rate and 100 rpm screw speed). The highest value (10.39) was recorded in treatment T17 (147.5 °C barrel temperature, 27.4 % feed moisture, 50 kg/hr feed rate and 160 rpm screw speed). The ANOVA was utilised to assess the variation of a* with the independent variables (Supplementary Table 3). The linear model was significant (p<0.05), with all independent variables-barrel temperature (A), feed moisture (B), feed rate (C) and screw speed (D)-exerting significant effects. The model R^2 was 0.765, the adjusted R^2 was 0.706 and the predicted R^2 was 0.561, indicating a reasonable agreement between the values. The regression equation in terms of coded factors is expressed in Equation 11:

$$a^* = 6.16+1.29A+1.05B-1.21C+1.57D \quad \text{(Eqn.11)}$$

Yellowness (b*): The b* values for the red gram analogues were found to vary between 27.39 and 43.73 (Table 3). The minimum b* value (27.39) was recorded in treatment T17 (147.5 °C barrel temperature, 27.4 % feed moisture, 50 kg/hr feed rate and 160 rpm screw speed). The maximum b* value (43.73) was observed in treatment T20 (120 °C barrel temperature, 18 % feed moisture, 60 kg/hr feed rate and 100 rpm screw speed). Analysis of variance was employed to evaluate the variation in b* with respect to barrel temperature (A), feed moisture (B), feed rate (C) and screw speed (D) (Supplementary Table 4). The linear model was determined to be significant. Among the independent variables, only barrel temperature and feeding moisture were found to be statistically significant (p<0.05). The model yielded an R^2 of 0.475 and an adjusted $R^2$of 0.344. The negative predicted R^2(-0.069) suggests that the overall mean may serve as a better predictor for this response than the current model. The regression equation representing b* in terms of coded factors is Equation 12:

$$b^* = 37.04-2.04A-2.38B+0.4673C-0.8031D \quad \text{(Eqn.12)}$$

Cooking quality of pigeon pea analogues

The cooking quality parameters, including cooking time, water absorption and solids loss, for the extruded tur dal analogues are summarised in Table 4.

Cooking time

The results indicated that cooking time varied between 3 and 9 min, showing a strong dependence on the hardness of the analogues. The minimum cooking time (3 min) was recorded for treatments T13 and T20, both processed at 120 °C barrel temperature, 18 % feed moisture and 100 rpm screw speed, at feed rates of 40 kg/hr and 60 kg/hr, respectively. Notably, these samples dissolved and disintegrated in boiling water within 2 min of cooking. Treatment T20 also exhibited the lowest integrity index (3.72). The maximum cooking time (9 min) was observed in treatment T8 (175 °C barrel temperature, 18 % feed moisture, 40 kg/hr feed rate and 220 rpm screw speed). A high positive correlation coefficient (r = 0.84) was found between product hardness and cooking time. Conversely, negative correlation coefficients were observed between hardness and water absorption (r = -0.60) and between hardness and solids loss (r = -0.62).

Discussion

Functional properties and mechanism

Influence on water absorption index

Water absorption index serves as an indicator of the degree of starch gelatinisation, quantifying the capacity of the starch granules to immobilise water (16). A positive correlation was observed between feed moisture (B) and water absorption index (WAI) (Fig. 1a). This enhancement is likely due to the reduction in melt viscosity at elevated moisture levels, which facilitates molecular mobility and improves thermal penetration, thereby promoting a higher degree of starch gelatinisation (17). These observations are consistent with studies on soy-enriched maize snacks (12) and whole pinto bean

Table 4. Cooking quality parameters of extruded tur dal analogues

Treatment	Cooking time (min)	Water absorption (%)	Solids loss (%)
T1	4.5	320.25±2.59	16.50±1.23
T2	4	470.14±4.52	24.00±1.51
T3	4	468.39±4.10	23.50±1.06
T4	4	469.47±1.75	23.90±1.44
T5	5	320.11±4.79	10.50±1.36
T6	4	465.34±3.96	23.50±1.26
T7	5	420.65±5.38	11.20±1.09
T8	9	260.16±4.74	11.12±1.23
T9	5	325.87±2.05	32.60±1.40
T10	4	363.55±5.40	14.32±1.22
T11	4	498.33±6.21	33.62±1.45
T12	4	465.71±6.58	23.45±1.10
T13	3	410.64±3.28	46.89±1.74
T14	4	264.54±2.75	25.83±0.67
T15	4	400.4±4.15	12.8±1.77
T16	4	428.77±2.83	36.62±1.18
T17	4.5	290.16±4.03	15.50±0.89
T18	4	305.63±4.50	21.77±0.56
T19	4.5	380.31±2.04	29.39±0.48
T20	3	477.6±3.89	38.76±1.14
T21	4	474.43±4.56	16.84±1.11

extrudates (18).

The influence of barrel temperature (A) was strongly modulated by feed moisture (B). Under high moisture conditions, increasing the barrel temperature (A) favoured the dissociation of amylose and amylopectin chains, resulting in an expanded matrix with an enhanced hydration capacity (19). Similar trends have been reported for extruded red bean, chickpea and lentil-corn blends (20, 21). Conversely, at lower moisture levels, elevated temperatures induced structural breakdown and starch degradation, leading to a decrease in WAI (22).

Effect of mechanical parameters on water absorption index

As depicted in Fig. 1b, WAI increased with rising screw speed (D). The intensification of mechanical shear at higher speeds likely accelerated the disruption of the crystalline structure of the starch, leading to increased gelatinisation (23). In contrast, an increase in feed rate resulted in a decline in WAI. A higher feed rate (C) increases the degree of barrel fill and reduces the mean residence time, consequently lowering the specific mechanical energy (SME) and the total thermal input available for the cooking process (21, 24)

Influence on water solubility index

The WSI serves as a quantitative indicator of soluble molecular components, primarily arising from the dextrinisation of starch. It evaluates the extent of macromolecular degradation into smaller, water-soluble fragments during the extrusion process (3, 19). As illustrated in Fig. 1c, WSI exhibited a positive correlation with barrel temperature (A) while being inversely affected by feed moisture (B). The elevation in barrel temperature (A) increases the thermal energy within the extruder, which promotes the thermal degradation of starch granules. This effect is particularly pronounced at lower moisture levels, where high shear and temperature facilitate more intensive molecular cleavage. These results align with the findings of one previous study regarding extruded rice-based snacks. (3).

Impact of residence time and mechanical shear on water solubility index

The WSI was observed to decrease with increasing feed rate (C) and screw speed (D), as shown in Fig. 1d. This trend is attributed to the reduction in mean residence time within the extruder barrel. A higher throughput rate or increased rotational speed limits the duration for which the material is subjected to high thermal and mechanical stresses, thereby restricting the extent of starch dextrinisation and the subsequent formation of soluble fragments. Similar inhibitory effects on WSI due to reduced residence time were reported in corn-lentil extrudates (21) .

Interpretation of integrity index

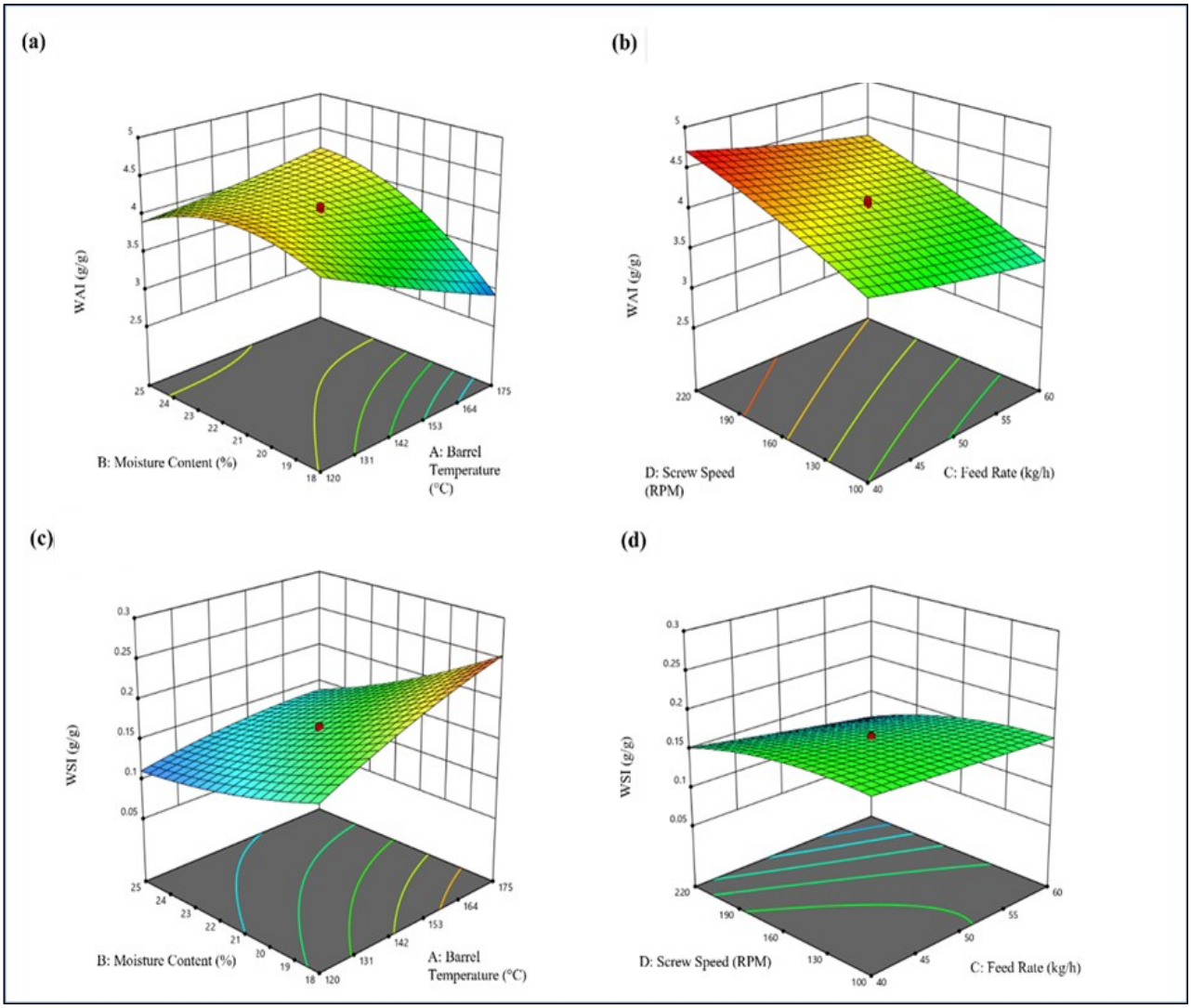


Fig. 1. Response surface plots showing the interaction effects of extrusion variables on functional properties of extruded red gram dal analogues: (a) effect of barrel temperature (A) and moisture content (B) on water absorption index (WAI); (b) effect of feed rate (C) and screw speed (D) on WAI; (c) effect of barrel temperature and moisture content on water solubility index (WSI); (d) effect of feed rate and screw speed on WSI.

The integrity index serves as a comprehensive measure of the yield and structural quality of the dal analogue after undergoing the sequential stresses of hydration, pressure cooking, homogenisation and drying.

Influence of feed moisture and hardness: The results indicated that the integrity index increased with higher feed moisture content during extrusion. This improvement is directly correlated with the increase in product hardness (8). A more compact and harder matrix better resists the mechanical forces of homogenisation and the thermal stresses of pressure cooking.

Interaction of barrel temperature and moisture: Barrel temperature showed a moisture-dependent effect: it increased the integrity index at lower moisture contents but caused a decrease as feeding moisture increased. The integrity index was observed to follow a similar behavioural trend to the hardness profile of the analogues, suggesting that the structural density achieved during extrusion is the primary determinant of cooking stability.

Mechanical parameters (feed rate and screw speed): The integrity index decreased with increasing feed rate, likely due to the concomitant decrease in hardness (8). Conversely, the index increased slightly with higher screw speeds. This phenomenon likely occurs because the material within the barrel is subjected to more severe mechanical shear at higher rotational speeds and lower feed rates. These conditions lead to a more thoroughly "sheared" and cooked product with increased firmness and structural integration (25).

Colour dynamics and Maillard reaction

Colour is a critical sensory attribute influenced primarily by the thermal and mechanical intensity of the extrusion process. The observed decrease in L* (lightness) and increase in a* (redness) as barrel temperature, screw speed and feed moisture increased are indicative of the Maillard reaction (Fig. 2). This non-enzymatic browning reaction occurs between amino acids and reducing sugars under heat (26). During extrusion, the material transitions into a translucent state, facilitating these chemical interactions.

Influence of temperature and residence time: The decrease in L* and b* with increasing barrel temperature is due to intensified thermal degradation and pigment transformation (27). Conversely, higher feed rates led to an increase in L* values. This is attributed to the reduced residence time in the extruder barrel; a faster throughput minimises the duration of mechanical and thermal energy absorption, thereby restricting the extent of browning in the dal analogues.

Moisture and shear effects: Higher feed moisture and screw speeds contributed to darker (L*) and redder (a*) products. Increased screw speed elevates mechanical shear, which can generate localised heat and promote structural breakdown, further accelerating Maillard precursors (27). While feed rate and screw speed were found to have a non-significant effect on the yellowness (b*) values (p>0.05), the significant impact of temperature and moisture suggests that thermal control is the primary driver of the yellow-to-brown color shift in red gram by-products.

Interpretation of cooking quality parameters

Relationship between hardness and cooking time

The discussion of cooking quality reveals that the structural density of the analogue dictates its behavior in boiling water. The positive correlation (r = 0.84) between hardness and cooking time suggests that as the internal matrix becomes more compact and rigid, the resistance to moisture penetration increases, thereby requiring longer durations to achieve desired softness. Optimal cooking time achieved through response surface methodology (RSM) is 5 min. Increased hardness necessitated longer hydrothermal treatment for complete starch gelatinisation (28).

Integrity index and disintegration

High cooking times were found to positively correlate with a high integrity index. In contrast, samples with low hardness and low integrity index (such as T13 and T20) lacked the structural strength to withstand boiling. The rapid disintegration and dissolution of these samples within 2 min indicates an insufficiently developed protein-starch network, likely due to the lower barrel temperatures (120 °C), which prevented adequate molecular cross-linking.

Water absorption and solids loss

The negative correlation between hardness and water absorption (r = -0.60) implies that denser analogues have lower hydration capacities during cooking. This is attributed to a reduced volume of capillary pores available for water uptake in harder extrudates (27). Furthermore, the negative correlation between hardness and solids loss (r = -0.62) suggests that a firmer, more integrated matrix effectively traps soluble components, resulting in lower leaching of solids into the cooking water. Consequently, analogues with higher hardness values demonstrated superior cooking stability, characterised by lower solids loss and better retention of grain shape.

Numerical optimisation of process parameters

The numerical optimisation aimed to engineer a structural matrix that balances rapid hydration with physical resilience. The transition from a raw milling by-product to a structured analogue is optimised where the desirability function reaches its peak, reflecting a synergistic balance between expansion and structural integrity. Unlike traditional pulses, which are limited by their natural biological structure, the optimised extrusion window (Barrel Temperature: 171.46 °C; Feed Moisture: 18.48 %) allows for a "designed" porosity. This is evidenced by the simultaneous maximization of the WAI and the Integrity Index, a combination that typically exhibits a trade-off in non-optimised treatments.

This finding aligns with recent advancements in pulse-based extrusion. For instance, recent investigations into faba bean and mung bean extrusion demonstrate that die temperatures above 135 °C are critical for disrupting starch crystallinity and creating the water-binding sites necessary for high-quality analogues (29, 30). The study further confirms that maintaining hardness within the 267–370 N range is essential for replicating the 'bite' of natural legumes, a structural requirement highlighted in recent 2025 trends for plant-based whole-food mimics. Furthermore, the high integrity index recorded at our optimised screw speed (220 rpm) suggests that mechanical energy promotes a more fibrous and cohesive internal network, like the anisotropic structures recently reported in high-moisture pulse extrudates where precise moisture-temperature control prevented over-plasticisation (31).

The significance of this optimisation lies in its ability to achieve a "convenience-quality" equilibrium. While traditional tur dal requires extensive pre-soaking or pressurised cooking, the optimised analogues leverage a pre-gelatinised starch framework that facilitates capillary water uptake without structural collapse. This technical framework positions red gram by-products not merely as fillers, but as a viable substrate for high-value, sustainable

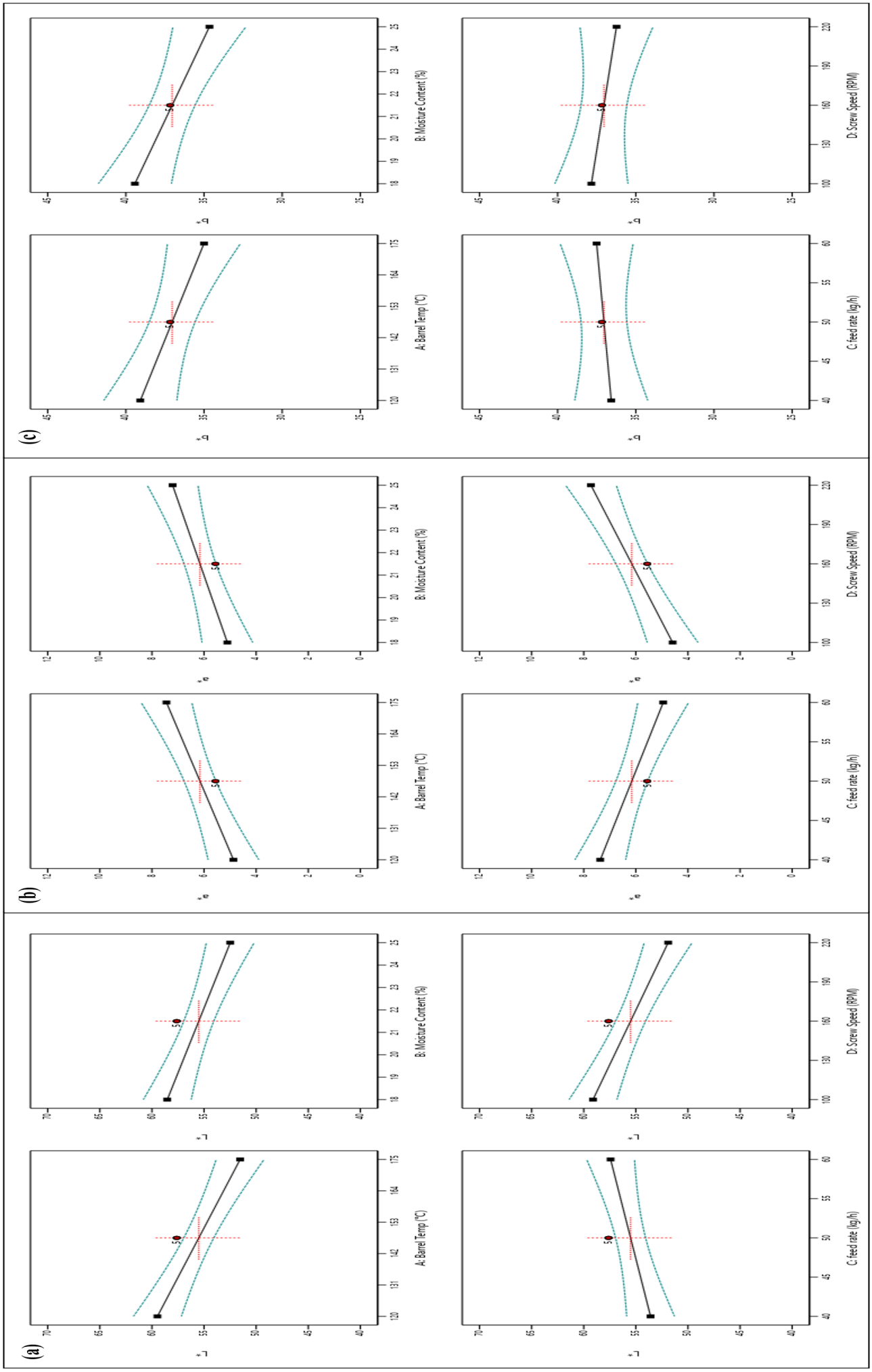


Fig. 2. Effect of extrusion process parameters on colour attributes of tur dal analogues: (a) L (lightness); (b) a (redness/greenness); (c) b* (yellowness/blueness). Note: The plots represent the main effects of barrel temperature (A), moisture content (B), feed rate (C) and screw speed (D), with confidence intervals indicated by dashed lines and the central point shown by the red marker.

protein alternatives that meet modern consumer demands for "clean-label" and minimally processed whole-food (32).

Optimal conditions and model validation

The identification of an optimal processing window-Barrel temperature: 171.46 °C, feed moisture: 18.48 %, feed rate: 60 kg/hr and screw speed: 220 rpm-represents a technical equilibrium between mechanical energy and hydrothermal plasticisation. With an overall desirability score of 0.734, these conditions align with recent findings in pulse-extrusion research, which suggest that temperatures exceeding 170 °C are necessary to achieve complete starch gelatinisation in high-protein matrices (30). This high-temperature regime, coupled with a moderate moisture level (18.48 %), facilitates the formation of a rigid, cross-linked macromolecular network.

Compared to traditional extrusion of whole pulses, the use of milling by-products in this study required higher mechanical shear (220 rpm) to compensate for the smaller particle size of the fines. This is consistent with recent comparative studies, where increased screw speeds were found to improve the texturisation of pulse-based flours by enhancing the melt viscosity and subsequent expansion (29). Furthermore, the optimised moisture content successfully balanced the trade-off between expansion and structural density; while higher moisture typically leads to denser products, the 18.48 % level allowed for sufficient internal vapour pressure to create the porous architecture required for rapid cooking without compromising the integrity index.

Conclusion

The transformation of red gram milling by-products into reconstituted dal analogues via twin-screw extrusion offers a robust strategy for food waste valorisation, directly contributing to global environmental sustainability goals (ESG 12: responsible consumption and production). Through a four-factor central composite design (CCD), this study demonstrated that the structural and functional quality of the analogues is a direct function of the starch-protein matrix development. While barrel temperature and feed moisture were the primary drivers of matrix density and Maillard-induced color dynamics, the optimised process (171.46 °C, 18.48 % moisture) successfully engineered a product that mimics the aesthetic and textural profile of natural tur dal.

Crucially, the optimised analogues provide a significant nutritional advantage by preserving the high-protein and mineral content of pulse fines in a highly bioavailable, pre-gelatinised form. The strong correlation between hardness and cooking time ($r = 0.84$) ensures that the final product maintains its structural integrity and "bite" while offering a 60–80 % reduction in cooking energy compared to traditional pulses. This reduction in preparation time directly supports ESG 7 (Affordable and clean energy) by lowering the household carbon footprint associated with pulse consumption.

Furthermore, the inverse relationship between hardness and solids loss ($r = -0.62$$) confirms that a well-gelatinised matrix minimises nutrient leaching, ensuring the retention of essential micronutrients during hydrothermal treatment. This technical framework establishes a viable pathway for producing nutrient-dense, convenience-focused, plant-based proteins.

Future research focus:

- Nutritional bioavailability: Investigating the impact of extrusion on the *in vitro* protein digestibility and mineral bio-accessibility of the analogues.
- Sensory and consumer acceptance: Conducting large-scale consumer sensory trials to evaluate the "mouthfeel" and flavour profile compared to traditional legumes.
- Fortification strategies: Exploring the incorporation of micro-nutrients or bioactive compounds (e.g., iron, zinc, or fibre) during the extrusion process to enhance the functional value of the final product.
- Life cycle assessment (LCA): Quantifying the precise carbon footprint reduction achieved by replacing traditional pulse processing with this upcycling technology.

Statement of novelty

While previous studies have explored the extrusion of pulse flour for snacks, this research presents a distinct technical advancement in the reconstitution of "true-to-type" dal analogues specifically from underutilised milling by-products (brokens and fines). The novelty of this work lies in 3 key areas:

- Waste valorisation of low-value streams: Unlike standard pulse extrusion which uses whole flours, this study provides a specific processing window to transform heterogeneous "fines" into a homogenous, high-value staple, directly addressing industrial efficiency in the pulse milling sector.
- Precision structural mimicry: We have successfully engineered a starch-protein matrix that doesn't just "look" like tur dal but matches its hydrothermal "bite" and resistance to solids loss. The identification of the integrity index as a critical quality marker (3.72 % to 18.60 %) provides a new benchmark for pulse analogue stability.
- Energy-efficient convenience: This study establishes a "convenience-quality" equilibrium, producing an analogue that reduces household cooking energy consumption by 60–80 % compared to natural pulses. This positions the research as a scalable solution for urban food security and sustainable "cook-ready" plant-based diets.

Acknowledgements

The authors acknowledge the support and facilities provided by Professor Jayashankar Telangana Agricultural University (PJTAU) and M/s Best Engineering Technologies Pvt. Ltd., Hyderabad, Telangana, India.

Authors' contributions

RG contributed to methodology, data collection, product development and writing-original draft. CVVS contributed to visualisation, supervision and manuscript review and editing. CSR contributed to visualisation, supervision and manuscript review and editing. BHB and BAK contributed to manuscript review and editing. All authors have read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used Gemini (Google AI) to improve the linguistic flow, refine the technical phrasing of the abstract and discussion sections and ensure compliance with the journal's formatting guidelines. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the accuracy and scientific integrity of the final manuscript. The AI tool was not used to generate, analyse, or interpret any primary research data or to draw scientific conclusions.

References

1. Singh B, Singh JP, Singh N, Kaur A. Saponins in pulses and their health promoting activities: A review. Food Chem 2017;233:540–9. https://doi.org/10.1016/j.foodchem.2017.04.161.
2. Tomar M, Singh P. Oat (*Avena sativa*). Boca Raton: CRC Press; 2024. https://doi.org/10.1201/9781003263302.
3. Ding Q-B, Ainsworth P, Tucker G, Marson H. The effect of extrusion conditions on the physicochemical properties and sensory characteristics of rice-based expanded snacks. J Food Eng 2005;66:283–9. https://doi.org/10.1016/j.jfoodeng.2004.03.019.
4. Alam MS, Kaur J, Khaira H, Gupta K. Extrusion and extruded products: changes in quality attributes as affected by extrusion process parameters: a review. Crit Rev Food Sci Nutr 2016;56:445–73. https://doi.org/10.1080/10408398.2013.779568.
5. Kothakota A. A study on evaluation and characterization of extruded product by using various by-products. Afr J Food Sci 2013;7:485–97. https://doi.org/10.5897/AJFS2013.1065.
6. Myers RH, Montgomery DC, Anderson-Cook CM. Response surface methodology: process and product optimization using designed experiments. John Wiley & Sons; 2016.
7. Kearns J, Rokey GJ, Huber GR. Extrusion of texturized proteins. Engormix 2013.
8. Rajender G, Satyanarayana CV, Rao CS, et al. Effect of extrusion parameters on physical properties of tur dal (pigeon pea) analogues developed from tur dal brokens. Asian J Microbiol Biotechnol Environ Sci 2023;25:370–6. https://doi.org/10.53550/AJMBES.2023.v25i02.032
9. Rajender G, Satyanarayana CV, Rao CS, Hari BB, Anila KB. Standardization, formulation and evaluation of tur dal analogues developed from red gram brokens. Pharma Innov 2022;11:6201–4.
10. Deshpande HW, Poshadri A. Physical and sensory characteristics of extruded snacks prepared from foxtail millet based composite flours. Int Food Res J 2011;18.
11. Alharaty G, Ramaswamy HS. Formulation and evaluation of a nutritionally enriched plant protein-based matrix using low temperature extrusion cooking-air drying technology. Foods 2025;14:1846. https://doi.org/10.3390/foods14111846.
12. Sahu C, Patel S, Tripathi AK. Effect of extrusion parameters on physical and functional quality of soy protein enriched maize based extruded snack. Appl Food Res 2022;2:100072. https://doi.org/10.1016/j.afres.2022.100072.
13. Ma X. Optimization of extrusion variables for improving the qualities of textured vegetable protein with green tea using response surface methodology. J Food Eng Process 2018;22:1–8. https://doi.org/10.53550/AJMBES.2023.v25i02.032
14. Hunter RS. Scales for the measurement of color difference. In: The measurement of appearance. New York: John Wiley & Sons; 1975. p. 133–40.
15. Kuna A, Lakshmiprasanna K, Kumar KV, Bhagyamma M, Rani VS. Evaluation of quick cooking red gram dhal (*Cajanus cajan* L.) developed with PJTSAU released varieties (TDRG-4, RGT-1 and WRGE-122). Asian J Dairy Food Res 2021. https://doi.org/10.18805/ajdfr.DR-1765.
16. Ding Q-B, Ainsworth P, Plunkett A, Tucker G, Marson H. The effect of extrusion conditions on the functional and physical properties of wheat-based expanded snacks. J Food Eng 2006;73:142–8. https://doi.org/10.1016/j.jfoodeng.2005.01.013.
17. M PL. Physical properties of extruded snacks enriched with soybean and moringa leaf powder. Afr J Food Sci Technol 2015;6. https://doi.org/10.14303/ajfst.2015.010.
18. Balandran-Quintana RR, Barbosa-Canovas GV, Zazueta-Morales JJ, Anzaldúa-Morales A, Quintero-Ramos A. Functional and nutritional properties of extruded whole pinto bean meal (*Phaseolus vulgaris* L.). J Food Sci 1998;63:113–6. https://doi.org/10.1111/j.1365-2621.1998.tb15688.x
19. Ring SG, Colonna P, I'Anson KJ, Kalichevsky MT, Miles MJ, Morris VJ, et al. The gelation and crystallisation of amylopectin. Carbohydr Res 1987;162:277–93. https://doi.org/10.1016/0008-6215(87)80223-9
20. Singh S, Gamlath S, Wakeling L. Nutritional aspects of food extrusion: a review. Int J Food Sci Technol 2007;42:916–29. https://doi.org/10.1111/j.1365-2621.2006.01309.x.
21. Lazou A, Krokida M. Structural and textural characterization of corn–lentil extruded snacks. J Food Eng 2010;100:392–408. https://doi.org/10.1016/j.jfoodeng.2010.04.024.
22. Wani SA, Kumar P. Development and parameter optimization of health promising extrudate based on fenugreek oat and pea. Food Biosci 2016;14:34–40. https://doi.org/10.1016/j.fbio.2016.02.002.
23. Suksomboon A, Limroongreungrat K, Sangnark A, Thititumjariya K, Noomhorm A. Effect of extrusion conditions on the physicochemical properties of a snack made from purple rice (Hom Nil) and soybean flour blend. Int J Food Sci Technol 2011;46:201–8. https://doi.org/10.1111/j.1365-2621.2010.02471.x.
24. Liang M, Huff HE, Hsieh F-H. Evaluating energy consumption and efficiency of a twin-screw extruder. J Food Sci 2002;67:1803–7. https://doi.org/10.1111/j.1365-2621.2002.tb08726.x.
25. İbanoğlu Ş, Ainsworth P, Özer EA, et al. Physical and sensory evaluation of a nutritionally balanced gluten-free extruded snack. J Food Eng 2006;75:469–72. https://doi.org/10.1016/j.jfoodeng.2005.04.060.
26. Yaylayan VA, Fichtali J, van de Voort FR. Production of Maillard reaction flavour precursors by extrusion processing. Food Res Int 1992;25:175–80. https://doi.org/10.1016/0963-9969(92)90134-Q.
27. Pasqualone A, Costantini M, Coldea TE, Summo C. Use of legumes in extrusion cooking: a review. Foods 2020;9:958. https://doi.org/10.3390/foods9070958.
28. Dalbhagat CG, Mishra HN. Effects of extrusion process conditions on system parameters; physicochemical properties and cooking characteristics of extruded fortified rice kernels. J Cereal Sci 2019;89:102782. https://doi.org/10.1016/j.jcs.2019.05.016.
29. Salvador-Reyes R, Clerici MTPS, Martínez-Villaluenga C. Enhancing the nutritional and bioactive benefits of faba bean flour by combining preprocessing and thermoplastic extrusion: a comprehensive study on digestion-resistant peptides. Food Res Int 2024;183:114231. https://doi.org/10.1016/j.foodres.2024.114231.
30. Messina V, Skylas DJ, Roberts TH, et al. Pulse proteins: processing, nutrition and functionality in foods. Foods 2025;14:1151. https://doi.org/10.3390/foods14071151.
31. Zang Y, Wang S, Gao Y, et al. High moisture extrusion of pulse proteins: texture, structure and *in vitro* digestion characteristics of extrudates.

Food Hydrocoll 2025;159:110676. https://doi.org/10.1016/j.foodhyd.2024.110676.

32. Moreira JB, de Carvalho LF, Matheus J, et al. Algae-based proteins and biomass as clean-label ingredients for the food industry. 2026. p. 37–57. https://doi.org/10.1007/978-981-95-2597-3_3

Additional information

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

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (https://creativecommons.org/licenses/by/4.0/)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.