Journal of Food Innovation, Nutrition, and Environmental Sciences
March, 2026, Volume 3; Issue 1:58-69
ISSN No:3078-5537

ORIGINAL RESEARCH ARTICLE

Optimization of an Instant Popcorn–Chickpea–Maize Composite Porridge for Reducing Protein–Energy Malnutrition in Under-Five Children

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DOI: https://doi.org/10.70851/jfines.2026.3(1).58.69

Article history
Received;
16 February, 2026
Revised;
19 March, 2026
Accepted;
21 March, 2026

Keywords
Extrusion cooking, Composite flour, Response surface methodology, Protein-energy malnutrition

ABSTRACT

Protein-energy malnutrition is still rampant in children below five years in Uganda because the main reason is that complementary feeding in Uganda is dominated by thin, nutrient-dilute cereal porridges. This study developed and optimized an instant maize-popcorn-chickpea composite porridge flour using extrusion cooking technology to improve protein density and instant reconstitution properties. A central composite design combined with response surface methodology was used to investigate the effects of barrel temperature (60-150 °C) and feed moisture (10-20%) on bulk density, water absorption capacity (WAC), swelling power (SP), water solubility index (WSI), and protein content. Extrusion conditions significantly ($p < 0.05$) influenced bulk density (0.45-0.69 g/cm^3), WAC (18-40 g water/100 g dry flour), SP (3.55-6.46 g/g), WSI (14.59-30.93%), and protein content (17.62-35.25%), and multi-response optimization predicted 132.66°C barrel temperature and 10% feed moisture as optimal (desirability = 0.681), which resulted in bulk density 0.54 g/cm^3, WAC 39.33 g water/100 g dry flour, WSI 29.17%, SP 4.49 g/g, and protein content 31.37%. Experimental values closely matched with the predicted values (relative deviation < 4%; $p > 0.05$). The optimized porridge exhibited significantly ($p \leq 0.05$) lower peak (185 cP), and setback (49.5 cP) viscosities compared with commercial soybean-based instant porridge (658 and 650 cP respectively), indicating reduced thickening and suitability for high solid complementary gruels. Sensory evaluation revealed high acceptability (overall score 7.57/9; n = 30), comparable to the commercial control except for aroma ($p \leq 0.05$). These findings demonstrate that extrusion processed maize-popcorn-chickpea flour offers a locally feasible instant complementary food with improved functional properties and strong consumer acceptance.

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Peer review under responsibility of Journal of Food Innovations, Nutrition, and Environmental Sciences.

A Publication of EcoScribe Publishers company Limited, Uganda.

1. INTRODUCTION

Protein-energy malnutrition (PEM) continues to pose a major constraint to healthy growth and development among young children in low- and middle-income countries. Despite global progress in reducing child undernutrition, sub-Saharan Africa remains disproportionately affected, with persistently high rates of stunting, wasting and micronutrient deficiencies (Black et al. 2013; UNICEF, WHO and World Bank Group 2023). These forms of undernutrition have lifelong implications for cognitive development, immune competence, school performance and future productivity. In Uganda, chronic undernutrition remains prevalent among children under five, reflecting ongoing challenges related to dietary quality, affordability of nutrient-dense foods and inconsistent access to appropriate complementary feeding options (UBOS and ICF 2022).

Complementary feeding practices in many low-income households are commonly based on thin cereal porridges prepared from maize or other staple grains. While these porridges are culturally acceptable and easy to prepare, they are often energy-dilute and limited in high-quality protein, essential amino acids and micronutrients such as iron, zinc and vitamin A (Dewey and Adu-Afarwuah 2008; Hotz and Gibson 2001). Commercial fortified complementary foods can improve nutrient intake, but their cost places them beyond the reach of many households. As a result, children who rely on unfortified cereal porridges are at heightened risk of inadequate dietary diversity and insufficient nutrient density during the critical window of complementary feeding.

Developing culturally acceptable, affordable composite flours using locally available cereals and legumes represents a practical and sustainable strategy for improving the nutritional value of complementary foods (Lutter and Dewey 2003; FAO 2011). Legumes such as chickpea offer high protein concentrations and complementary amino acid profiles to cereals, improving overall protein quality when blended (Plahar et al. 2003). They also provide additional fat, dietary fibre and micronutrients, contributing to the nutrient density required for rapid growth in early childhood. However, the utilisation of cereal–legume blends in households is often limited by lengthy cooking times, beany flavours, and the presence of antinutritional factors including phytates, tannins and trypsin inhibitors, which can reduce nutrient bioavailability (Alonso et al. 2000).

Extrusion cooking provides a high-temperature, short-time (HTST) processing approach capable of addressing many of these limitations. The process improves starch gelatinisation, enhances digestibility, reduces bulk density and accelerates rehydration attributes particularly important for young children with small gastric capacity (Guy 2001; Singh et al. 2007). Extrusion also decreases antinutritional factors and enables production of instantised flours that require minimal cooking time, improving convenience at household level (Duguma et al. 2021). Given the increasing emphasis on locally produced, nutrient-dense complementary foods in sub-Saharan Africa, extrusion offers a promising platform for upgrading cereal-based porridges using regionally accessible ingredients.

In this context, the present study developed an extruded instant composite porridge flour formulated from maize, popcorn and chickpea. Response surface methodology was applied to optimise extrusion conditions using barrel temperature and feed moisture as key processing variables. The resulting flours were evaluated for pasting properties, and sensory acceptability relative to commercial instant porridge flour. The study aims to contribute evidence supporting the development of cost effective, nutrient enhanced complementary foods suited to local production and consumption in low-resource settings.

2. MATERIALS AND METHODS

2.1 Raw materials and flour preparation

Maize (Zea mays), popcorn maize (Zea mays everta) and chickpea (Cicer arietinum) were sourced from local markets in Kampala, Uganda. Raw materials were cleaned to remove debris. Chickpeas were lightly roasted (~120 ºC for 20 min) to improve flavour and reduce beany notes and antinutritional factors (Alonso et al. 2000). Each ingredient was milled using a hammer mill and sieved through a 500 µm mesh to obtain uniform flour. Flours were stored in airtight bags at ambient temperature until blending.

2.2 Composite flour formulation

Based on complementary feeding considerations and cereal–legume protein complementarity (Lutter and Dewey 2003; FAO 2011), a composite blend of maize:popcorn:chickpea flour (60:30:10, w/w) was selected. The 60:30:10 ratio was selected based on preliminary trials that evaluated protein content, sensory acceptability, and extrusion processability at ratios ranging from 50:30:20 to 70:20:10. The selected ratio provided the best balance of protein enrichment from chickpea, sensory acceptability from popcorn, and extrusion processability from maize. Flours were mixed in a ribbon blender for 5 min.

2.3 Extrusion processing

Extrusion was conducted using a laboratory-scale twin-screw extruder (LT70-L, Shandong Light M&E, China). The first two barrel zones were set at 60 °C and 90 °C; the final zone barrel temperature was varied according to the experimental design. Feed moisture content was adjusted by spraying calculated amounts of water onto the blend and equilibrating for 30 min in sealed bags. The 30-minute equilibration period in sealed bags is consistent with protocols reported for fine flour systems (<500 µm) in laboratory-scale extrusion studies (Wondimu and Emire 2016). The fine particle size facilitated rapid moisture uptake and distribution. Extrudates were oven-dried at 50 °C for 30 min, cooled and milled into instant flour.

2.4 Experimental design and optimisation

A central composite design (CCD) within response surface methodology (RSM) was applied to optimise extrusion conditions, using barrel temperature (60–150 °C) and feed moisture content (10–20%) as independent variables (Myers et al. 2016). Twelve runs, including centre-point replicates, were performed. Each CCD run was performed as a single extrusion run. All analytical measurements (proximate, functional properties) were conducted in triplicate on the flour from each run. Center-point conditions (15% MC, 100 °C) were replicated four times to estimate pure error. Response surface models were fitted as second-order polynomials using Design-Expert® 13 (Stat-Ease, Inc., Minneapolis, USA). Model terms were evaluated for significance and non-significant terms were removed to improve model parsimony. Where higher-order terms (e.g., $X_1^2X_2$) were statistically significant, they were retained to improve model fit, as supported by sequential model sum of squares analysis and non-significant lack-of-fit tests. Model hierarchy was maintained by including all lower-order component terms. Pasting and sensory properties were evaluated on the optimized product as post-optimization validation measures rather than as RSM response variables, because including them as optimization targets would have required their measurement for all 12 CCD runs. Multi-response optimisation used a desirability function to identify conditions that maximised protein content and targeted functional properties appropriate for complementary porridges, including reduced viscosity and acceptable solubility (Mensa-Wilmot et al. 2001). A commercial instant porridge flour (soybean-fortified cereal blend) was purchased locally and used as a control for benchmarking.

2.5 Proximate composition and energy

Moisture, crude protein, crude fat, ash and crude fibre were determined in triplicate using AOAC standard methods (AOAC 2016). Moisture content was determined by oven drying at 105 °C to constant weight (AOAC Method 925.10). Crude protein was determined by the Kjeldahl method (AOAC Method 2001.11) using a nitrogen conversion factor of 6.25. Crude fat was extracted using the Soxhlet method (AOAC Method 920.39). Ash content was determined by incineration in a muffle furnace at 550 °C (AOAC Method 923.03). Crude fibre was determined by acid–alkali digestion (AOAC Method 978.10). All proximate composition results are reported on a wet-weight (as-is) basis unless otherwise stated. Carbohydrate content was calculated by difference as:

$$\boldsymbol{Carbohydrate}\ (\%) = 100 - (moisture + crude\ protein + crude\ fat + ash + crude\ fibre)$$

Gross energy (kcal/100 g) was determined using an isoperibol bomb calorimeter (Parr Instruments, Model 1261, Moline, IL, USA) following the manufacturer's instructions.

2.6 Functional properties

Bulk density, water absorption capacity (WAC), swelling power and water solubility index (WSI) were determined using standard procedures (Leach et al. 1959; Chandra et al. 2015; Chandla et al. 2017). Bulk density (g/cm^3) was calculated as the ratio of sample mass to occupied volume in a graduated cylinder. WAC was determined by dispersing flour in water, centrifuging, and expressing water retained by the sediment as percentage of water absorbed relative to dry flour mass (g water/100 g dry flour) (Chandra et al. 2015). Swelling power and WSI were determined by heating flour–water suspensions (90 ºC, 30 min), centrifuging, drying the supernatant to quantify dissolved solids, and calculating swelling power (g/g) and WSI (%) as the proportion of soluble solids relative to the dry sample (Leach et al. 1959; Chandla et al. 2017).

2.7 Pasting properties

Pasting properties were measured using a Rapid Visco Analyzer (RVA-4, Newport Scientific, Warriewood, NSW, Australia) following the reported procedure of Ding et al. (2006). Flour (3.0 g, adjusted to 14% moisture basis) was dispersed in 25 mL distilled water in the RVA canister. The standard heating–cooling profile was applied: holding at 50 °C for 1 min, heating to 95 °C at 6 °C/min, holding at 95 °C for 5 min, cooling to 50 °C at 6 °C/min, and holding at 50 °C for 2 min (Ding et al. 2006). Peak viscosity, breakdown, setback and pasting temperature were recorded from the RVA viscosity profile.

2.8 Sensory Evaluation

The sensory evaluation study received approval from the Higher Degrees Committee of the School of Food Technology, Nutrition and Bioengineering, Makerere University. Consumer acceptability testing was conducted with a panel of 30 untrained consumers recruited from Makerere University. Panelists were provided with informed consent forms prior to participation, and participation was entirely voluntary. Porridge samples were prepared by reconstituting the optimized extruded flour and the commercial control with boiling water at a standardized solids concentration. Samples were coded with randomised three-digit numbers and presented at ambient temperature in a balanced order. Panelists were provided with water for rinsing between samples. Acceptability was evaluated on a 9-point hedonic scale (1 = dislike extremely to 9 = like extremely) for appearance, color, aroma, taste, mouthfeel, flavor, aftertaste, and overall acceptability.

2.9 Statistical analysis

All measurements were conducted in triplicate (three independent analytical determinations from the flour of each extrusion run) and are presented as mean ± standard deviation. Response surface model fitting was performed using second-order polynomial regression in Design-Expert® 13 (Stat-Ease, Inc., Minneapolis, USA). Analysis of variance (ANOVA) was used to evaluate the significance of regression models, individual model terms, and lack-of-fit. Coefficients of determination (R^2) were used to assess model adequacy. Center-point replication (n = 4) provided the estimate of pure error. Model validation was performed by comparing predicted and experimental values using a one-sample t-test at p = 0.05. Independent-samples t-tests were used to compare the optimized product with the commercial control for pasting and sensory properties. Where ANOVA indicated significant differences, Fisher's least significant difference (LSD) test was applied to separate means. Statistical significance was set at $p < 0.05$ (Myers et al. 2016).

3. RESULTS AND DISCUSSION

3.1 Proximate composition of chickpea, maize and popcorn flours

The proximate composition of the raw flours is presented in **Table 1**. Moisture contents were similar across all samples (9.15%–9.76%), falling below the 12% threshold recommended for flour stability and supporting comparable storage life prior to processing. Chickpea flour exhibited substantially higher crude protein (40.48%) compared to maize (24.38%) and popcorn (28.03%). This high protein density is characteristic of legumes and justifies the inclusion of chickpea to address the protein deficits common in cereal-based complementary foods (Jukanti et al. 2012). Maize flour contained the highest carbohydrate proportion (60.21%), confirming its role as the primary energy contributor in the composite blend. Notably, popcorn flour showed a slightly higher protein and fat content than standard maize, which may contribute to improved energy density and sensory characteristics in the final extrudates. The relatively high crude protein values for maize (24.38%) and popcorn (28.03%) reflect the use of whole-grain, unrefined flours inclusive of germ and aleurone fractions, which are protein-rich. The standard nitrogen conversion factor of 6.25 was applied; use of a cereal-specific factor (5.70) would yield lower values. All Kjeldahl determinations were verified in triplicate with standard reference materials. Crude fibre values were determined by acid–alkali digestion (AOAC Method 978.10), which captures primarily cellulose and lignin and is known to underestimate total dietary fibre. Total dietary fibre analysis (e.g., AOAC Method 991.43) would be expected to yield considerably higher values. All flours were whole-grain, unrefined products.

Table 1. Proximate composition of chickpea, maize and popcorn flours (mean ± SD, n = 3)

Flour	Moisture (%)	Ash (%)	Crude fat (%)	Crude protein (%)	Crude fibre (%)	Carbohydrate (%)
Chickpea	9.76 ± 0.77	2.69 ± 0.10	8.08 ± 0.33	40.48 ± 1.78	0.34 ± 0.00	38.65 ± 0.02
Maize	9.26 ± 1.39	1.22 ± 0.04	4.08 ± 0.10	24.38 ± 1.27	0.25 ± 0.00	60.21 ± 0.34
Popcorn	9.15 ± 0.09	0.27 ± 0.05	4.64 ± 0.09	28.03 ± 0.77	0.28 ± 0.00	57.63 ± 0.09

Values are means ± standard deviation of triplicate measurements.

3.2 Effect of extrusion process variables on functional and nutritional properties

3.2.1 Bulk density

Bulk density of the extruded flours ranged from 0.45 to 0.69 g/cm^3 (**Table 2**). The highest bulk density (0.69 g/cm^3) was observed at 20% moisture content (MC) and 100 °C barrel temperature (BT), while the lowest (0.45 g/cm3) occurred at 10% MC and 100 °C BT. Analysis of variance indicated that the model was significant (p = 0.0348), with an R^2 of 0.8770, indicating that 87.70% of the variation in bulk density was explained by the extrusion parameters. The lack-of-fit test was non-significant (p = 0.6561), confirming model adequacy. Center-point conditions were independently replicated four times (separate extrusion runs). The observed variation in bulk density (0.61–0.66 g/cm^3) reflects inherent run-to-run variability in the extrusion process and was used to estimate pure error in the RSM analysis.

Regression analysis (**Table 3**) revealed that moisture content, the interaction between moisture content and barrel temperature, and the quadratic term of moisture content significantly influenced bulk density (p < 0.05). The regression equation for bulk density (BD, g/cm^3) in terms of coded variables is:

$$\boldsymbol{BD} = -3.683 + 0.48X_1 + 0.0356X_2 - 0.00361X_1X_2 - 0.0138{X_1}^2 - 0.000031{X_2}^2 + 0.000106{X_1}^2X_2$$

where X_1 = moisture content (%) and X_2 = barrel temperature (°C).

The three-dimensional response surface plot (**Figure 1**) shows that moisture content exerted the dominant effect on bulk density. Increasing moisture content led to higher bulk density, particularly at lower barrel temperatures. This trend reflects reduced expansion during extrusion due to plasticisation of the melt, which lowers specific mechanical energy (SME) and limits bubble growth at the die exit, resulting in denser extrudates (Wondimu and Admassu Emire 2016; Singh et al. 2007). Conversely, higher barrel

Journal of Food Innovation, Nutrition, and Environmental Sciences
March, 2026, Volume 3; Issue 1: 58-69
ISSN No:3078-5537

temperatures promoted starch gelatinisation and vapour expansion, producing more porous structures with lower bulk density. From a practical standpoint, controlling bulk density is important for complementary foods: excessively dense flours may resist rapid hydration and form lumps during preparation, whereas very low bulk density can reduce the mass of flour delivered per spoon, potentially affecting caregiver perception and portion control.

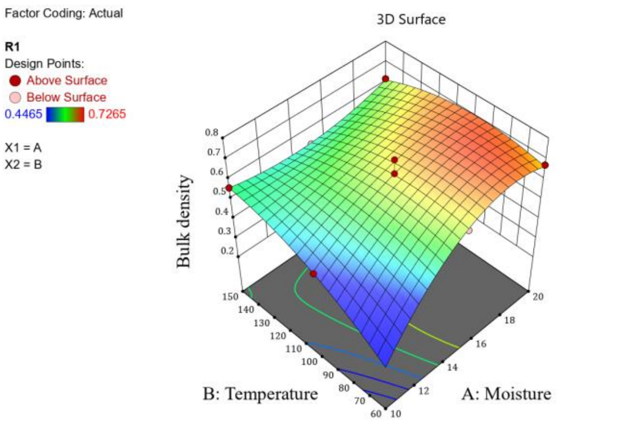

Fig. 1. Response surface plots for the effect of extrusion process parameters (Barrel temperature & Moisture content) on Bulk Density of the Chickpea-Popcorn-Maize flour.

3.2.2 Water absorption capacity (WAC)

The water absorption capacity of the extrudates ranged from 18 to 40 g water/100 g dry flour (**Table 2**). The highest WAC (40 g water/100 g dry flour) was observed at multiple conditions, including 15% MC/100 °C (Run 1) and 10% MC/150 °C (Run 5), indicating that high WAC can be achieved through different combinations of moisture and temperature. The lowest value (18 g water/100 g dry flour) occurred at 15% MC and 60 °C BT. ANOVA (Table 3) showed that the linear effect of BT, the interaction MC × BT, and the quadratic term BT^2 significantly influenced WAC ($p = 0.0019$). The model had a high coefficient of determination ($R^2 = 0.9315$) and a non-significant lack-of-fit ($p = 0.4166$), indicating good model adequacy.
The regression equation for WAC (%) is:

$$\boldsymbol{WAC} = -141.572 + 9.120X_1 + 1.878X_2 - 0.0475X_1X_2 - 0.127{X_1}^2 - 0.00476{X_2}^2$$

The response surface (**Figure 2**) demonstrates that barrel temperature was the primary driver of WAC. WAC serves as a critical indicator of the degree of starch gelatinisation and the extent of macromolecular modification during extrusion. At higher temperatures, the combined effect of thermal energy and mechanical shear disrupts the semi-crystalline structure of starch granules, breaking hydrogen bonds and exposing previously buried hydroxyl groups. These exposed sites facilitate increased water binding through hydrogen bonding, leading to higher WAC (Kumar et al. 2010; Wang et al. 2015).

The significant interaction between moisture and temperature suggests that at lower moisture levels, the melt viscosity is higher, leading to greater mechanical shear and more intense starch fragmentation, which further enhances water uptake. However, the quadratic effect of temperature indicates a threshold; excessively high temperatures can lead to starch dextrinization the breakdown of starch into smaller, more soluble dextrins which may eventually reduce the water-holding capacity of the matrix (Qiu et al. 2024).

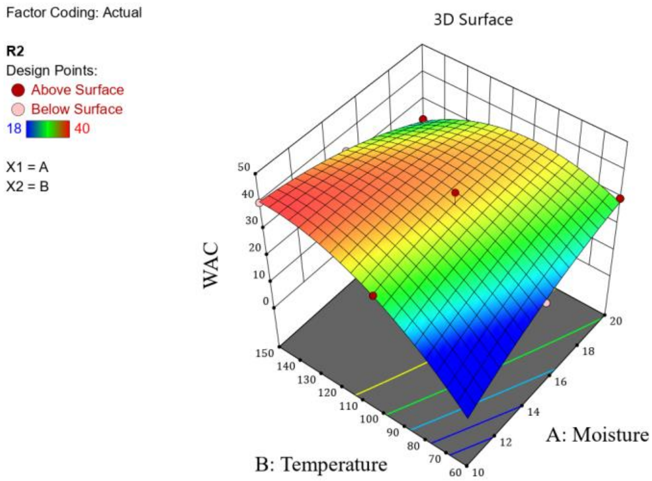

Fig. 2. Response surface plots for the effect of extrusion process parameters (Barrel temperature & Moisture content) on the Water Absorption Capacity of the Chickpea-Popcorn-Maize flour

From a nutritional and practical perspective, high WAC is a desirable trait for instant complementary flours. It ensures that the porridge can be reconstituted quickly with warm water to achieve a smooth, consistent texture without the need for prolonged boiling. Furthermore, a high WAC indicates that the starch has been sufficiently "pre-cooked" (gelatinised), which is essential for improving the digestibility of the cereal-legume blend for infants with limited digestive enzyme activity. These findings align with Hernández-Santos et al. (2025), who noted that optimised extrusion parameters are vital for balancing starch modification and maintaining the functional integrity of the final product.

Table 2. Effect of process variables on functional and nutritional properties of the extrudates

Run	Feed moisture (%)	Barrel temperature (°C)	Bulk density (g/cm³)	Water absorption capacity (g water/100 g dry flour)	Water solubility index (%)	Swelling power (g/g)	Protein content (%)	Gross energy (kcal/100 g)
1	15	100	0.61	40	30.54	5.37	31.54	471.12
2	15	150	0.53	34	30.93	3.55	25.97	446.44
3	20	150	0.62	23	21.47	5.70	35.25	468.50
4	20	60	0.67	30	19.78	5.11	17.62	446.57
5	10	150	0.56	40	28.24	4.24	30.61	472.38
6	15	60	0.63	18	14.59	3.76	27.83	443.40
7	10	100	0.45	30	28.67	3.74	29.68	451.00
8	20	100	0.69	33	21.74	6.46	27.83	419.17
9	15	100	0.66	35	23.28	5.93	30.61	464.08
10	15	100	0.64	35	20.41	5.03	31.54	447.00
11	15	100	0.64	35	23.95	5.91	31.54	445.65
12	15	100	0.66	35	27.76	4.69	32.46	445.64

Values are individual run results from the central composite design

3.2.3 Swelling power

Swelling power (SP) values varied from 3.55 to 6.46 g/g (**Table 2**). The maximum SP (6.46 g/g) was recorded at 20% MC and 100 °C BT, while the minimum (3.55 g/g) was observed at 15% MC and 150 °C BT. ANOVA (Table 3) showed that the linear effect of MC and the quadratic term MC^2 significantly influenced swelling power ($p = 0.0412$), while the lack-of-fit was non-significant ($p = 0.4731$), indicating an adequate model. The model for SP was significant ($p = 0.0412$, $R^2 = 0.8677$), with moisture content (linear and quadratic terms) being the primary influencing factor.

The regression equation for SP (g/g) is:

$$\boldsymbol{SP} = -36.72 + 3.895X_1 + 0.444X_2 - 0.035X_1X_2 - 0.109{X_1}^2 - 0.00076{X_2}^2 + 0.0011{X_1}^2X_2$$

The largest positive coefficient was associated with MC (3.895), indicating that moisture content was the dominant factor influencing swelling power, consistent with the regression analysis showing significance for MC and MC^2 terms. As shown in Figure 3, swelling power increased with increasing MC up to about 20%, particularly at moderate temperatures (~100 °C), and then declined at higher temperatures (150 °C). At higher feed moisture levels, starch granules gelatinise more extensively, allowing greater water uptake and granule expansion during hydration, which enhances SP. In contrast, low moisture combined with high temperature promotes excessive starch breakdown, producing shorter-chain dextrins that cannot swell effectively, thereby reducing SP. The direct effect of barrel temperature on swelling power was not statistically significant in the regression model, and therefore the temperature-related trends should be interpreted cautiously. These trends agree with Wang et al. (2015), who reported that starch granule structure and its interactions with protein components are key determinants of swelling behaviour. Similar observations have been made by Huang et al. (2022) and Singh et al. (2007), who found that increased moisture during extrusion favoured granule deformation, formation of a more continuous solid matrix, and improved structural integrity of extrudates.
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Table 3. Regression coefficients for each response surface equation and model fit parameters

Effect	PC	Bulk Density	WAC	WSI	SP
(Intercept)	-141.178	-3.683	-141.572	23.818	-36.724
MC	21.581	0.48*	9.12	-0.568	3.895*
BT	1.742	0.0356	1.878*	0.0832*	0.4436
MC × BT	-0.191*	-0.00361*	-0.0475*	-	-0.0349
MC^2	-0.756	-0.0138*	-0.0127	-	-0.1087*
BT^2	-0.00192*	-0.000031	-0.00476*	-	-0.000759
$MC^2 \times BT$	0.00672*	0.000106*	-	-	0.001053
R^2	0.9822	0.877	0.9315	0.5041	0.8677
LoF	0.1983	0.6561	0.4166	0.5087	0.4731
p-value	0.0003	0.0348	0.0019	0.0426	0.0412

* implies a significant effect at $p < 0.05$

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ISSN No:3078-5537

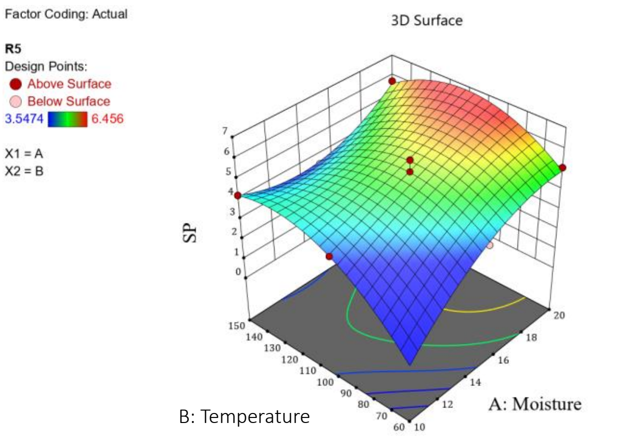

Fig. 3. Response surface plots for the effect of extrusion process parameters (Barrel temperature & Moisture content) on Swelling Power of the Chickpea-Popcorn-Maize flour.

From a product perspective, moderate-to-high SP is desirable for instant complementary porridges, as it contributes to a smooth, cohesive texture after reconstitution, without excessive thickness. The present results suggest that controlling MC around 20% and maintaining BT near 100 ºC provides a good balance between sufficient starch gelatinisation (high SP) and avoidance of over-degradation that would compromise texture and water-holding properties.

3.2.4 Water solubility index (WSI)

The water solubility index of the extrudates ranged from 14.59% to 30.93% (**Table 2**). The highest WSI (30.93%) was observed at 15% moisture content (MC) and 150 ºC barrel temperature (BT), whereas the lowest value (14.59%) occurred at 15% MC and 60 ºC BT. ANOVA (Table 3) showed that the overall model was significant (p = 0.0426), with an R^2 of 0.5041, and the lack-of-fit was non-significant (p = 0.5087), The model was statistically significant (p = 0.0426), though the relatively low R^2 (0.5041) suggests that additional factors not captured by the current design may influence WSI. The non-significant lack-of-fit (p = 0.5087) indicates the model form is adequate, but predictive power is limited.

The regression equation for WSI (%) is:

$$\boldsymbol{WSI} = 23.818 - 0.568X_1 + 0.0832X_2$$

The linear term of BT was the only significant model term for WSI (p = 0.0426), highlighting barrel temperature as the main factor controlling solubility. WSI reflects the amount of soluble material released from flour when dispersed in water and is commonly used as an indicator of starch degradation and protein solubilisation. As shown in **Figure 4**, WSI increased consistently with increasing BT, particularly at low-to-moderate MC. Maximum solubility was achieved at 150 ºC and 15% MC, while low temperature (60 ºC) at the same MC gave the minimum WSI.

At higher BT, intense thermal and mechanical energy within the barrel promotes starch depolymerisation and the release of free polysaccharides from granules, thereby increasing WSI (Dalbhagat et al. 2019; Sobukola et al. 2013). Similar trends were reported by Sahu et al. (2022), who found that higher extrusion temperatures increased the solubility of starch molecules due to greater macromolecular breakdown in maize-based extrudates.

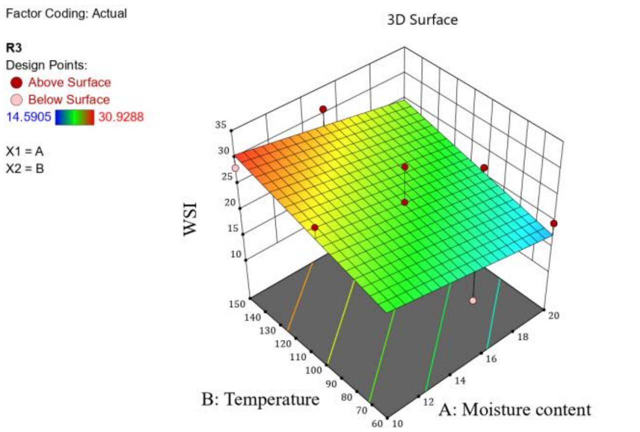

Fig. 4. Response surface plots for the effect of extrusion process parameters (Barrel temperature & Moisture content) on Water Solubility Index of the Chickpea-Popcorn-Maize flour

Recent reviews by Chang et al. (2021) and Wang et al. (2015) further confirm that extrusion-induced starch degradation and protein unfolding enhance solubility and functional properties of cereal-based foods, improving instantisation and digestibility. However, if both temperature and moisture are excessively high, over degradation can occur, which may compromise other functional properties such as viscosity and texture of the reconstituted porridge. Therefore, while moderate increases in WSI are desirable for rapid dispersion and instantisation, process conditions must be optimised to avoid excessive breakdown that could weaken the porridge "body" and mouthfeel.

3.2.5 Protein content

The protein content of the extrudates varied significantly across processing conditions, ranging from 17.62% to 35.25% (**Table 2**). The highest protein content (35.25%) was recorded at 20% moisture content (MC) and 150 °C barrel temperature (BT), while the lowest (17.62%) occurred at 20% MC and 60 °C BT. ANOVA (Table 3) indicated a highly significant model (p = 0.0003) with an R^2 of 0.9822. Significant model terms included the negative interaction between MC and BT, as well as the quadratic terms BT^2 and $MC^2 \times BT$. The lack-of-fit was non-significant (p = 0.1983), confirming the model's high predictive accuracy. Crude protein was determined by Kjeldahl nitrogen analysis (N × 6.25), which measures total nitrogen rather than functional protein. Extrusion cooking does not alter total nitrogen in a fixed-composition blend; the observed variations are attributed to differences in moisture loss during processing, leading to concentration effects on a wet-weight basis. The variation in apparent crude protein across extrusion conditions reflects differential moisture loss rather than true protein synthesis or destruction, as confirmed by the Kjeldahl method measuring total nitrogen. The regression equation for protein content (%) is:

$$\boldsymbol{PC} = -141.178 + 21.581X_1 + 1.742X_2 - 0.191X_1X_2 - 0.756{X_1}^2 - 0.00192{X_2}^2 + 0.00672{X_1}^2X_2$$

As illustrated in the response surface plot (**Figure 5**), protein content was maintained or slightly increased under conditions of high temperature and moisture. While extrusion cooking is primarily known for enhancing protein quality rather than quantity, the observed variations may be attributed to moisture loss concentrating the solids or heat-induced denaturation improving protein extractability during analysis. These findings align with Nosworthy et al. (2018) and Cargo-Froom et al. (2023), who reported that extrusion does not drastically alter the total crude protein content of pulse-based flours.
Crucially, although total protein remains relatively stable, the combination of high temperature, pressure, and mechanical shear during extrusion causes significant protein denaturation. This unfolding of complex protein structures makes peptide bonds more accessible to digestive enzymes, thereby substantially improving protein digestibility and absorption (Poojary and Lund 2022). For a complementary food aimed at reducing protein-energy malnutrition, this enhancement in protein bioavailability is as vital as the total protein concentration itself.

3.3 Optimum processing conditions

A multi-response numerical optimization was performed using DesignExpert® 13 (Stat-Ease, Inc., Minneapolis, USA) to identify the optimal extrusion parameters. Equal importance (weight = 3) was assigned to all response variables (bulk density, WAC, WSI, swelling power, and protein content), and optimization was performed within the experimental ranges of the input factors (barrel temperature and feed moisture content).

The desirability function selected a solution with a barrel temperature of 132.66 ºC and feed moisture content of 10%, achieving a desirability score of 0.681. Under these conditions, the predicted values for the key functional and nutritional properties were: bulk density 0.54 g/cm^3, water absorption capacity 39.33%, water solubility index 29.17%, protein content 31.37%, and swelling power 4.49 g/g. These optimized parameters balance product quality attributes critical for instant complementary porridge flours.

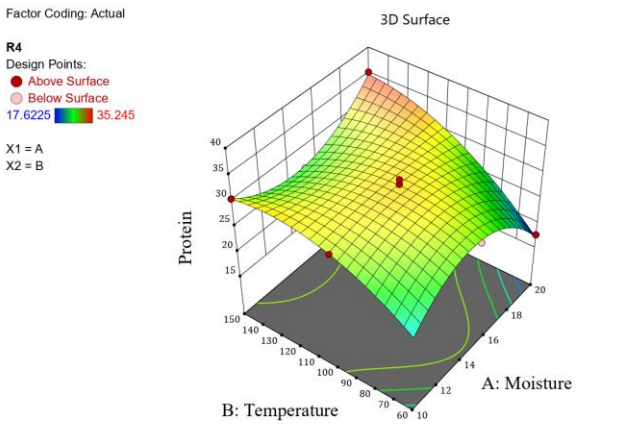

Fig. 5. Response surface plots for the effect of extrusion process parameters (Barrel temperature & Moisture content) on Protein Content of the Chickpea-Popcorn-Maize flour.

3.4 Validation of results

The suitability of the developed regression models for predicting the functional and nutritional properties of the extruded chickpea–popcorn–maize flour was evaluated by comparing predicted and experimental values (**Table 4**). The p-values from the one-sample t-test ranged from 0.029 to 0.068 across the five response variables. While some individual p-values fall below 0.05, the relative deviations between predicted and experimental values are below 4% indicating practical agreement between model predictions and experimental outcomes. This distinction between statistical significance and practical significance is important in model validation, as small absolute differences may reach statistical significance with precise measurements.

Although minor deviations were observed, with predicted values slightly differing from experimental measurements, these differences were small (relative deviations below 4%) and within acceptable experimental error margins. Such discrepancies may arise from inherent variations in physical parameters during processing, such as ambient humidity, temperature fluctuations, and slight differences in raw material properties or measurement precision.

Overall, the response surface models demonstrated adequate predictive capability across all key quality attributes, including protein content and functional properties critical for complementary food performance. The small relative deviations (<4%) between predicted and experimental values confirm that the optimization approach reliably captures the effects of extrusion parameters on product characteristics, providing a practical tool for guiding process adjustments to achieve desired product quality.

3.5 Pasting properties of the chickpea–popcorn-based porridge and a commercial control

The pasting properties of the optimized maize–popcorn–chickpea extruded porridge and the commercial control instant porridge are presented in **Table 5**. The optimized porridge exhibited significantly ($p \leq 0.05$) different pasting characteristics compared to the commercial soybean-based instant porridge. Peak viscosity was significantly ($p \leq 0.05$) lower in the optimized porridge (185 cP) compared to the commercial product (658 cP). This low peak viscosity is attributed to molecular and structural damage of starch granules during extrusion (Ilo and Berghofer 1999; Singh et al. 2007), where the severe thermal and mechanical shear conditions likely destroyed the crystalline regions of the starch, resulting in partial dextrinization and reduced swelling during RVA heating. Trough viscosity was significantly lower in the optimized porridge (90.5 cP) compared to the commercial control (589 cP), indicative of weaker paste strength. Breakdown viscosity was significantly higher in the optimized porridge (94.5 cP) than the commercial control (69 cP), reflecting greater susceptibility of the pre-gelatinized starch to shearing. Final viscosity was significantly lower in the optimized porridge (140 cP) compared to the commercial control (1239 cP), indicating lower re-association of starch polymers during cooling. Setback viscosity, a measure of the tendency of starch to retrograde, was also significantly ($p \leq 0.05$) lower in the optimized porridge (49.5 cP) compared to the commercial control (650 cP). The lower setback indicated limited amylose re-association, a feature typical of extruded flours in which starch fragmentation prevents the development of a continuous gel network. This is an attractive attribute in complementary foods because it results in less post-cooking thickening. Peak time was significantly ($p \leq 0.05$) shorter in the optimized porridge (2.299 min) compared to the commercial control (5.4 min), indicating faster hydration and swelling of the pre-gelatinized starch fractions. The higher pasting temperature in the optimized porridge (96.54 °C) compared to the commercial control (87.625 °C) indicated that the remaining ungelatinized starch or starch–lipid complexes would require temperatures close to boiling for complete hydration. From a nutritional functionality standpoint, the reduced viscosity profile of the optimized porridge is beneficial for infant feeding, because the lower viscosity allows more flour solids to be added while maintaining a drinkable consistency, resulting in a higher energy and nutrient density per unit volume. Such observations have also been made in other extruded composite flours for complementary feeding (Akande et al. 2017; Forsido et al. 2019). In general, the pasting behavior of the maize–popcorn–chickpea composite flour was greatly modified during extrusion to produce an instant flour which reconstitutes quickly, is less thickening, and has functional properties suitable for complementary feeding applications.

Table 4. Predicted and experimental values of the model

Response	Predicted Value	Experimental Value	p-value (t-test)	Deviation	Relative Deviation (%)	Prediction Error (%)
Protein content (%)	31.37	30.85 ± 0.42	0.068	−0.52	−1.67	−1.66
Bulk density (g/cm^3)	0.54	0.52 ± 0.01	0.031	−0.02	−3.85	−3.70
Water absorption capacity (g water/100 g dry flour)	39.33	38.70 ± 0.65	0.042	−0.63	−1.62	−1.60
Water solubility index (%)	29.17	28.95 ± 0.38	0.029	−0.22	−0.76	−0.75
Swelling power (g/g)	4.49	4.37 ± 0.11	0.039	−0.12	−2.74	−2.67

Note: p-values from the one-sample t-test are reported. p-values > 0.05 indicate no significant difference between predicted and experimental values at the 95% confidence level. While some individual p-values fall below 0.05, the relative deviations between predicted and experimental values are all below 4%, indicating practical agreement between the model predictions and experimental outcomes.

3.6 Sensory Evaluation of the Optimized Porridge

Consumer acceptability of the chickpea-popcorn instant porridge was compared with that of a commercial soybean-based instant porridge (Table 6), and mean acceptability scores of the optimized formulation on a 9-point hedonic scale were between 6.57 and 7.63, while those of the commercial control were between 7.03 and 7.97. No significant differences ($p > 0.05$) existed between the two porridges in terms of appearance, color, taste, mouthfeel, flavor, aftertaste, or overall acceptability, but the exception was aroma, for which the chickpea–popcorn porridge received significantly lower scores ($p \leq 0.05$) than the commercial control. Similar overall acceptability scores indicate that the utilization of roasted chickpea flour and popcorn did not result in a negative impact on consumer perception in general, and the smooth mouthfeel of the optimized porridge may be due to starch gelatinization and protein denaturation caused by extrusion, allowing for uniform hydration and cohesive paste formation during reconstitution. The lower aroma score could be due to volatile compounds originating from the whole-grain chickpea and popcorn, especially considering that the ingredients were not dehulled before processing, and legume-derived volatiles and thermal reaction products formed during extrusion could have led to the distinct aroma detected by the panelists. Nonetheless, although the aroma rating was slightly reduced, the overall acceptability of the chickpea–popcorn porridge was statistically comparable to that of the commercial product, meaning the optimized formulation may compete with market alternatives, while additionally contributing to improved nutritional functionality.

Table 5. Comparison of the pasting properties of the optimized maize–popcorn–chickpea extruded porridge and a commercial control instant porridge

Pasting properties	Optimized extruded porridge	Commercial Porridge
Peak viscosity (cP)	185^{b}±31.88	658^{a}±4.16
Trough I (cP)	90.5^{b}±6.24	589^{a}±1.39
Breakdown viscosity (cP)	94.5^{a}±25.64	69^{b}±2.772
Final viscosity (cP)	140^{b}±6.93	$1,239^{a}$±0.00
Setback (cP)	49.5^{b}±0.69	650^{a}±1.39
Peak time (min)	2.299^{b}±1.71	5.4^{a}±0.00
Pasting temperature (°C)	96.54^{a}±1.02	87.625^{b}±0.59

Values are means ± SD (n=3). Values in the same row with different superscripts are significantly ($p \leq 0.05$) different.

Table 6. Sensory properties of the optimized maize–popcorn–chickpea extruded porridge and a commercial control instant flour.

Attributes	Optimized porridge	Control
Appearance	7.633^{a}±1.15	7.067^{a}±1.23
Color	7.533^{a}±1.09	7.100^{a}±1.14
Aroma	6.567^{b}±1.19	7.967^{a}±1.55
Taste	7.433^{a}±0.97	7.533^{a}±1.04
Mouth feel	7.433^{a}±0.99	7.167^{a}±1.01
Flavor	7.267^{a}±1.04	7.433^{a}±1.01
After taste	7.333^{a}±1.13	7.033^{a}±1.03
Overall acceptance	7.567^{a}±0.94	7.500^{a}±0.86

Values show mean ± SD (n = 30) at 5%. Figures in the same row with the same superscript are not significantly different ($p > 0.05$).

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CONCLUSION

An instant maize–popcorn–chickpea composite porridge flour was developed and process-optimized by employing extrusion cooking technology. Barrel temperature and feed moisture significantly affected the major functional properties that are key determinants of reconstitution and texture, including bulk density, water absorption capacity (WAC), water solubility index (WSI), swelling power, and crude protein content. Response surface methodology was employed to establish the optimum conditions of 132.66 °C and 10% feed moisture, which resulted in bulk density of about 0.52 g/cm³, WAC ~38.7%, WSI ~28.95%, swelling power ~4.37 g/g, and protein content ~30.85% upon validation of the flour. The peak viscosity and final viscosities of the optimized composite were much lower, whereas the setback was significantly reduced when compared with a commercial soybean-based instant porridge, indicating minimal post-cooking thickening and suitability for preparing higher solids porridges that can deliver more nutrients per serving. Sensory evaluation showed high overall acceptability, which was comparable to the commercial control, but with aroma rated significantly lower. The envisioned pathway for this product is centralized production using extrusion technology, with the final instant flour distributed to households for reconstitution with hot water. Further studies should assess amino acid composition, true protein digestibility (e.g., PDCAAS or DIAAS), mineral bioavailability, and residual antinutritional factors to fully characterise the nutritional quality of the optimized flour. Additionally, future work should report all values on a dry-weight basis for improved comparability, assess viscosity measurement at solids levels commonly used by caregivers, and determine shelf-life stability under typical storage conditions.

CONFLICT OF INTEREST

All authors declare that they do not have any conflicts of interest that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

The data used to support the findings of this study are available upon reasonable request from the corresponding author.

AUTHORS' CONTRIBUTIONS

Mugabi R., conceived the research idea involved in conceptualization, experimental works, data analysis, study design, and manuscript writing; Logose N.P. and Nangobi P. were involved in the study design, experimental works, data collection, analysis and writing. All the authors read and approved the final manuscript.

ETHICS STATEMENT

The sensory evaluation study received approval from the Higher Degrees Committee of the School of Food Technology, Nutrition and Bioengineering, Makerere University. All participants provided informed consent prior to participation, and involvement was entirely voluntary.

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