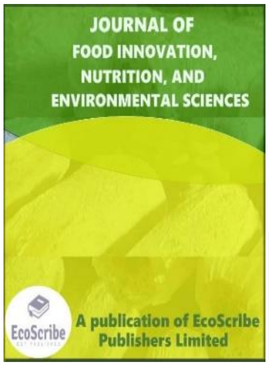

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ORIGINAL RESEARCH ARTICLE

Optimization of Ingredient Levels for Gluten-Free Instant Noodles from Red Sorghum Flour Using Response Surface Methodology

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ABSTRACT

Gluten-free instant noodles produced from 100% red sorghum (*Sorghum bicolor*) flour require specific additives to compensate for the structural absence of wheat gluten. This study employed Response Surface Methodology (RSM) with a four-factor, three-level Central Composite Rotatable Design (CCD) across 25 runs to optimize the levels of starch, xanthan gum, glycerol monostearate (GMS), and carboxymethylcellulose (CMC). The goal was to enhance cooking quality and consumer acceptability. The independent variables included starch (65–110 g/100 g sorghum flour), xanthan gum (5–20 g/100 g sorghum flour), GMS (5–15 g/100 g sorghum flour), and CMC (2–10 g/100 g sorghum flour). All ingredient levels are expressed on a flour-weight basis (baker's percentage). Measured responses focused on cooking loss, cooking time, water absorption capacity, moisture content, sensory texture, and overall acceptability. Statistical analysis revealed that xanthan gum significantly increased cooking loss ($p<0.05$), shortened cooking time ($p<0.001$), and increased water absorption ($p<0.01$). GMS reduced moisture content ($p<0.01$) and improved sensory texture ($p<0.001$). All tested hydrocolloids and emulsifiers positively impacted overall acceptability ($p<0.01$). The optimal formulation was determined to be 69.46 g/100 g flour starch, 16.48 g/100 g flour xanthan gum, 10.19 g/100 g flour GMS, and 10.00 g/100 g flour CMC, yielding a desirability score of 0.79. Model-predicted values for this blend included a 2.09% cooking loss, 3.00-minute cooking time, and high sensory scores (6.97 for texture; 6.95 for overall acceptability). Experimental validation of the optimized formulation using three independent batches confirmed good agreement between predicted and observed values, with all responses falling within the 95% prediction intervals. These results suggest that optimized 100% red sorghum noodles show promise for achieving cooking quality and consumer acceptance approaching that of wheat-based instant noodles, although direct comparative validation with a wheat-based control is needed in future studies.

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1. INTRODUCTION

Instant noodles have become a major global food product due to their convenience, affordability, and flavor diversity (Akajiaku et al., 2017). Consumption has increased sharply over recent decades, driven by urbanization and changing lifestyles (Park et al., 2011). Industrial instant noodles are classified into two categories based on drying method: fried noodles (moisture content 2–5%) and hot-air dried noodles (moisture content 8–12%) (Obadi et al., 2021). Regardless of processing method, cooking time, cooking loss, and texture retention are the primary quality attributes determining consumer acceptance.

To meet evolving consumer demands for improved nutrition and eating quality, various functional additives are incorporated into noodle formulations (Li et al., 2014). These include antioxidants for color stabilization, protein sources for gluten fortification or replacement, and emulsifiers for surface property enhancement. Hydrocolloids and phosphates are particularly important for modifying dough rheology, improving water absorption, and reducing cooking loss (Ahmed et al., 2016; Gasparre & Rosell, 2019). Additionally, ingredients such as dietary fiber, legume flours, and nutraceutical compounds have been used to develop health-promoting or functionally enhanced noodle products (Bustos et al., 2011; Krishnan & Prabhasankar, 2012).

Although wheat flour remains the dominant raw material for noodle production globally, there is growing interest in utilizing indigenous cereals such as sorghum (*Sorghum bicolor*), particularly in wheat-importing countries. Sorghum is rich in phenolic compounds with demonstrated antioxidant, anti-inflammatory, and anti-diabetic properties (Xu et al., 2021), and offers nutritional advantages and potential to reduce reliance on wheat imports, thereby conserving foreign exchange (Akajiaku et al., 2017). From a health perspective, sorghum-based noodles are naturally gluten-free, making them suitable for consumers with celiac disease or gluten intolerance (Palavecino et al., 2020). However, eliminating wheat flour also removes the gluten network that provides structural integrity, potentially resulting in weak textural properties if not adequately compensated.

Several factors influence the quality of gluten-free sorghum noodles. Kernel size, flour particle size, and starch gelatinization degree during cooking are the major factors affecting non-wheat noodle quality (Liu et al., 2012). Blending sorghum and wheat flours, for example in a 50:50 ratio, can improve the physicochemical properties of noodle dough (Anggreini et al., 2018); however, sorghum starch properties depend on the variety and the interaction with added structural improvers (Beta & Corke, 2001). In gluten-free products, the combination of hydrocolloids, such as xanthan gum and carboxymethylcellulose, and emulsifiers, such as GMS, can be used to improve the structure, but their synergistic effects in noodles made entirely from sorghum flour have not been reported. Recent studies showed that sorghum flour can be used to produce gluten-free pasta with acceptable cooking quality and sensory characteristics when appropriate structural improvers are used (Cervini et al., 2021; Oliveira et al., 2022); however, there is limited information on how to optimise the starch level, hydrocolloids, and emulsifiers to achieve textures similar to wheat noodles. Most previous studies focused on individual factors or two factors at most, leaving a knowledge gap in understanding the interactions of these components in sorghum-based formulations. This study is the first to simultaneously optimize starch, xanthan gum, GMS, and CMC in a 100% sorghum flour noodle system using RSM, addressing the gap left by prior single- or two-factor investigations. Response surface methodology (RSM) was used to model these effects and to determine the ingredient levels that would maintain low cooking loss and cooking time, while increasing water absorption and consumer acceptability.

2. MATERIALS AND METHODS

2.1 Raw materials and flour preparation

Red sorghum grains (*Sorghum bicolor* (L.) Moench, variety NASARRI-M060) were obtained from the National Semi-Arid Resources Research Institute (NaSARRI), Serere, Uganda, and this variety was selected after preliminary screening of five local sorghum varieties because it was found to produce the best noodle cooking quality, texture, and sensory acceptability. Food-grade corn starch (≥99% purity), xanthan gum (E415), glycerol monostearate (GMS, E471), and sodium carboxymethylcellulose (CMC, E466; degree of substitution 0.7–0.9) were obtained from certified ingredient suppliers in Kampala, Uganda, and were used as received. All non-sorghum ingredients were food-grade commercial materials used as received for formulation optimization purposes. Milk powder (full-cream, spray-dried), margarine (80% fat), fresh eggs (grade A), sodium bicarbonate, sodium chloride, and spices were obtained from local markets, while all reagents used for analysis were of analytical grade (≥99% purity) and were used without further purification.

2.2 Sorghum flour preparation

Preparation of sorghum flour involved cleaning dried sorghum grains to remove extraneous material and visibly damaged kernels, and then the cleaned grain was milled in a disc mill (Staunch, Lebanon) fitted with a 0.5 mm (500 μm) screen. The fine flour was vacuum-sealed in polyethylene bags and stored at room temperature (25 ± 2 °C) until further use.

2.3 Experimental design and optimization

Response Surface Methodology (RSM) was applied to optimize the noodle formulation. A 4-factor, 3-level central composite rotatable design (CCRD) with four independent variables, namely starch (X_1), xanthan gum (X_2), GMS (X_3), and CMC (X_4), was developed based on preliminary trials and published literature. The design consisted of 16 factorial points (2^4), 8 axial points (2 × 4, α = 2.0), and 1 center point replicated 7 times, yielding a total of 25 experimental runs. All independent variable levels are expressed on a flour-weight basis (g per 100 g sorghum flour), which is a standard convention in cereal science formulation studies (baker's percentage). The design was generated using Design-Expert software (version 13.0, Stat-Ease Inc., Minneapolis, MN, USA), and the same software was used for response surface modeling and optimization. Response variables were: cooking loss (Y_1), cooking time (Y_2), water absorption capacity (Y_3), moisture content (Y_4), sensory texture (Y_5), and overall acceptability (Y_6) determined for each run. The experimental data were then fitted to a second-order polynomial regression model.

$$Y = \beta_0 + \sum_{i=1}^{4} \beta_i X_i + \sum_{i=1}^{4} \beta_{ii} X_i^2 + \sum_{i<j}^{4} \beta_{ij} X_i X_j + \varepsilon$$

Where Y is the predicted response; β_0 is the intercept; β_i, β_{ii}, and β_{ij} are the linear, quadratic, and interaction coefficients, respectively; and X_i, X_j are the coded independent variables.

Table 1. Independent variables and their coded levels for the CCRD (all levels expressed as g/100 g sorghum flour

Independent variables	**Symbol**	**Coded values**		
		-1	0	+1
Starch	X_1	65	87.5	110
Xanthan	X_2	5	12.5	20
Glyceryl	X_3	5	10	15
CMC	X_4	2	6	10

2.4 Noodle preparation and processing

The preparation of the noodles was based on the method of Pakhare et al. (2016) with some modifications. The base dry mix for 100 g of sorghum flour contained sorghum flour (76 g), sodium chloride (2 g), sodium bicarbonate (4 g), white pepper powder (2 g), garlic powder (6 g), and chicken seasoning (4 g), and the amounts of starch, xanthan gum, GMS, and CMC according to the design (Table 2) were added to the base and mixed in a planetary mixer (KitchenAid K45SS, USA) at low speed (60 rpm) for 5 min to get a uniform distribution of the ingredients. The independent variable levels in Table 2 are expressed on a flour-weight basis (g/100 g sorghum flour). For example, in a run with xanthan gum at 20 g/100 g flour, the actual xanthan gum mass in the total dough (~476 g dry + 300 mL liquid) is approximately 15.2 g, corresponding to ~2.0% of total dough weight. The liquid phase was prepared by dissolving the milk powder (45 g) in hot water (120 mL, 80 ± 2 ºC) with continuous stirring, and then the melted margarine (39 g) at 40 ºC and beaten whole egg (150 g, approximately three large eggs) were added and mixed until uniform. The liquid mixture (about 300 mL in total) was then added slowly into the dry ingredients over about 2 min at low speed (60 rpm) while mixing, and the dough was then kneaded at medium speed (120 rpm) for 10 min until the dough was smooth and free of visible lumps. The dough was then passed through a manual roller to a thickness of about 2 mm and rested for 40 min at room temperature (25 ± 2 °C) covered with polyethylene film to prevent drying and to further hydrate the starch, and then the sheets were cut into noodles using a mechanical pasta machine (Model PM-100, China) with 2 mm × 2 mm cutting dies, resulting in strands of 20 ± 2 cm length, 2.0 ± 0.2 mm width, and 1.8 ± 0.2 mm thickness.

2.5 Dehydration and storage

Fresh noodle strands were arranged in a single layer on perforated plastic trays (40 cm × 30 cm) without overlapping to ensure uniform air circulation. Drying was performed in a forced-air convection dehydrator (Model NL-FD-4935, Saachi, China) at 65 ºC for 3 h with an air velocity of 1.5 m/s. The mean final moisture content of dried noodles across all 25 experimental runs was 8.2 ± 1.5% (w/w). Dried noodles were cooled to ambient temperature (22 ± 2 ºC) in a desiccator for 30 min, then packaged in heat-sealed aluminum laminate bags in 100 g portions. Packaged samples were stored in a desiccator at ambient temperature (22 ± 2 °C) until analysis. All quality evaluations were completed within 7 days of production to minimize storage effects.

2.6 Determination of cooking quality

2.6.1. Optimal cooking time

Optimal cooking time (OCT) was determined according to AACC International Method 66-50.01 (AACC, 2000). Dried noodles (25 g) were immersed in vigorously boiling distilled water (300 mL) in a 500 mL beaker maintained at constant boiling temperature using a hot plate. At 30 s intervals beginning at 2 min, a single strand was removed, rinsed with cold water, and compressed between two glass micro- 6 scope slides. The OCT was recorded as the time required for the opaque white core at the center of the strand to disappear completely, indicating full starch gelatinization. Determinations were performed in triplicate, and the mean value was used for subsequent cooking quality tests.

Table 2. Central composite design matrix with estimated values of responses

Run	Processing parameters				Measured responses					
	Starch (%)	Xanthan (%)	Glyceryl (%)	CMC (%)	Cooking Loss (%)	Cooking Time (min)	WAC (%)	Moisture (%)	Texture (sensory score)	Consumer acceptability
1	65	5	5	2	1.23±0.14	3.33±0.58	121.61±5.61	9.83±0.09	6.2±1.01	6±1.03
2	65	5	5	10	1.56±0.16	3.33±0.58	184.61±18.26	9.86±0.25	5.35±1.23	4.75±1.21
3	65	5	15	2	1.34±0.04	3.0±0.0	138.0±7.07	8.70±0.32	6.65±1.50	6.8±1.36
4	65	5	15	10	1.62±0.34	3.0±0.0	131.65±4.76	8.65±0.43	5.65±1.46	5.55±1.10
5	65	20	5	2	1.86±0.64	3.0±0.0	177.85±10.36	9.42±0.18	5.85±1.42	6.0±1.41
6	65	20	5	10	2.55±0.35	3.0±0.0	169.37±18.06	9.04±0.21	5.65±1.23	5.75±1.07
7	65	20	15	2	2.26±0.17	3.0±0.0	199.60±5.16	8.23±0.29	5.75±1.45	5.75±1.21
8	65	20	15	10	2.11±0.30	3.0±0.0	143.79±21.45	8.76±0.03	4.2±0.89	4.05±1.05
9	110	5	5	2	1.88±0.47	3.67±0.58	146.27±14.09	8.75±0.42	5.35±1.53	5.1±1.41
10	110	5	5	10	1.47±0.61	3.67±0.58	131.04±5.11	9.81±0.29	6.7±0.73	6.4±0.88
11	110	5	15	2	1.67±0.38	3.0±0.0	141.95±21.91	8.40±0.04	7.0±1.03	8.0±1.18
12	110	5	15	10	1.38±0.17	3.33±0.58	110.29±11.28	8.36±2.06	4.65±1.35	4.95±1.15
13	110	20	5	2	1.85±0.67	3.67±0.58	183.40±9.55	10.71±0.33	6.45±1.10	6.3±1.08
14	110	20	5	10	1.49±0.55	3.0±0.0	153.20±6.82	9.40±0.27	6.7±1.34	6.4±1.10
15	110	20	15	2	1.43±0.13	3.33±0.58	167.94±14.55	8.43±0.32	6.1±1.37	6.2±1.32
16	110	20	15	10	1.65±0.29	3.0±0.0	155.75±4.76	8.20±0.60	5.15±1.39	5.65±1.27
17	65	13	10	6	2.53±0.10	3.33±0.58	151.20±15.53	8.90±0.67	5.05±1.28	5.0±1.03
18	110	13	10	6	1.98±0.37	3.33±0.58	156.81±13.47	8.20±0.84	6.3±1.13	6.4±1.64
19	88	5	10	6	1.76±0.86	3.0±0.0	132.96±7.00	8.68±0.77	5.15±1.09	5.05±1.28
20	88	20	10	6	1.58±0.54	3.0±0.0	152.73±22.38	9.55±0.56	6.7±1.30	6.9±1.25
21	88	13	5	6	1.53±0.40	3.0±0.0	122.72±15.10	8.02±0.40	6.2±1.40	6.5±1.05
22	88	13	15	6	1.52±0.07	3.0±0.0	122.39±30.24	7.64±0.46	5.5±1.61	5.7±1.38
23	88	13	10	2	1.48±0.16	3.0±0.0	161.28±4.68	6.94±0.18	6.75±1.21	6.9±1.02
24	88	13	10	10	1.36±0.26	3.0±0.0	175.60±7.83	7.03±0.19	6.2±1.58	6.4±1.54
25	88	13	10	6	1.19±0.07	3.0±0.0	155.72±7.41	6.97±0.11	5.3±1.89	5.7±1.74

Cooking quality values are mean ± SD of three independent determinations. Sensory scores (texture and overall acceptability) are mean ± SD (n = 30 semi-trained panelists)

The dish containing dried residue was cooled in a desiccator and weighed (W_1). Cooking loss was calculated as:

$$\text{Cooking loss (\%)} = \frac{W_{residue}}{W_{sample}} \times 100$$

where $W_{residue}$ is the weight of the dried solids recovered from the cooking water, and W_{sample} is the dry weight of the noodle sample before cooking.

2.6.3 Water absorption capacity (WAC)

The WAC of the noodles was determined as the weight gain after cooking, and twenty-five grams of the noodles were cooked to their OCT, rinsed with cold distilled water, and drained for 30 s on a mesh screen. The WAC of the noodles was calculated as follows:

$$WAC\ (\%) = [\frac{(W_{cooked} - W_{uncooked})\ /}{W_{uncooked}}] \times 100$$

where W_{cooked} is the weight of cooked and drained noodles, and $W_{uncooked}$ is the weight of uncooked noodles.

2.7 Moisture content analysis

Moisture content was determined gravimetrically according to AOAC Method 925.10 (AOAC International, 2005), and 3 g of ground noodle sample was weighed into a pre-dried aluminum dish of known constant weight. The samples were dried in a hot-air oven at 105°C for 3 h, then cooled in a desiccator to room temperature and reweighed, and the weight loss was calculated as moisture content. All measurements were performed in triplicate, according to the following equation:

$$\text{Moisture (\%)} = \frac{W_1 - W_2}{W_1} X100$$

where W_1 is the sample weight before drying, and W_2 is the sample weight after drying.

2.8 Consumer acceptability and sensory evaluation

The study protocol for the consumer acceptability and sensory evaluation of the gluten-free sorghum noodles was reviewed and approved by the Research and Higher Degrees Committee of the School of Food Technology, Nutrition, and Bioengineering, Makerere University. Before participation, all panelists were briefed on the nature of the study and required to sign an informed consent form, affirming their voluntary participation and lack of known allergies to the ingredients used. Sensory evaluation was conducted to assess the consumer acceptability of the developed products using a semi-trained panel of 30 students and staff from the Department of Food Technology and Nutrition. Panelists were recruited based on their familiarity with and frequent consumption of noodle products to ensure informed feedback.

For the evaluation, 50 g portions of each noodle sample were prepared according to their predetermined optimum cooking times and served warm in coded plastic containers. To minimize order-related bias, sample presentation was randomized using a balanced complete block design. Panelists evaluated the samples using a 9-point hedonic scale, ranging from 1 ('dislike extremely') to 9 ('like extremely'), with a mean score of 5.0 established as the threshold for minimum commercial acceptability. Drinking water was provided for panelists to rinse their mouths between samples to prevent flavor carryover and ensure palate cleansing.

2.9 Statistical analysis

All experimental data were analyzed and interpreted using standard statistical methods. Response surface modeling and optimization were carried out using Design-Expert version 13.0 (Stat-Ease Inc., Minneapolis, MN, USA). RSM was used for regression model fitting, coefficient estimation, and multi-response optimization. The results were expressed as mean ± standard deviation of three independent measurements, and differences among the experimental runs were compared using one-way analysis of variance (ANOVA) and the means were separated using Duncan's Multiple Range Test (DMRT) using SPSS version 26.0 (IBM Corp., Armonk, NY, USA). One-way ANOVA with DMRT was used as a complementary analysis to compare mean responses across individual experimental runs and to identify statistically distinguishable groups, providing additional information about run-to-run variability not captured by the regression models alone. Differences were considered statistically significant at $p < 0.05$. The suitability of the fitted response surface models was checked using the coefficient of determination (R^2), adjusted R^2, and the lack-of-fit test to confirm that the models adequately described the experimental data. For individual model term screening within the RSM framework, a threshold of $p < 0.10$ was used following established RSM practice (Myers et al., 2016), as this helps retain potentially important terms in exploratory optimization. However, model-level significance was assessed at the conventional $p < 0.05$ threshold, and marginal models ($0.05 < p < 0.10$) are explicitly identified as such in the results.

3. RESULTS AND DISCUSSION

3.1 Regression model analysis for cooking quality and consumer acceptability

The response surface methodology (RSM) was used to optimize the formulation of the noodle based on the effects of the four variables, i.e., starch (X_1), xanthan gum (X_2), GMS (X_3) and carboxymethyl cellulose (X_4) on both cooking quality and sensory properties, and the coefficients of regression and overall model statistics and their corresponding significance levels are given in Table 3.

The models for cooking time, moisture content, texture, and overall acceptability had good predictive power ($R^2 = 0.85$–0.93) and were statistically significant ($p < 0.05$). The models for cooking loss and water absorption capacity had a moderate fit ($R^2 = 0.78$) and were marginally significant ($p = 0.0726$ and $p = 0.0752$, respectively), suggesting that additional factors not controlled in the present study may influence these responses. Results from these two marginal models should be interpreted with caution.

Table 3. Regression coefficients and statistical parameters for cooking quality and consumer acceptability models

Model	**Cooking loss**	**Cooking time**	**Water abs capacity**	**Moisture content**	**Texture**	**Overall acceptability**
Intercept	+1.61***	+3.04**	+145.92***	+7.65**	+5.63*	+5.81*
X_1-Starch	-0.12***	+0.11*	-3.96	-0.06	-0.002	+0.07
X_2-Xanthan	+0.16**	-0.07***	+14.72*	+0.03	+0.50*	+0.58*
X_3-Glyceryl	-0.025	-0.11*	-4.38	-0.53*	+0.15***	+0.18**
X_4-CMC	+0.01	-0.03	-4.53	-0.01	+0.16***	+0.20**
X_1X_2	-0.19**	-0.0007	+1.05	+0.19	-0.08	-0.19**
X_1X_3	-0.043	-0.04	+0.15	-0.09	-0.10	-0.192**
X_1X_4	-0.12***	-0.042	-5.06	-0.04	-0.26**	-0.17**
X_2X_3	-0.0098	+0.08**	+2.83	-0.05	-0.28**	-0.26*
X_2X_4	+0.031	-0.083**	-7.16	-0.15	-0.17***	-0.17**
X_3X_4	-0.012	+0.042	-7.21	+0.05	+0.12	+0.03
X_1^2	+0.56*	+0.230*	+8.59	+0.78**	+0.85*	+0.73*
X_2^2	-0.015	-0.045	-1.51	+1.35*	-0.37	-0.46**
X_3^2	-0.417	-0.04	-22.77***	+0.057	-0.48***	-0.39***
X_4^2	-0.27	-0.04	+23.11**	-0.79**	+0.30	+0.21
Model Statistics						
R^2	0.78	0.85	0.78	0.86	0.90	0.93
Adjusted R^2	0.47	0.63	0.47	0.66	0.75	0.84
C.V%	15.67	4.59	10.89	6.34	6.19	5.03
p-value	0.0726	0.018	0.0752	0.0126	0.0032	0.0004

* Marginally significant at $p < 0.10$ (used for exploratory term screening in RSM following Myers et al., 2016); ** significant at $p < 0.05$; *** significant at $p < 0.01$. Note: A relaxed threshold of $p < 0.10$ is used for individual term screening to retain potentially important factors in the exploratory optimization framework. Model-level significance is assessed at $p < 0.05$; models with $0.05 < p < 0.10$ are reported as marginally significant.

3.2 Cooking quality parameters

3.2.1 Cooking Loss

Cooking loss is associated with the physical strength of the noodles during hydrothermal processing, and it was in the range of 1.19–2.55% for all formulations (Table 2). The quadratic model ($R^2 = 0.78$, $p = 0.0726$) was marginally significant for this response, and results should therefore be interpreted with caution given the exploratory nature of this model. Starch was the only variable that affected this response because the linear term of the starch (X_1, $p < 0.01$) had a negative effect, and the quadratic term (X_1^2, $p < 0.1$) had a positive effect on this response. Consequently, the non-linear effect implied that there may be an optimal level of starch; cooking loss decreased with the increase in starch content to some extent, and then increased with higher starch content, possibly because the hydrocolloid network was diluted or disrupted at higher starch concentration (Li et al., 2014).

Significant interaction effects were found between starch and xanthan gum (X_1X_2, $p < 0.05$) and starch and CMC (X_1X_4, $p < 0.01$), both with negative coefficients, which indicates a synergistic effect. The presence of hydrocolloids results in a reinforcement of the noodle structure and a reduction in the solid leaching during cooking, and indeed, as can be seen in the response surface plot (Figure 1), the presence of xanthan gum produces a decrease in the cooking loss at intermediate levels of starch, due to the well-known binding and network-forming capacity of the hydrocolloids in gluten-free systems (Palavecino et al., 2017; Kraithong & Rawdkuen, 2020). The cooking loss values were below the

8% limit for good pasta quality (Teterycz et al., 2020) in all formulations, and far lower than that reported for sorghum-based pasta (7.41–10.12%, Benhur et al., 2015), which can be attributed to the optimization of the hydrocolloid levels to increase the water binding and the structural integrity of the noodle, the possible formation of amylose-lipid complexes with GMS, which limits the solubilization of starch (Pili et al., 2013), and the relatively short cooking times, which limit the time during which the starch can leach into the cooking water. alone.

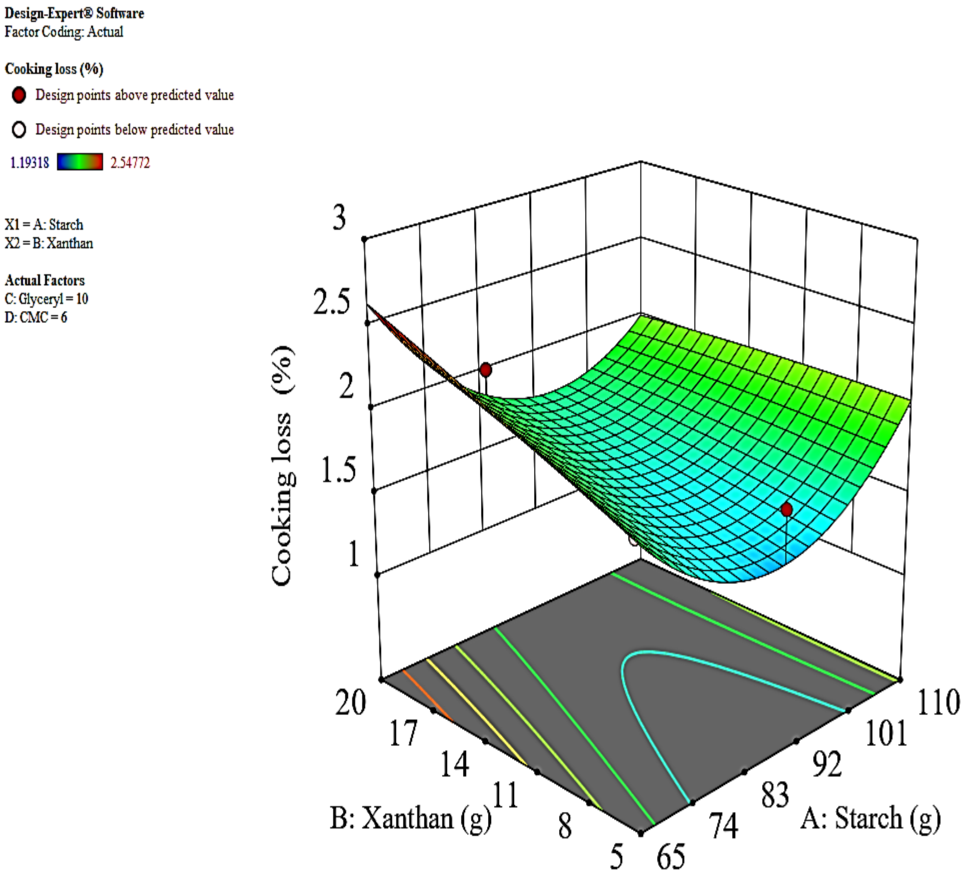

Fig. 1. Response surface plot showing interactive effects of starch (X_1) and xanthan gum (X_2) on cooking loss, with GMS (X_3) and CMC (X_4) held constant at their center-point values (10 g/100 g flour and 6 g/100 g flour, respectively)

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3.2.2 Cooking time

Cooking times for the noodle samples varied from 3.00 to 3.67 min across the formulations used, and the quadratic regression model demonstrated a high predictive capacity ($R^2 = 0.85$, $p = 0.018$). Cooking time was significantly influenced by the amount of starch used, and the linear (X_1, $p < 0.1$) and quadratic (X_1^2, $p < 0.05$) terms related to starch amount showed significance. An increase in starch content led to longer cooking times, which may be explained by the higher number of starch granules to be completely gelatinized. Xanthan gum negatively affected cooking times (X_2, $p < 0.01$) and is expected to shorten the time required for noodles' cooking because this ingredient might have facilitated water penetration into the noodles; nevertheless, its interactions with GMS (X_2X_3, $p < 0.05$) and CMC (X_2X_4, $p < 0.05$) complicated this process: xanthan-GMS interaction increased cooking time, whereas xanthan-CMC interaction decreased it. Consequently, the cooking times obtained were within the commercially accepted range (2.82–4.00 min; Koh et al., 2022) and significantly lower than those observed for conventional wheat pasta.

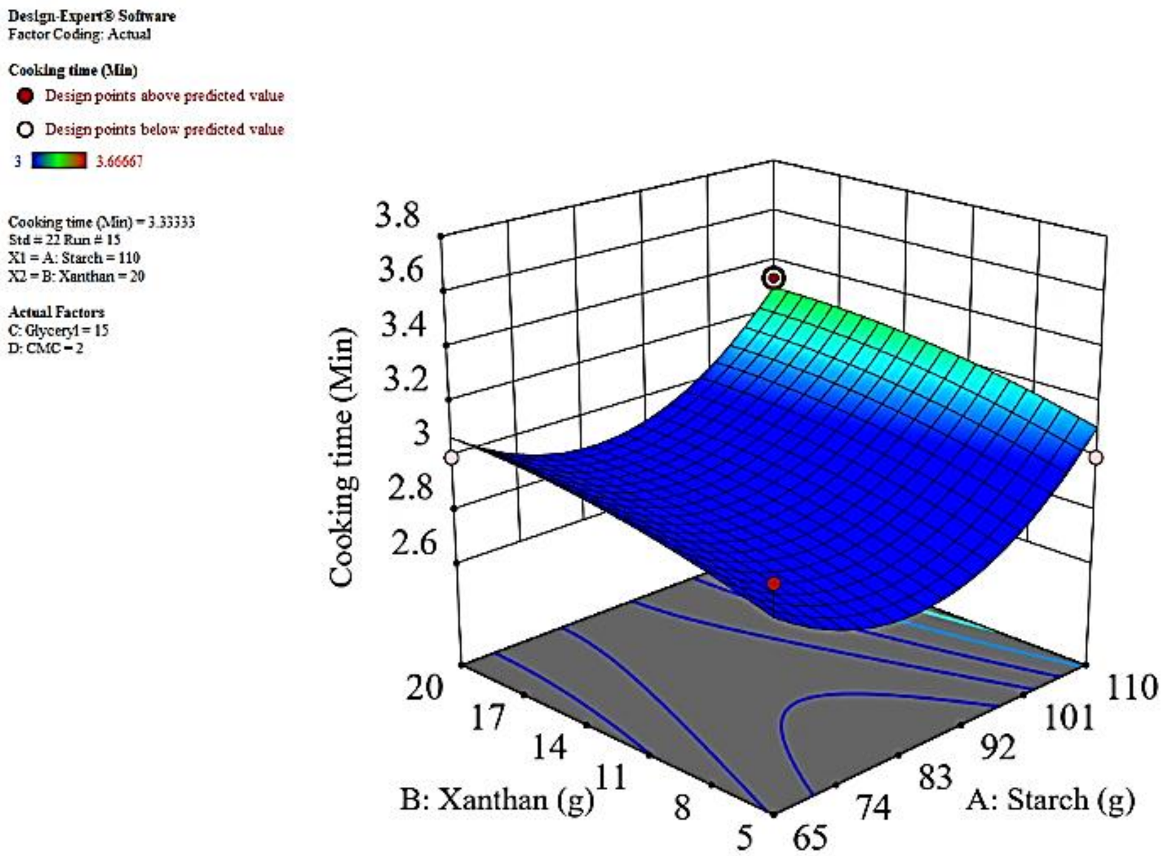

Fig. 2. Response surface plot showing the combined effects of starch (X_1, 65–110 g/100 g sorghum flour) and xanthan gum (X_2, 5–20 g/100 g sorghum flour) on the optimal cooking time (min) of gluten-free red sorghum instant noodles. Glycerol monostearate (X_3) and CMC (X_4) were held constant at their center-point values of 10.0 and 6.0 g/100 g sorghum flour, respectively

3.2.3 Water absorption capacity

The water absorption capacity varied between 110.29 and 199.60%, and the fitted quadratic model was marginally significant ($R^2 = 0.78$, $p = 0.0752$); therefore, these results should be interpreted with appropriate caution. Xanthan gum (X_2) exerted a positive main effect ($p < 0.1$) on the response due to its high water-binding capacity arising from interactions with the outer chains of amylopectin (Srikaeo et al., 2018; Gasparre & Rosell, 2019). Similarly, Raungrusmee et al. (2020) reported that increasing xanthan gum concentration significantly enhanced the tensile strength and functional properties of gluten-free noodles. The quadratic term for CMC (X_4^2, $p < 0.05$) had a positive effect on water absorption, while the quadratic term for GMS (X_3^2) had a significant negative effect ($p < 0.01$), indicating that there is an optimum level of the lipid-based emulsifier, and above that level it might form hydrophobic barriers that limit water penetration into the noodle matrix. formulations.

3.2.4 Moisture content

The moisture content of the samples varied between 6.94% and 10.71% (Table 2) and the fitted quadratic model showed a satisfactory fit ($R^2 = 0.86$, $p = 0.0126$). GMS had the highest influence as both the linear (X_3, $p < 0.1$) and the quadratic (X_3^2, $p < 0.01$) terms were significantly negative since it contains amphiphilic properties leading to formation of amylose-lipid inclusion complexes, limiting the number of free hydroxyl groups and binding at starch-water interfaces where it acts as hydrophobic barriers reducing water retention (De Pilli et al., 2012; Kaur & Singh, 2000). Xanthan gum (X_2, $p < 0.1$) had a positive linear term due to its capability to absorb water through hydrogen bonds (Gasparre & Rosell, 2019). The quadratic term (X_1^2, $p < 0.05$) for starch had a positive contribution since water binds inside gelatinized granules, whereas the quadratic term (X_4^2, $p < 0.05$) for CMC had a negative contribution, probably caused by phase separation (Mohammadi et al., 2014).

The lack of interaction terms indicates that moisture content is mainly influenced by additive terms. The surface plot (Figure 4) shows an extensive plateau region for intermediate values of moisture content (~8.0-9.0%), suggesting that the formulation is robust concerning moisture retention with slight fluctuations in starch and xanthan gum concentrations. Moisture values obtained lie within the target range of industry specifications for hot air-dried instant noodles (8-12%, Obadi et al., 2021) for balancing the microorganism stability during storage and rehydration performance. The center point moisture (~7.0-8.9%) content was similar to moisture values in sorghum-wheat composite noodles (8.0-9.5%, Akajiaku et al., 2017) and 100% rice flour gluten-free noodles (7.8-9.2%, Cervini et al., 2021) suggesting successful moisture regulation despite the use of 100% sorghum flour. For practical formulations, moisture content can be successfully controlled using GMS (decrease moisture) or xanthan gum (increase moisture).

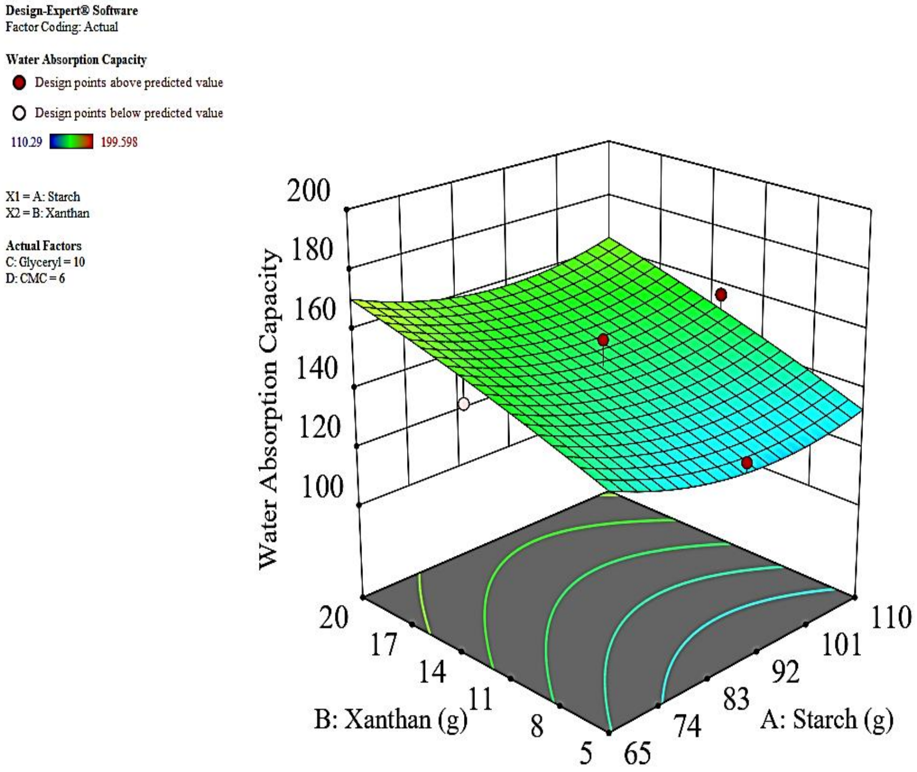

Fig. 3. Response surface plot showing the effect of xanthan gum (X_2) concentration on water absorption capacity, with starch (X_1) held at center-point value (87.5 g/100 g flour), GMS (X_3) at 10 g/100 g flour, and CMC (X_4) at 6 g/100 g flour.

3.3 Consumer acceptability

3.3.1 Texture

Sensory texture scores, evaluated using a 9-point hedonic scale by 30 semi-trained panelists, ranged from 4.2 to 7.0. The model demonstrated excellent predictive capability ($R^2 = 0.90$, $p = 0.0032$). Both xanthan gum (X_2, $p < 0.1$) and its quadratic term (X_1^2, $p < 0.1$) positively influenced texture scores, as did GMS (X_3, $p < 0.01$) and CMC (X_4, $p < 0.01$). However, significant negative interactions were observed for starch-CMC (X_1X_4, $p < 0.05$), xanthan-GMS (X_2X_3, $p < 0.05$), xanthan-CMC (X_2X_4, $p < 0.01$), and the GMS quadratic term (X_3^2, $p < 0.01$).

The positive effect of xanthan gum aligns with its demonstrated ability to enhance firmness in gluten-free systems (Gasparre & Rosell, 2019), while CMC and xanthan have been widely reported as effective texture improvers (Mohammadi et al., 2014; Lubowa et al., 2024). The response surface plot **(Figure 5)** shows that texture scores increased with moderate levels of both xanthan and starch, consistent with the formation of structured networks through hydrocolloid-starch interactions.

Texture development in gluten-free noodles depends critically on starch gelatinization and retrogradation dynamics during cooking and cooling (Marti et al., 2010). The observed sensory texture scores may reflect varying degrees of amylose retrogradation, with higher scores indicating greater perceived firmness associated with network formation (Devesa & Anaya, 2003). The interaction between water, starch, protein, and hydrocolloid additives ultimately determines textural quality, a parameter strongly correlated with overall consumer acceptance in noodle products (Yu, 2003; Gull et al., 2015).

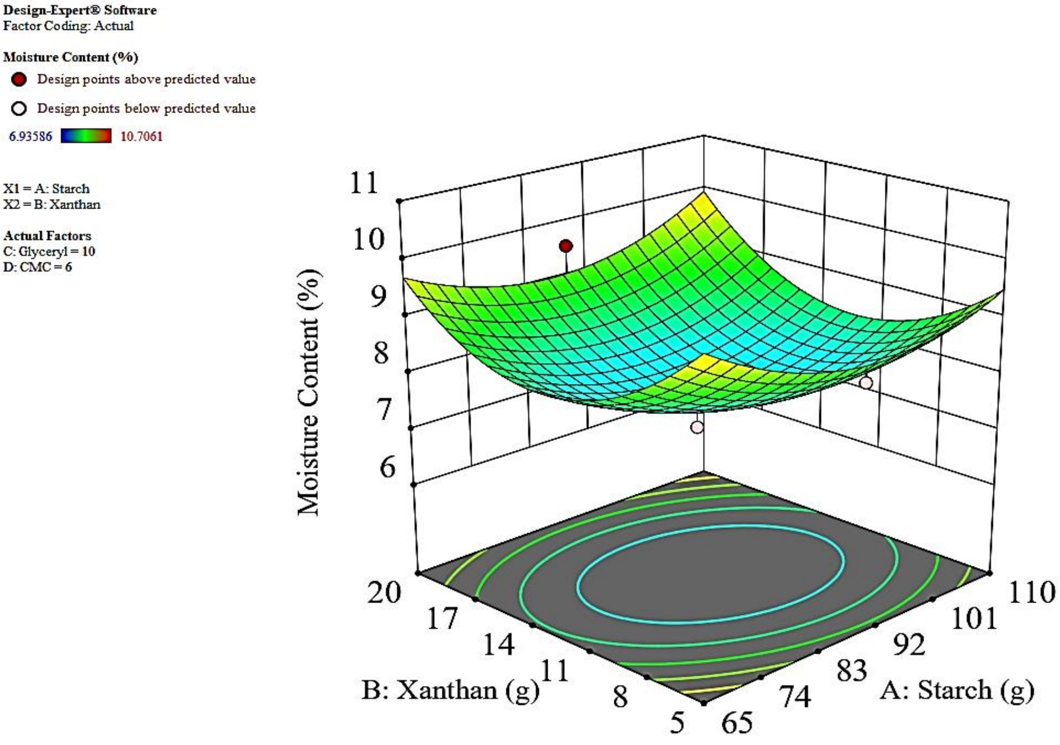

Fig. 4. Response surface plot illustrating the moisture content (%) of cooked gluten-free red sorghum instant noodles as a function of starch (X_1, 65–110 g/100 g sorghum flour) and xanthan gum (X_2, 5–20 g/100 g sorghum flour). Glycerol monostearate (X_3) and CMC (X_4) were held constant at their center-point values of 10.0 and 6.0 g/100 g sorghum flour, respectively.

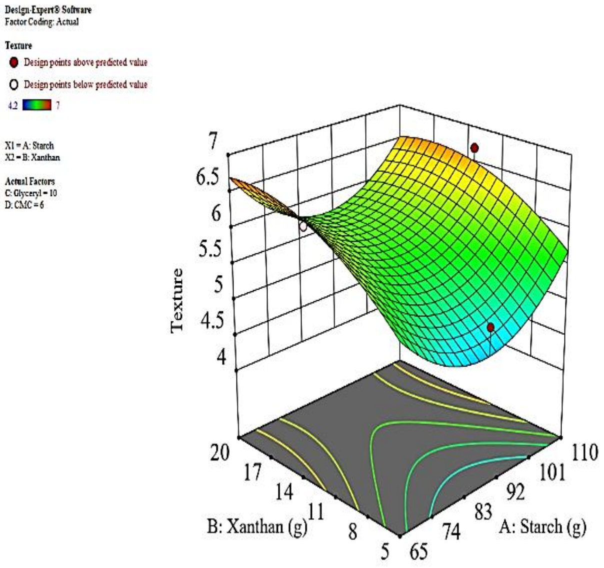

Fig.5.Response surface plot showing sensory texture scores (9-point hedonic scale, 1 = 'dislike extremely' to 9 = 'like extremely'; n = 30 semi-trained panelists) of gluten-free red sorghum instant noodles as influenced by starch (X_1, 65–110 g/100 g sorghum flour) and xanthan gum (X_2, 5–20 g/100 g sorghum flour). Glycerol monostearate (X_3) and CMC (X_4) were held constant at their center-point values of 10.0 and 6.0 g/100 g sorghum flour, respectively.

3.3.2 Overall acceptability–

Overall acceptability scores ranged from 4.05 to 6.9, with the model exhibiting the highest predictive power among all responses ($R^2 = 0.93$, $p = 0.0004$). Xanthan gum positively influenced acceptability (X_2, $p < 0.01$), as did glyceryl monostearate (GMS) (X_3, $p < 0.1$), CMC (X_4, $p < 0.1$), and the starch quadratic term (X_1^2, $p < 0.01$). Conversely, numerous interaction terms negatively affected acceptability: starch-xanthan (X_1X_2, $p < 0.1$), starch-GMS (X_1X_3, $p < 0.1$), starch-CMC (X_1X_4, $p < 0.1$), xanthan-GMS (X_2X_3, $p < 0.01$), xanthan-CMC (X_2X_4, $p < 0.1$), as well as quadratic terms for xanthan (X_2^2, $p < 0.001$) and GMS (X_3^2, $p < 0.1$).

These complex interactions suggest that ingredient balance is more critical than individual component levels in determining consumer acceptance. The highest overall acceptability (6.9) was achieved at 66.14% starch, 13.55% xanthan, 12.99% glyceryl, and 10% CMC, while the lowest score (4.05) occurred at 90.96% starch, 20% xanthan, 8.34% GMS, and 2% CMC. The response surface plot (Figure 6) clearly demonstrates that acceptability decreased with increasing starch and xanthan concentrations beyond optimal levels, likely due to excessive firmness or undesirable mouthfeel characteristics.

These complex interactions suggest that ingredient balance is more critical than individual component levels in determining consumer acceptance, a finding consistent with observations in other gluten-free pasta systems (Sholichah et al., 2021).

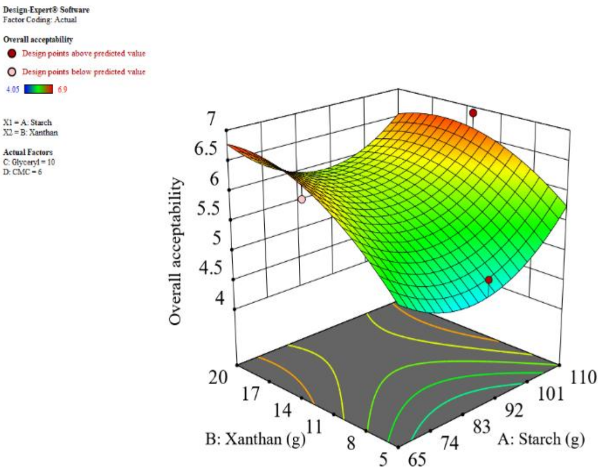

Fig 6. Response surface plot showing overall acceptability scores (9-point hedonic scale; n = 30 semi-trained panelists) of gluten-free red sorghum instant noodles as a function of starch (X_1, 65–110 g/100 g sorghum flour) and xanthan gum (X_2, 5–20 g/100 g sorghum flour). Glycerol monostearate (X_3) and CMC (X_4) were held constant at their center-point values of 10.0 and 6.0 g/100 g sorghum flour, respectively.

3.4 Process optimization.

Multi-response optimization using the desirability function approach was employed to identify the optimal formulation balancing all quality parameters. This methodology has been successfully applied in analogous cereal product optimization studies (Liu et al., 2021). The optimization criteria were established as follows: minimize cooking loss, cooking time, and moisture content; maximize water absorption capacity, texture, and overall acceptability. All independent variables were constrained within experimental ranges.

The model-predicted optimal noodle formulation contained: 69.46 g starch, 16.49 g xanthan gum, 10.19 g GMS, and 10.00 g CMC per 100 g sorghum flour. The overall desirability was 0.79, and at these levels, the model estimated: Cooking loss of 2.09%, Cooking time of 3.00 minutes, Water uptake of 179.98%, Moisture content of 7.66%, Texture rating of 6.97 (on a scale of 9), and Overall liking rating of 6.95 (on a scale of 9) **(Table 4).**

Table 4. Optimization constraints and predicted responses at Optimal formulation

Variable/Response	Goal	Lower limit	Upper limit	Predicted values
Independent Variables				
X_1: Starch (g/100g)	In range	65	110	**69.46**
X_2: Xanthan (g/100g)	In range	5	20	**16.486**
X_3: Glyceryl monostearate (g/100g)	In range	5	15	**10.19**
X_4: CMC (g/100g)	In range	2	10	**10.00**
Response variables				
Cooking loss (%)	Minimize	1.19	2.55	**2.09**
Cooking time (min)	Minimize	3.00	3.67	**3.00**
Water Absorption Capacity (%)	Maximize	110.29	199.60	**179.98**
Moisture Content (%)	Minimize	6.94	10.71	**7.66**
Texture (score)	Maximize	4.2	7.0	**6.97**
Overall acceptability (score)	Maximize	4.05	6.9	**6.95**
Overall Desirability				**0.79**

3.5 Model validation

To confirm the predictive adequacy of the optimized formulation, three independent batches of the optimized noodle formulation were prepared following the exact processing conditions described in Sections 2.4 and 2.5, and all six response variables were measured. The experimentally observed values were compared with the model-predicted values and assessed against the 95% prediction intervals **(Table 5).**

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Table 5. Comparison of model-predicted and experimentally validated response values for the optimized formulation

Response Variable	Predicted Value	Observed Value (mean ± SD, n=3)	Within 95% PI
Cooking loss (%)	2.09	2.14 ± 0.11	Yes
Cooking time (min)	3.00	3.00 ± 0.00	Yes
WAC (%)	179.98	176.42 ± 8.37	Yes
Moisture content (%)	7.66	7.81 ± 0.29	Yes
Texture (sensory score)	6.97	6.83 ± 0.45	Yes
Overall acceptability	6.95	6.79 ± 0.38	Yes

SD is the Standard Deviation and PI is the Prediction Interval

All experimentally observed values fell within the 95% prediction intervals of the respective models, confirming that the quadratic regression models adequately predicted the response values at the optimized conditions.

CONCLUSION

The gluten-free noodle formulation was optimized using response surface methodology (RSM) by studying the effects of varying starch, xanthan gum, GMS, and CMC levels on the cooking properties and sensory scores. Quadratic models developed for the responses showed good predictive power (R^2 = 0.78–0.93) for texture and overall acceptability (R^2 = 0.90 and 0.93, respectively), while models for cooking loss and water absorption were marginally significant and should be interpreted with caution. Starch level had a non-linear effect on cooking loss and cooking time; therefore, the starch level should be optimized to avoid high values of these responses. Xanthan gum enhanced the water absorption, texture, and overall liking, but very high levels of xanthan gum decreased the consumer acceptance. Interactions between the hydrocolloids, particularly starch and CMC and xanthan and GMS, had a marked effect on several quality traits, highlighting the importance of hydrocolloid combinations in gluten-free noodle systems. All of the noodle samples showed cooking loss below the generally accepted limit of 8%, and the optimized formulation (69.46 g/100 g flour starch, 16.49 g/100 g flour xanthan gum, 10.19 g/100 g flour GMS, and 10.00 g/100 g flour CMC) resulted in an overall desirability of 0.79 and showed good quality characteristics for all responses. Experimental validation of the optimized formulation confirmed good agreement between predicted and observed values. These results are promising and suggest that 100% red sorghum noodles with appropriate hydrocolloid and emulsifier combinations can achieve acceptable cooking quality and consumer acceptability. However, direct comparison with a wheat-based control product was not performed in this study and is recommended for future work. The optimized formulation should be tested at pilot scale and evaluated for nutritional properties in detail before commercial use.

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.

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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