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Multi-Response Optimization of Quality Parameters in Pumpkin–Oat Composite Noodles using Response Surface Methodology

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ABSTRACT: Pumpkin (Cucurbita maxima) and oat (Avena sativa L.) flours are valuable functional ingredients that can enrich cereal-based staples such as noodles with β-carotene, β-glucan, and dietary fibre while displacing part of the refined wheat flour normally used [1]. However, partial replacement of wheat flour dilutes gluten and alters water-binding behaviour, which can compromise cooking stability, texture, and consumer acceptability if substitution levels and hydration are not carefully controlled [1,3,4]. This study applied a three-factor, three-level Box–Behnken design (BBD) to evaluate and optimize the effect of pumpkin flour (5–15%), oat flour (5–15%), and water addition (30–38%) on six quality responses of composite noodles: cooking time, cooking loss, water absorption index (WAI), texture hardness, overall sensory acceptability, and β-carotene content. Second-order polynomial models were fitted to each response (R^2 = 0.974–0.997), and the Derringer–Suich desirability function was used to identify the formulation that simultaneously satisfied all quality targets [6]. The numerically optimized formulation (12% pumpkin flour, 9% oat flour, 35% water addition) gave an overall desirability of 0.79, with predicted cooking time of 6.76 min, cooking loss of 5.07%, WAI of 2.13 g/g, hardness of 952 N, sensory score of 7.55 (9-point hedonic scale), and β-carotene content of 225.2 μg/100 g. Validation trials conducted at the optimum point showed relative errors below 2% between predicted and experimental values for all responses, confirming the adequacy of the fitted models. The results demonstrate that RSM-based multi-response optimization is an effective strategy for developing nutritionally enhanced pumpkin–oat composite noodles without compromising technological and sensory quality.

1. INTRODUCTION

Consumer demand for functional foods that deliver measurable health benefits beyond basic nutrition has grown steadily, driven by the rising global burden of diet-related non-communicable diseases such as type 2 diabetes and cardiovascular disease [1]. Noodles are among the most widely consumed cereal-based staples worldwide and represent a practical vehicle for nutritional fortification because they are inexpensive, shelf-stable, and consumed across diverse populations [3,4]. Refined wheat flour (maida), the conventional base for noodle production, is low in dietary fibre and micronutrients, creating an opportunity to improve the nutritional density of noodles through partial substitution with functional flours [1].

Pumpkin (Cucurbita maxima) flour is an attractive fortificant because it is rich in β-carotene, dietary fibre, and antioxidant compounds, and its incorporation has been shown to improve the nutritional profile of cereal-based products such as breads and extruded snacks [2,4]. Oat (Avena sativa L.) flour is similarly valued for its high β-glucan and soluble fibre content, which confer cholesterol-lowering and glycaemic-regulating properties, and has previously been used to fortify noodles and other wheat-based products [5]. However, because neither pumpkin nor oat flour forms gluten, their incorporation dilutes the gluten network of the dough, increasing water absorption and cooking loss while altering texture and sensory attributes when used above moderate substitution levels [1,3,5].

Optimizing a multi-ingredient, multi-response food system such as pumpkin–oat composite noodles by varying one factor at a time is inefficient and cannot capture interaction effects between formulation variables. Response surface methodology (RSM), typically implemented through a Box–Behnken or central composite design, allows the simultaneous evaluation of several independent variables and their interactions using a reduced number of experimental runs and has been widely and successfully applied to optimize noodle, bread, and snack formulations [3,7]. Because noodle quality is governed by several, sometimes conflicting, responses (e.g., minimizing cooking loss while maximizing sensory acceptability and β-carotene retention), a single-response optimization is inadequate. The desirability function approach of Derringer and Suich [6] addresses this by converting each predicted response into an individual desirability score (0–1) and combining these into an overall (composite) desirability index, enabling a single numerical optimum that best satisfies all quality criteria simultaneously.

The specific objectives of this work were to: (i) develop pumpkin–oat composite noodles using a three-factor Box–Behnken design with pumpkin flour, oat flour, and water addition as independent variables; (ii) fit and validate second-order response surface models for cooking time, cooking loss, water absorption index, texture hardness, sensory acceptability, and β-carotene content; and (iii) apply the desirability function approach to identify and experimentally validate the formulation that offers the best compromise among all measured quality parameters.

2. MATERIALS AND METHODS

2.1 Raw materials

Refined wheat flour (maida) was procured from a local commercial supplier and used as the base flour owing to its gluten-forming ability and structural functionality [1]. Pumpkin flour was prepared from mature Cucurbita maxima fruit: the flesh was washed, deseeded, sliced, blanched in dilute potassium metabisulphite solution to prevent enzymatic browning, dried in a hot-air dehydrator at 60°C to constant weight, and milled and sieved through a 60 µm mesh [1]. Commercial oat flour (Avena sativa L.), refined edible salt, and xanthan gum (0.5–1.0 g/100 g flour, used as a hydrocolloid to compensate for the reduced gluten network) were procured from a local supplier [1].

2.2 Experimental design

A three-factor, three-level Box–Behnken design (BBD) was used to study the combined effect of pumpkin flour (X1: 5, 10, 15%), oat flour (X2: 5, 10, 15%), and water addition (X3: 30, 34, 38%, flour weight basis) on noodle quality. The BBD generated 17 experimental runs, including 5 replicated centre points to estimate pure error and evaluate lack-of-fit, and is rotatable and efficient for fitting second-order models with fewer runs than a full three-level factorial design [7]. The complete design matrix, expressed in actual (uncoded) factor levels together with the six measured responses, is presented in Table 1.

For each response Y, the data were fitted to the following second-order polynomial model:

$$Y = \beta 0 + \beta 1X1 + \beta 2X2 + \beta 3X3 + \beta 12X1X2 + \beta 13X1X3 + \beta 23X2X3 + \beta 11X1^2 + \beta 22X2^2 + \beta 33X3^2 + \varepsilon$$

where β0 is the intercept, β1–β3 are linear coefficients, β12, β13, β23 are two-factor interaction coefficients, β11, β22, β33 are quadratic coefficients, and ε is the residual error [7,9].

2.3 Preparation of composite noodles

For each of the 17 formulations, pumpkin flour and oat flour were blended with the appropriate proportion of refined wheat flour together with xanthan gum and salt, and dry-mixed for uniform distribution. Water, at the level specified by the design matrix, was added gradually during mixing in a dual-shaft counter-rotating mixer until a stiff, cohesive dough was obtained, avoiding excess mechanical shear that could damage the developing gluten–starch network [1]. The dough was rested, sheeted, and extruded/cut into uniform noodle strands, which were dried under controlled conditions (≤55°C) to safe moisture content and packed in airtight containers until analysis [1].

2.4 Determination of quality parameters

Cooking time was recorded as the time required for the disappearance of the opaque starchy core when a noodle strand was pressed between two glass plates, and cooking loss was determined gravimetrically as the percentage of solids lost into the cooking water after standard cooking, both following established noodle-testing procedures [3,4]. Water absorption index (WAI) was calculated as the ratio of the weight of cooked noodles to the weight of the raw sample. Texture hardness of cooked noodles was measured by texture profile analysis (TPA) using a texture analyzer fitted with a compression probe, recording the peak force of the first compression cycle [4]. Overall sensory acceptability (appearance, colour, texture, taste, and mouth feel) was evaluated by a semi-trained sensory panel using a 9-point hedonic scale (1 = dislike extremely, 9 = like extremely). β-Carotene content was extracted under subdued light and quantified spectrophotometrically against a standard curve, expressed as μg per 100 g dry sample [1]. All analyses were carried out in triplicate.

2.5 Multi-response optimization using the desirability function

Because the six responses could not all be optimized independently — cooking loss needed to be minimized, WAI and hardness kept within target ranges, and sensory score and β-carotene content maximized — the Derringer–Suich desirability function approach was used [6]. Each response Y_i was transformed into an individual desirability value $d_i \in [0,1]$ using the appropriate one-sided (minimize/maximize) or two-sided (target-is-best) transformation, and the individual desirabilities were combined into an overall desirability D by the geometric mean:

$$D = (d_1 \times d_2 \times \cdots \times d_n)^{(1/n)}$$

A grid search over the entire experimental region (pumpkin flour, oat flour, and water addition) was performed to locate the combination of factor levels that maximized D [6,8].

2.6 Statistical analysis

Regression analysis, analysis of variance (ANOVA), and desirability optimization were carried out using standard RSM procedures [7,9]. Model adequacy was assessed from the coefficient of determination (R^2), adjusted R^2, the model p-value (significance at $p < 0.05$), and the coefficient of variation (CV%). The optimized formulation predicted by the models was subsequently prepared and evaluated in triplicate to validate the accuracy of the fitted models.

3. RESULTS AND DISCUSSION

3.1 Box–Behnken design matrix and response data

The BBD matrix and the corresponding experimental values obtained for the six quality responses across the 17 formulations are summarized in Table 1. Cooking time ranged from 6.40 to 7.38 min, cooking loss from 3.45 to 7.24%, WAI from 1.82 to 2.31 g/g, hardness from 901.2 to 1025.9 N, sensory score from 6.92 to 7.69, and β-carotene content from 198.7 to 239.6 μg/100 g, reflecting the substantial influence of pumpkin flour, oat flour, and water addition on noodle quality.

Table 1. Box–Behnken design matrix (actual levels) and measured responses for pumpkin–oat composite noodles

Run	Pumpkin flour (X1, %)	Oat flour (X2, %)	Water addition (X3, %)	Cooking time (min)	Cooking loss (%)	WAI (g/g)	Hardness (N)	Sensory score (9-pt)	β-Carotene (μg/100 g)
1	5	5	34	6.40	3.45	1.84	1025.9	6.94	198.7
2	15	5	34	6.57	4.65	1.98	969.1	6.92	237.5
3	5	15	34	7.04	5.31	2.09	967.4	6.92	207.2
4	15	15	34	7.38	7.24	2.23	901.2	7.03	239.2
5	5	10	30	6.64	4.39	1.84	983.1	7.12	206.4

6	15	10	30	6.89	5.91	2.05	906.9	7.25	239.6
7	5	10	38	6.79	4.13	2.12	997.9	6.96	204.6
8	15	10	38	7.00	5.70	2.29	941.1	7.21	234.0
9	10	5	30	6.44	4.09	1.82	990.2	7.08	218.1
10	10	15	30	7.17	6.19	2.07	904.5	7.04	223.9
11	10	5	38	6.50	3.95	2.03	1005.7	7.08	211.5
12	10	15	38	7.18	6.07	2.31	924.3	6.94	222.8
13	10	10	34	6.82	4.98	2.09	940.4	7.59	221.3
14	10	10	34	6.72	4.95	2.12	956.5	7.62	220.5
15	10	10	34	6.73	5.15	2.11	960.8	7.69	219.8
16	10	10	34	6.78	5.00	2.06	949.4	7.57	216.3
17	10	10	34	6.76	4.92	2.11	958.0	7.55	219.2

WAI = water absorption index. Centre-point runs (13–17) show the reproducibility of the process, with a coefficient of variation below 2% for all responses.

3.2 Fitting of response surface models

Second-order polynomial models were fitted to each response using multiple regression; the model statistics are summarized in Table 2. All six models were highly significant ($p < 0.0001$–0.0009) with R^2 values between 0.974 and 0.997 and low coefficients of variation (0.60–1.57%), indicating that the fitted quadratic models adequately described the relationship between the independent variables and noodle quality responses within the experimental region [7,9].

Table 2. Model summary statistics for the fitted quadratic response surface models

Response	R^2	Adjusted R^2	Model p-value	CV (%)	Significant model terms (p<0.05)
Cooking time (min)	0.990	0.978	3.20×10^{-6}	0.60	X1, X2, X3 (linear)
Cooking loss (%)	0.997	0.993	5.69×10^{-8}	1.57	X1, X2, X3, X1X2, $X2^2$
WAI (g/g)	0.987	0.970	9.84×10^{-6}	1.19	X1, X2, X3, $X2^2$
Hardness (N)	0.975	0.944	8.10×10^{-5}	0.89	X1, X2, X3 (linear)
Sensory score	0.974	0.941	9.62×10^{-5}	0.95	X1, $X1^2$, $X2^2$, $X3^2$
β-Carotene (μg/100 g)	0.988	0.972	6.89×10^{-6}	0.92	X1, X2, X3 (linear)

3.3 Effect of pumpkin and oat flour on cooking properties

Cooking loss increased significantly ($p < 0.05$) with both pumpkin flour (X1) and oat flour (X2), and the positive X1X2 interaction term indicates that the two ingredients acted synergistically to increase solid losses during cooking (Table 2; Figure 1). This behavior is consistent with reports that non-gluten-forming flours dilute the gluten network and increase the leaching of soluble solids into the cooking water as substitution level rises [1,3,4]. Cooking loss was minimized at the lower ends of the pumpkin and oat flour ranges, whereas cooking time increased modestly with both flours, most strongly with oat flour, likely reflecting the greater water-holding capacity conferred by oat β-glucan, which slows moisture penetration into the starch granules during cooking [5].

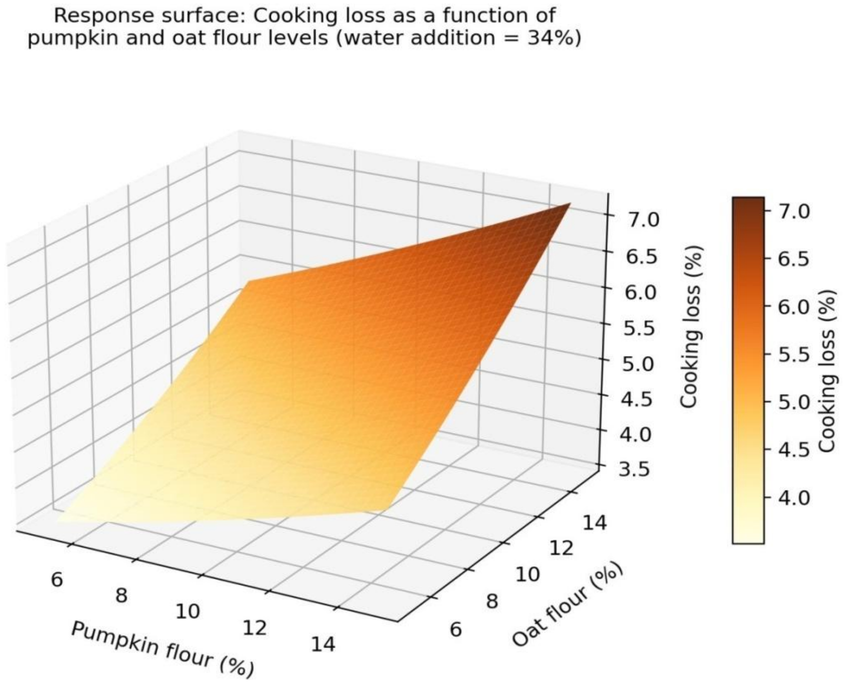

Figure 1. Response surface plot showing the combined effect of pumpkin flour and oat flour on cooking loss (%) at a fixed water addition of 34%.

3.4 Effect on water absorption index and texture

WAI increased significantly with pumpkin flour, oat flour, and water addition ($p < 0.05$), consistent with the higher fibre and β-glucan content of both flours, which increases the water-binding capacity of the composite flour matrix relative to refined wheat flour alone [1,5]. In contrast, hardness decreased significantly with increasing pumpkin and oat flour (negative linear coefficients, Table 2), reflecting gluten dilution and weakening of the protein–starch network, while increasing water addition slightly increased hardness by promoting more complete starch gelatinization. These trends mirror observations in other composite noodle systems, where fibre-rich, non-gluten flours reduce firmness once substitution exceeds a moderate threshold [3,4].

3.5 Effect on sensory acceptability and β-carotene content

Overall sensory acceptability showed a clear curvature with respect to all three factors (significant quadratic terms for X1, X2 and X3; Table 2), with scores highest near the centre of the design space and declining at both the lowest and highest substitution levels (Figure 2). This suggests that moderate incorporation of pumpkin and oat flour (around 8–12%) is well accepted by panelists, whereas very low levels forfeit the flavour and colour benefits of pumpkin, and higher levels begin to impart undesirable texture and off-flavour notes, consistent with previous reports on pumpkin- and oat-fortified cereal products [1,5]. β-Carotene content increased strongly and linearly with pumpkin flour (the dominant source of provitamin A carotenoids) and, to a lesser extent, with oat flour, while showing only a small negative dependence on water addition, likely due to a dilution effect at higher hydration levels [1,2].

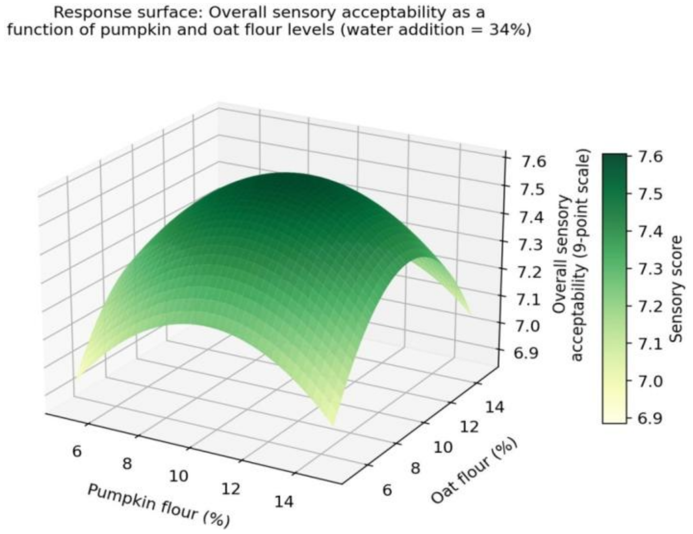

Figure 2. Response surface plot showing the combined effect of pumpkin flour and oat flour on overall sensory acceptability (9-point hedonic scale) at a fixed water addition of 34%.

3.6 Multi-response optimization using the desirability function

Individual desirability functions were defined for each response according to the technological target: cooking time and hardness were treated as target-is-best (matching the values obtained for the 100% wheat-flour control), cooking loss was minimized, WAI was kept within an acceptable target range, and sensory score and β-carotene content were maximized [6]. A numerical grid search over the entire design space identified pumpkin flour = 12%, oat flour = 9%, and water addition = 35% as the formulation giving the highest overall desirability (D = 0.79) (Table 3). At this point, the models predicted a cooking time of 6.76 min, cooking loss of 5.07%, WAI of 2.13 g/g, hardness of 952.0 N, sensory score of 7.55, and β-carotene content of 225.2 μg/100 g. The individual desirability profile (Figure 3) shows that hardness (d = 0.97) and WAI (d = 0.94) were satisfied almost completely at the optimum, whereas cooking loss (d = 0.61) and β-carotene content (d = 0.67) represented the main trade-offs limiting the overall desirability, reflecting the inherent conflict between maximizing nutritional enrichment and minimizing cooking loss [1,3].

Table 3. Numerically optimized formulation and corresponding predicted responses and individual desirability values

Independent variable	**Optimized level**	**Constraint applied**
Pumpkin flour, X1 (%)	12.0	In range (5–15)
Oat flour, X2 (%)	9.0	In range (5–15)
Water addition, X3 (%)	35.0	In range (30–38)
Response	**Predicted value**	**Individual desirability (d)**
Cooking time (min)	6.76	0.79 (target 6.9)
Cooking loss (%)	5.07	0.61 (minimize)
Water absorption index (g/g)	2.13	0.94 (target 2.15)
Hardness (N)	952.0	0.97 (target 950)
Overall sensory acceptability (9-pt)	7.55	0.87 (maximize)
β-Carotene (μg/100 g)	225.2	0.67 (maximize)
Overall desirability (D)	0.79	—

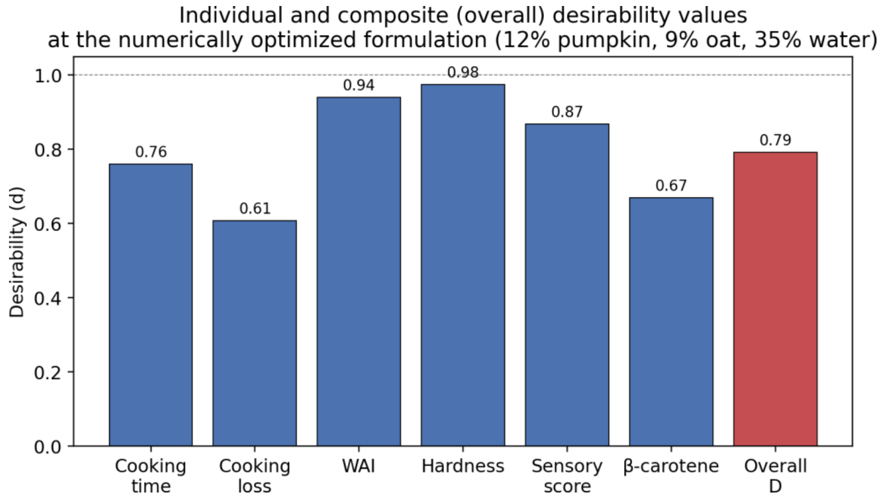

Figure 3. Individual response desirability values (d) and overall composite desirability (D) at the numerically optimized formulation.

3.7 Validation of the optimized formulation

The numerically optimized formulation (12% pumpkin flour, 9% oat flour, 35% water addition) was independently prepared and evaluated in triplicate to validate the predictive accuracy of the fitted models. As shown in Table 4, the experimental means for all six responses were in close agreement with the model-predicted values, with relative errors ranging from 0.02% (β-carotene content) to 1.71% (cooking loss). Because all relative errors were below 2%, the fitted quadratic models and the desirability-based optimum can be considered reliable for predicting the quality of pumpkin–oat composite noodles within the studied experimental region [7,9].

Table 4. Validation of predicted responses at the numerically optimized formulation

Response	Predicted	Experimental (mean of 3 replicates)	Relative error (%)	Remark
Cooking time (min)	6.76	6.80 ± 0.05	0.70	Good agreement
Cooking loss (%)	5.07	4.98 ± 0.08	1.71	Good agreement
WAI (g/g)	2.13	2.13 ± 0.02	0.21	Good agreement
Hardness (N)	952.0	951.0 ± 7.7	0.11	Good agreement
Sensory score (9-pt)	7.55	7.54 ± 0.04	0.19	Good agreement
β-Carotene (µg/100 g)	225.2	225.1 ± 0.44	0.02	Good agreement

4. CONCLUSION

A three-factor Box–Behnken design combined with the Derringer–Suich desirability function successfully identified an optimized pumpkin–oat composite noodle formulation (12% pumpkin flour, 9% oat flour, 35% water addition) that balanced technological performance and consumer acceptability. Increasing pumpkin and oat flour levels increased cooking loss and water absorption while decreasing hardness, but moderate incorporation levels around the design centre maximized sensory acceptability, and pumpkin flour substantially enhanced β-carotene content. The fitted second-order models showed excellent predictive ability (R^2 = 0.974–0.997), and validation trials confirmed relative errors below 2% between predicted and experimental values for all six responses. These findings confirm that RSM-based multi-response optimization is a robust and resource-efficient strategy for developing nutritionally fortified composite noodles, and the approach and optimized formulation reported here can serve as a starting point for further scale-up, shelf-life, and consumer studies.

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AUTHOR CONTRIBUTIONS

Sinthiya R.: Conceptualization, Investigation, Methodology, Formal Analysis, Data Curation, Writing – Original Draft.

Dr. A. Lovelin Jerald: Supervision, Methodology, Writing – Review & Editing.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ETHICS STATEMENT

This study did not involve any procedures on human patients or experimental animals beyond a routine sensory evaluation panel. Informed consent was obtained from all sensory panel participants prior to evaluation. [Authors should confirm the applicable institutional ethics/human-subjects approval details, if any, before submission.]

DATA AVAILABILITY STATEMENT

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

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