

Optimization of Cowpea (*Vigna unguiculata* L.) Flour-enriched Bread Formulation Using Response Surface Methodology (RSM)

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Abstract

Cowpea is an important source of plant-based proteins and provides an essential amino acid profile that complements wheat, which is deficient in lysine and threonine. This study aimed to determine the optimal incorporation level of cowpea flour (*Vigna unguiculata* L.) in the formulation of bread comparable to conventional wheat bread. To achieve this, the amounts of yeast, improver, the ice/water ratio, and the cowpea flour proportion were varied using the Response Surface Methodology (RSM). The Box-Behnken experimental design was employed to analyze interactions among the factors, and multiple regression models were subsequently developed. The results indicated that incorporating 5% cowpea flour constituted the optimal level for nutritional enrichment. The optimal processing conditions were identified as an ice/water ratio of 0.45%, 14.66 g of yeast, and 7.07 g of improver to obtain a bread with characteristics comparable to the control (100% wheat flour). Sensory evaluation further revealed that the optimized bread exhibited good overall acceptability. These findings highlight the relevance of the Box-Behnken design in identifying factor interactions and optimizing baking conditions. Furthermore, the moderate incorporation of cowpea flour appears to be a promising strategy for improving the nutritional value of bread without significantly compromising its technological and sensory quality. These findings confirm the relevance of the Box-Behnken design for optimizing bread-making conditions and suggest that the moderate incorporation of cowpea flour represents a promising approach to enhance the nutritional value of bread without compromising its technological or sensory quality.

Keywords

Vigna unguiculata L.; Bread fortification; Response Surface Methodology; Box-Behnken design; Sensory evaluation

1. Introduction

Bread is a staple food widely consumed across the world. Its final quality results from a complex interaction between

its main ingredients (flour, water, yeast, etc.) and the technological parameters applied during the breadmaking process [1]. In Senegal, as in many African countries, the wheat flour sector faces major structural challenges [2]. Indeed, the demand for wheat flour remains high, while its supply depends heavily on imports, a dependency further exacerbated by the Ukrainian crisis [3]. This situation has led to a sharp rise in global wheat prices, directly affecting flour costs and, consequently, national food security [4].

In this context, the search for alternative solutions to reduce wheat dependency while improving the nutritional value of bakery products has become crucial. The incorporation of locally available legume flours, particularly cowpea (*Vigna unguiculata*) flour, represents a promising approach. Cowpea is a plant-based source rich in proteins, fibers, and minerals, whose partial substitution for wheat flour can enhance the nutritional quality of bread [5].

Like most plant-based proteins, those found in cereals exhibit an essential amino acid profile that is unbalanced relative to human nutritional requirements [6].

Wheat, although a major source of carbohydrates and energy, is particularly deficient in essential amino acids such as lysine and threonine [7]. In contrast, cowpea contains high levels of essential amino acids such as lysine, leucine, and tyrosine [8]. Its incorporation into wheat-based formulations can therefore provide a more balanced protein profile, while strengthening food security in regions with limited access to animal protein sources [9].

Several studies have demonstrated the feasibility of using cowpea and other legume flours in various food products such as bread, biscuits, pasta, and fritters [10-12]. According to [13], cereal-legume blending offers both agro-nomic advantages (reduced fertilizer and pesticide needs, improved productivity) and nutritional benefits (complementary amino acid profiles). Furthermore, the enrichment of wheat flour with proteins and lysine has been shown to enhance the biological value and nutritional quality of bakery products [14]. However, the partial substitution of wheat with legume flours alters the rheological properties of the dough and affects the sensory and textural characteristics of bread, mainly due to the absence of gluten [15].

Therefore, optimizing breadmaking conditions is essential to reconcile nutritional improvement with the maintenance of desirable technological and sensory properties. The present study aims to evaluate the effects of four technological variables: yeast quantity, improver proportion, ice/water ratio, and cowpea flour incorporation rate on bread quality. The methodological approach is based on the Response Surface Methodology (RSM), using a Box-Behnken design to model interactions among the studied factors and identify optimal breadmaking conditions [16]. The expected outcomes will help determine the optimal formulation and process parameters for producing cowpea-enriched bread with satisfactory physicochemical and sensory characteristics. Ultimately, this approach could contribute to the valorization of local resources, the reduction of wheat import dependency, and the improvement of the nutritional quality of bread consumed in Senegal.

2. Materials and Methods

2.1 Materials

2.1.1 Plant material

The plant materials used in this study consisted of refined wheat flour and cowpea (*Vigna unguiculata*) flour. The wheat flour was a commercially refined wheat flour (100% wheat), with a minimum protein content of 10%, an average moisture content of 14 %, and an ash content of approximately 0.70 g/100 g, as declared by the manufacturer. The cowpea flour was commercially obtained from a local market and used as purchased, without any additional processing by the authors. To improve reproducibility and better characterize its functional contribution, the flour was subjected to proximate analysis prior to formulation. The cowpea flour presented a moisture content of 6.33%, protein content of 23.25%, lipid content of 1.90%, and ash content of 1.30%.

2.1.2 Additional ingredients

The additional ingredients used in this study included fine iodized table salt, dry baker's yeast (commercially available in 500 g packages containing *Saccharomyces cerevisiae*), ice, and water. A commercial baking improver was also used. According to compositional analysis performed prior to dough preparation, the baking improver contained 8.17% protein and 8.75% moisture. The improver was declared by the supplier to contain fungal amylase as its main functional enzyme. The product was used as supplied, without further modification.

2.2 Methods

2.2.1 Experimental design and statistical analysis

Response Surface Methodology (RSM) was employed to evaluate the effects of yeast amount (X_1), improver level

(X_2), ice/water ratio (X_3), and cowpea flour incorporation rate (X_4) on bread volume (Y_1), bread weight (Y_2), mixing time (Y_3), and fermentation time (Y_4). A Box-Behnken experimental design was adopted, as it is particularly suitable for investigating factor interactions and modeling quadratic effects. The design consisted of twenty-seven (27) experimental runs, conducted within a single block. The experimental run order was fully randomized to minimize systematic bias and order effects. Experimental data were fitted to a second-order polynomial model including linear, quadratic, and interaction terms. Statistical analyses were performed using Statgraphics Centurion software (version 19.7.01). Model adequacy was assessed by analysis of variance (ANOVA), considering the overall model significance (model p-value), the coefficient of determination (R^2), the adjusted coefficient of determination (adjusted R^2), the coefficient of variation (CV), as well as the lack-of-fit test. However, for some responses, the lack-of-fit test could not be computed due to the absence of replicated experimental points, which resulted in a zero estimate of pure error. In such cases, model adequacy was primarily assessed using R^2 , adjusted R^2 , coefficient of variation (CV), and the statistical significance of the regression model. Factor effects were considered statistically significant at a 5% probability level ($p < 0.05$). All experimental results represent the mean values of analyses performed in triplicate.

2.2.2 Experimental breadmaking procedure

Bread production was carried out following a standard baking protocol comprising kneading, dividing and shaping, fermentation, and baking. Kneading was conducted in two phases: first, a 1-minute dry mix during which wheat flour, cowpea flour, salt, yeast, and improver were simultaneously introduced into the mixer (M72, Macadams) to obtain a homogeneous blend of dry ingredients; followed by a 12-minute kneading phase at two speeds (4 minutes at low speed and 8 minutes at high speed), during which the ice/water mixture was gradually incorporated to ensure proper dough hydration and optimal gluten network development. Indeed, the ice/water ratio (X_3) was prepared with a constant total mass of 630 g for all experimental runs. The specific amounts of ice and water were adjusted according to the targeted ratios: 0.25 (157.5 g ice + 472.5 g water), 0.50 (315 g ice + 315 g water), and 0.75 (472.5 g ice + 157.5 g water). This design maintained a constant total mass while isolating the thermal effect of varying ice proportions on dough mixing and fermentation. The ice/water ratio is defined as the mass fraction of ice in the ice-water mixture. After kneading, the dough was divided into units of equal mass and mechanically shaped using a dough molder (Macadams SM 380) to obtain the desired final form. The shaped dough pieces were then subjected to controlled fermentation for 2 hours at 30 °C under appropriate relative humidity to promote yeast activity and volume development. Following fermentation, superficial cuts were made on the dough pieces to facilitate the release of carbon dioxide and prevent deformation during baking. Finally, the fermented dough was baked at 250 °C for 15 minutes, with a 4-second steam injection at the beginning of baking to produce a thin, glossy crust and a soft crumb structure.

2.2.3 Measurement and analysis of response variables

2.2.3.1 Bread mass

The bread mass (Y_2) was measured 20 minutes after baking to allow adequate cooling and stabilization of internal moisture. Each loaf was weighed using a precision balance (DENSI model TP-600A, 0.01 g accuracy).

2.2.3.2 Bread volume

The specific volume of the bread (Y_1), expressed in cm^3 , was determined using the seed displacement method with a volumeter (Macadams W13).

2.2.4 Sensory evaluation

Based on the optimized formulation, a sensory evaluation was conducted to assess the acceptability of the control bread (100% wheat flour) and the optimized bread containing 5% cowpea flour. The evaluation focused on the following sensory attributes: taste, texture, aroma, color, and overall acceptability. A total of 69 untrained subjects (aged 18-55 years, regular bread consumers) were recruited for the study. Verbal informed consent was obtained from all participants prior to testing. Each panelist received two bread samples, coded randomly to avoid bias, and presented under standardized conditions (room temperature, uniform lighting). Samples were cut into identical pieces (~50 g) and served on disposable plates. Panelists were instructed to cleanse their palate with water between samples. Sensory attributes were rated using a 9-point hedonic scale (1 = extremely unpleasant, 9 = extremely pleasant). Sensory data were expressed as mean values $\pm$ standard deviation. To determine whether the observed differences between the two bread formulations were statistically significant, inferential statistical analysis was performed. Mean sensory scores were compared using Student's t-test at a 5% significance level ($p < 0.05$). When

the assumption of normality was not met, the corresponding non-parametric equivalent test was applied.

All statistical analyses were carried out using appropriate statistical software, ensuring an objective and rigorous interpretation of sensory differences between the formulations.

3. Results and Discussion

3.1 Effects of Variables on Bread Volume

Table 1 presents the experimental matrix of the Box-Behnken design, showing the combinations of the studied factors as well as the observed values of the different response variables.

Table 1. Experimental design and observed response values obtained from the breadmaking trials

Sample	Yeast (g) (X1)	Improver (g) (X2)	Ice/Water Ratio (m/m) (X3)	Cowpea Flour (%) (X4)	Bread Volume (cm ³) (Y1)	Bread Mass (g) (Y2)	Kneading Time (min) (Y3)	Fermentation Time (min) (Y4)
1	15	7.5	0.5	17.5	484	153	12	60
2	20	7.5	0.25	17.5	610	145	12	90
3	10	7.5	0.25	17.5	550	145	16	90
4	15	7.5	0.75	5	950	145	16	90
5	10	7.5	0.5	5	900	145	12	90
6	20	7.5	0.75	17.5	550	145	17	90
7	20	10	0.5	17.5	625	145	12	90
8	15	7.5	0.25	5	740	150	12	90
9	15	5	0.5	30	456	149	15	60
10	15	7.5	0.5	17.5	471	153	13	60
11	15	5	0.75	17.5	585	145	17	90
12	15	10	0.5	5	900	135	12	90
13	15	7.5	0.75	30	456	145	16	60
14	20	7.5	0.5	5	800	140	12	90
15	10	5	0.5	17.5	634	141	13	90
16	15	10	0.75	17.5	550	145	17	90
17	20	5	0.5	17.5	634	145	15	90
18	15	10	0.25	17.5	530	145	12	90
19	15	10	0.5	30	414	149	15	60
20	10	7.5	0.5	30	456	149	16	60
21	15	7.5	0.5	17.5	580	149	14	60
22	10	10	0.5	17.5	589	145	14	90
23	15	5	0.25	17.5	540	145	12	90
24	15	5	0.5	5	900	145	12	90
25	10	7.5	0.75	17.5	480	145	21	90
26	20	7.5	0.5	30	456	149	15	60
27	15	7.5	0.25	30	414	145	15	60

Table 1 shows marked variations in bread volume (414 to 950 cm³) and bread weight (135 to 153 g), resulting in a wide range of specific volume values. These variations confirm that technological parameters such as yeast and improver proportions, the ice/water ratio, and cowpea flour content exert differentiated and combined effects on the physical and technological properties of bread. In particular, samples formulated with low levels of cowpea flour exhibited higher specific volumes, whereas higher substitution levels led to denser breads with reduced gas retention capacity. These observations are similar to those reported by [17], who highlighted that enriching wheat flour with plant-based materials of high nutritional value, although beneficial from a health perspective, may impair the technological and sensory performance of bread due to the presence of fiber-rich or phenolic compound fractions. These components interfere with the formation of the gluten network, thereby reducing the retention of fermentation gases and, consequently, the final bread volume [17]. Similarly, [18] demonstrated that variations in technological ingredients such as yeast, salt, or improvers significantly affect dough texture and crumb structure. Overall, the observed variability reflects the complex and interactive effects of formulation and processing parameters on the technological quality of cowpea-enriched bread.

The regression equations of the developed models are presented in Table 2, together with the experimental results obtained for the different combinations of the Box-Behnken design.

Table 2. Regression equations of the developed models

Response (Y)	Significant factors (X)	Regression equation (second-order polynomial)	R ² (%)	R ² -Adj (%)	p-value	Lack-of-fit	CV (%)
Bread volume (Y₁)	X ₄ , X ₂ ² , X ₄ ²	(Y ₁ = 511,667 + 5,5*X ₁ - 11,75*X ₂ + 15,5833*X ₃ - 211,5*X ₄ + 41,375*X ₁ ² + 9,0*X ₁ *X ₂ + 2,5*X ₁ *X ₃ + 25,0*X ₁ *X ₄ + 50,5*X ₂ ² - 6,25*X ₂ *X ₃ - 10,5*X ₂ *X ₄ + 0,25*X ₃ ² - 42,0*X ₃ *X ₄ + 111,125*X ₄)	94.18	90.55	0.0000	Not available	8.38
Bread weight (Y₂)	X ₄ , X ₁ ² , X ₂ ² , X ₃ ²	(Y ₂ = 151,667 - 0,0833333*X ₁ - 0,5*X ₂ - 0,416667*X ₃ + 2,16667*X ₄ - 3,54167*X ₁ ² - 1,0*X ₁ *X ₂ + 1,25*X ₁ *X ₄ - 4,16667*X ₂ ² + 2,5*X ₂ *X ₄ - 2,79167*X ₃ ² + 1,25*X ₃ *X ₄ - 2,66667*X ₄ ²)	64.68	34.41	0.0884	Not available	2.07
Mixing time (Y₃)	X ₃ , X ₄ , X ₃ ²	(Y ₃ = 13,0 - 0,75*X ₁ - 0,166667*X ₂ + 2,08333*X ₃ + 1,33333*X ₄ + 0,958333*X ₁ ² - 1,0*X ₁ *X ₂ - 0,25*X ₁ *X ₄ - 0,166667*X ₂ ² + 1,95833*X ₃ ² - 0,75*X ₃ *X ₄ + 0,0833333*X ₄ ²)	83.54	71.47	0.0004	Not available	8.20
Fermentation time (Y₄)	X ₄ , X ₁ ² , X ₂ ² , X ₃ ²	(Y ₄ = 60,0 - 15,0*X ₄ + 15,0*X ₁ ² + 15,0*X ₂ ² + 15,0*X ₃ ²)	100	100	Undetermined (pure error = 0)	Not available	0.00

Legend: X₁: Yeast amount; X₂: Improver level; X₃: Ice/water ratio; X₄: Cowpea flour incorporation rate.

Not available: the lack-of-fit test could not be computed due to the absence of replicated experimental points. The Y₄ model showed zero pure error, leading to an undetermined model *p*-value.

The regression equations obtained reflect the significant influence of the technological factors studied on the measured responses. Analysis of the coefficients shows that the ice/water ratio (X₃) exerts a determining effect on most variables, particularly on volume (Y₁) and fermentation time (Y₄), highlighting its key role in dough structure and aeration. In contrast, the incorporation of cowpea flour (X₄) generally exerts a negative effect on volume and, to a lesser extent, on weight. This negative effect is likely due to the absence of gluten, which limits gas retention. Indeed, the incorporation of legume flours into bread dough dilutes the gluten and affects both its development and the starch-protein complexes, which are crucial for dough rheology and bread quality [19]. However, yeast (X₁) and improver (X₂) have a positive influence on dough weight and mixing time, underscoring their importance in protein network development and bread texture. The quadratic effects (X₁×X₂, X₃×X₄, etc.) indicate that some factors may either reinforce or attenuate the responses.

3.2 Analysis of the Response Factors

3.2.1 Effects of variables on bread volume

The results of the analysis of variance (ANOVA) for the regression model of bread volume are presented in Table 3, highlighting the significant factors and interactions influencing bread development. Figure 1 shows the estimated response surface (A) and the standardized Pareto chart (B) for bread volume.

Table 3. Analysis of variance for bread volume

Source	F-value	Probability (p)
A: Yeast	0.15	0.700
B: Improver	0.68	0.420
C: Ice/Water ratio	1.20	0.290
D: Cowpea flour	220.88	0.000
AA	4.21	0.060
AD	1.03	0.330
BB	6.28	0.020
BD	0.18	0.680
CD	2.90	0.110
DD	30.44	0.000

Legend: AA: quadratic effect of yeast, BB: quadratic effect of improver, DD: quadratic effect of cowpea flour, CD: interaction between ice/water ratio and cowpea flour, BD: interaction between improver and cowpea flour, AD: interaction between yeast and cowpea flour.

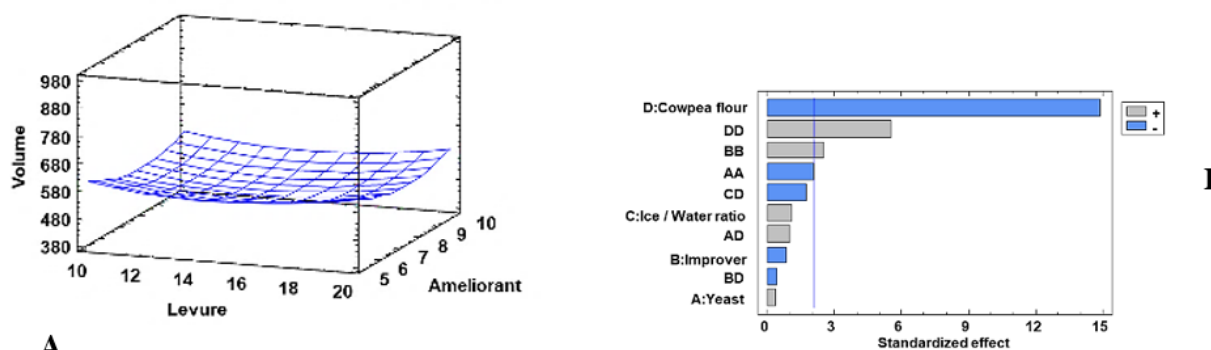


Figure 1. Estimated Response Surface (A) and Standardized Pareto Chart (B) for loaf volume.

Bread volume is a key criterion for the characterization and acceptability of baked products. The regression model developed for this response showed a high coefficient of determination ($R^2 = 90.55\%$), indicating a satisfactory fit between predicted and experimental values. However, the interpretation of factor effects was based exclusively on the analysis of variance. As shown in the ANOVA results (Table 3), cowpea flour (D) exhibited a highly significant linear effect on bread volume ($F = 220.88$; $p < 0.001$), as well as a significant quadratic effect (DD; $p < 0.001$), confirming that this factor is the primary determinant of loaf volume within the studied domain. In contrast, yeast (A) and the ice/water ratio (C) did not significantly influence bread volume ($p > 0.05$). The improver (B) showed no significant linear effect; however, its quadratic term (BB) was statistically significant ($p = 0.020$), indicating a non-linear relationship and the existence of an optimal level beyond which bread volume may decrease.

The negative effect associated with increasing levels of cowpea flour on volume can be attributed to the dilution of the gluten network caused by the incorporation of a non-gluten legume flour. This dilution reduces dough viscoelasticity and gas retention capacity, leading to lower loaf volume. Similar reductions in bread volume have been reported in legume-enriched breads due to weakened gluten structure, interactions with non-starch polysaccharides, and increased dietary fiber content, which competes with gluten for water and disrupts network formation [20-29].

Overall, these findings demonstrate that bread volume is predominantly governed by the proportion of cowpea flour, while the improver affects this response mainly through a quadratic effect, highlighting the importance of formulation optimization to achieve an acceptable loaf volume while improving nutritional quality.

3.2.2 Effects of variables on bread mass

The results of the analysis of variance (ANOVA) for the regression model of bread weight are presented in Table 4, highlighting the significant factors and interactions influencing bread mass development. Figure 2 shows the estimated response surface (A) and the standardized Pareto chart (B) for bread weight.

Table 4. Analysis of variance for bread mass

Source	F-value	Probability (p)
A: Yeast	0.01	0.920
B: Improver	0.33	0.570
C: Ice/Water ratio	0.23	0.630
D: Cowpea flour	6.27	0.030
AA	7.45	0.016
AB	0.45	0.520
AD	0.70	0.420
BB	10.31	0.010
BD	2.78	0.120
CC	4.63	0.049
CD	0.70	0.418
DD	4.22	0.059

Legend: AA: quadratic effect of yeast, BB: quadratic effect of improver, DD: quadratic effect of cowpea flour, CC: quadratic effect of ice/water ratio, CD: interaction between ice/water ratio and cowpea flour, BD: interaction between improver and cowpea flour, AD: interaction between yeast and cowpea flour, AB: interaction between yeast and improver

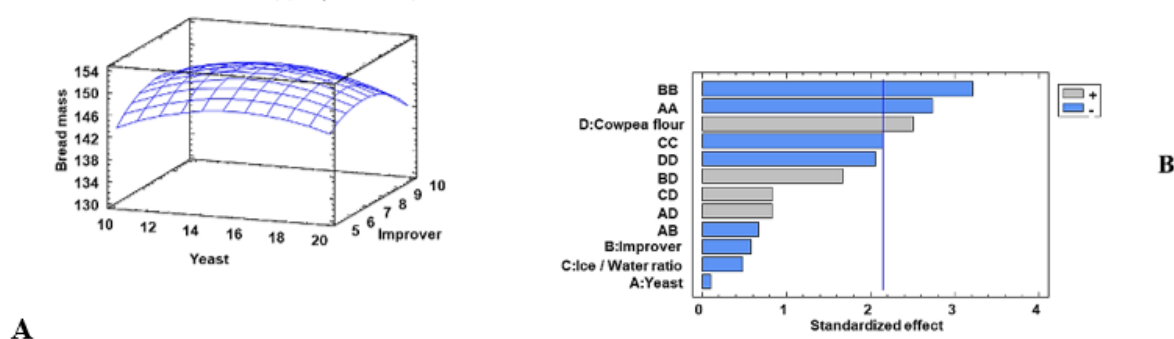


Figure 2. Estimated Response Surface (A) and Standardized Pareto Chart (B) for bread mass.

Analysis of variance (ANOVA) revealed that bread weight was significantly affected by cowpea flour (D), as well as by the quadratic effects of yeast (AA), improver (BB), and ice/water ratio (CC) ($p < 0.05$). In contrast, the linear effects of yeast, improver, and ice/water ratio, as well as interaction terms, were not statistically significant within the studied domain and were therefore not considered as determining factors for this response.

The positive linear effect of cowpea flour indicates that increasing its incorporation level leads to higher loaf weight. This increase can be primarily attributed to the high protein (generally above 20%) and dietary fiber contents of cowpea flour, which enhance the water absorption and water-holding capacity of the composite flour [30].

Legume proteins are rich in polar amino acids, which exhibit a strong affinity for water, thereby promoting greater dough hydration and moisture retention during mixing and baking [31]. Similar effects have been reported in composite flours enriched with red bean, mung bean, chickpea, and other legume flours, where increased water absorption resulted in higher final bread weight [22, 32, 33].

The significant quadratic effects of yeast, improver, and ice/water ratio indicate the existence of optimal processing conditions. Beyond these optimal levels, excessive yeast or improver addition, as well as deviations in hydration temperature, may negatively affect dough structure and moisture retention, leading to variations in bread weight. These results emphasize that bread weight is governed not only by formulation composition, particularly cowpea flour incorporation, but also by the careful control of technological parameters to achieve a balanced dough system.

3.2.3 Effects on variables of kneading time

The results of the analysis of variance (ANOVA) for the regression model of bread kneading time are presented in Table 5, highlighting the significant factors and interactions influencing the development of this parameter. Figure 3 shows the estimated response surface (A) and the standardized Pareto chart (B) for bread kneading time.

Table 5. Analysis of variance for kneading time

Source	F-value	Probability (p)
A: Yeast	4.48	0.051
B: Improver	0.22	0.644
C: Ice/Water ratio	34.59	0.000
D: Cowpea flour	14.17	0.002
AA	3.25	0.091
AB	2.66	0.124
AD	0.17	0.689
BB	0.10	0.758
CC	13.59	0.002
CD	1.49	0.240
DD	0.02	0.878

Legend: AA: quadratic effect of yeast, BB: quadratic effect of improver, DD: quadratic effect of cowpea flour, CC: quadratic effect of ice/water ratio, CD: interaction between ice/water ratio and cowpea flour, AD: interaction between yeast and cowpea flour, AB: interaction between yeast and improver

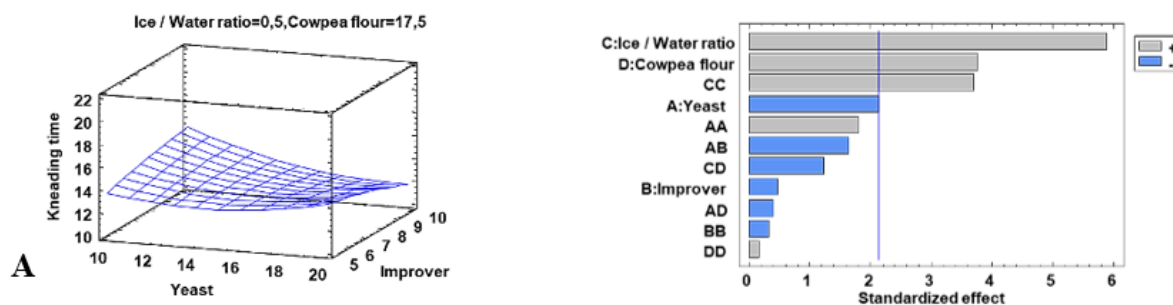


Figure 3. Estimated Response Surface (A) and Standardized Pareto Chart (B) for kneading time.

The analysis of variance (ANOVA) results indicate that kneading time is significantly affected by the ice/water ratio (C, $F = 34.59$; $p < 0.001$), cowpea flour content (D, $F = 14.17$; $p = 0.002$), and the quadratic effect of the ice/water ratio (CC, $F = 13.59$; $p = 0.002$). In contrast, yeast (A), improver (B), and all interaction terms, including the combination of ice/water ratio and cowpea flour (CD, $p = 0.240$), were not statistically significant. These results

indicate that kneading time is mainly controlled by the independent effects of the ice/water ratio and cowpea flour.

The increase in kneading time with higher cowpea flour levels can be attributed to its high content of non-gluten proteins (albumins and globulins) and dietary fibers, which strongly absorb water. As reported by [14], greater water absorption prolongs the time needed to develop a stable and homogeneous dough network. Similarly, increasing the ice/water ratio leads to longer kneading times due to enhanced hydration of protein and fiber components [34]. The significant quadratic effect of the ice/water ratio (CC) indicates a non-linear relationship, suggesting that there is an optimal range for this factor to achieve the desired dough consistency.

3.2.4 Effects on variables on fermentation time

Figure 4 shows the estimated Response Surface (A) and the Standardized Pareto Chart (B) for Fermentation time.

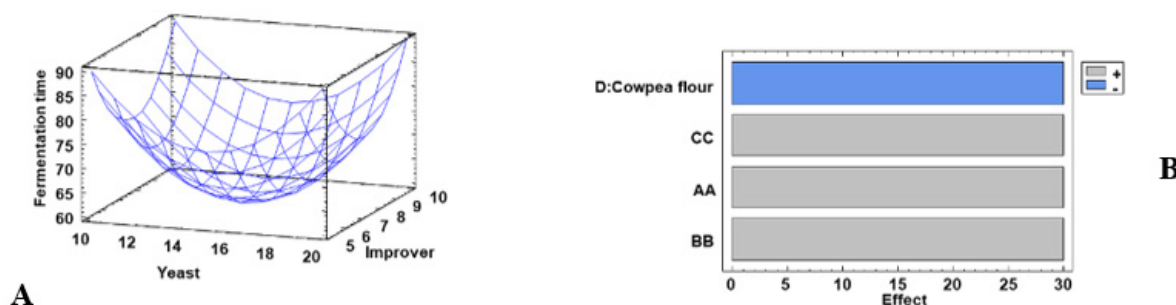


Figure 4. Estimated Response Surface (A) and Standardized Pareto Chart (B) for Fermentation time.

The analysis of variance (ANOVA) shows that cowpea flour and the quadratic effects of the ice/water ratio, yeast, and improver exert major influence on this response, with comparable effect magnitudes. In practice, cowpea flour has a negative effect on fermentation time, whereas the other factors exert positive effects. Furthermore, the reduction in fermentation time observed with the incorporation of non-breadmaking legume flours, such as cowpea, may be attributed to alterations in the wheat gluten network, leading to reduced gas-holding capacity and a less extensible dough structure [35]. Similar findings were reported by [36], who noted that increasing the proportion of legume flour decreases dough development time as the dough reaches its maximum consistency, particularly with the addition of 25% legume flour. Temperature is also a critical factor, as the metabolic activity of yeast and enzymes is directly dependent on thermal conditions. Lower temperatures slow enzymatic and yeast activity, thereby prolonging the time required to reach optimal fermentation [37].

Yeast and improvers generally act to shorten fermentation time [38]. However, the results of this study indicate that beyond a certain threshold, overdosing yeast or improvers may lengthen fermentation time. Excessive yeast can saturate the medium or, in high-sugar doughs, increase osmotic pressure, partially inhibiting yeast activity [39]. Similarly, excessive improver, often containing ascorbic acid or enzymes, may rigidify or weaken the gluten network, reducing gas retention and increasing fermentation duration [40]. Therefore, fermentation time is strongly modulated by the interaction among cowpea flour, yeast, improver, and the ice/water ratio, and requires precise dosing of each component to ensure a high-quality final product. These findings are consistent with the work of [41], in which high levels of legume flour resulted in the development of a weakened gluten structure, compromising dough stability, strength, elasticity, and handling properties, and ultimately reducing loaf volume. Thus, to enhance nutritional value while achieving acceptable bread quality, formulation optimization is essential.

3.3 Optimization of the Cowpea-Enriched Bread Formulation

The model predicted that the incorporation of 5% cowpea flour represented the optimal level for nutritional enrichment. The optimal conditions also included an ice/water ratio of 0.45 m/m, 14.66 g of yeast, and 7.07 g of improver. Figure 5 shows the overlay contour plot.

This optimized formulation was subsequently subjected to sensory analysis against the control (100% wheat flour) to evaluate consumer acceptability. Figure 5 shows that the contour plot depicts the effects of four independent variables: bread volume (blue), bread mass (red), kneading time (magenta), and fermentation duration (green) on

bread quality. The volume contours indicate a clear optimum, suggesting specific kneading and fermentation conditions maximize loaf volume. Mass contours partially overlap with volume, implying that optimizing volume may also enhance mass, though trade-offs exist. Kneading time and fermentation duration strongly influence both volume and mass, underscoring their key roles in dough development and final loaf structure. Overall, the plot highlights the importance of carefully managing kneading and fermentation to balance volume, mass, and texture, supporting the use of response surface methodology for process optimization.

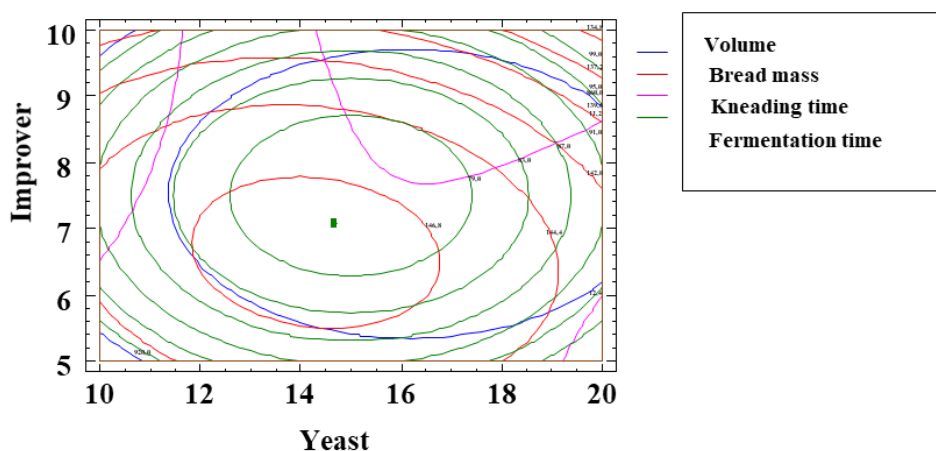


Figure 5. Overlay contour plot.

3.4 Sensory Evaluation

The results of the sensory evaluation are as follows:

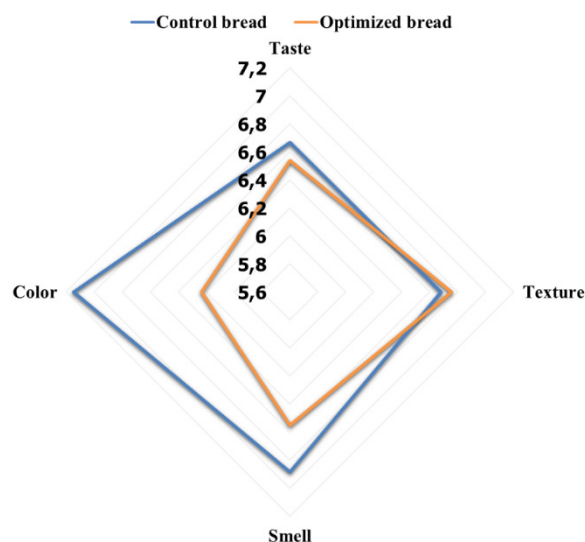


Figure 6. Radar chart of the control bread and the optimized bread.

The radar plot (Figure 6) comparing the control bread (in blue) to the optimized bread enriched with 5% cowpea flour (in red) reveals significant variations in sensory attributes. The taste of the optimized bread is slightly lower than that of the control but remains within an acceptable range ($>6/9$), with no statistically significant difference ($p = 0.691$), indicating that cowpea incorporation does not substantially affect flavor perception. Similarly, the texture shows a slight improvement in the enriched bread, although this change is not statistically significant ($p = 0.835$), suggesting a minor positive effect on crumb structure. In contrast, color exhibits a significant decrease compared to

the control ($p = 0.011$), likely due to the naturally darker hue of cowpea flour, while aroma is slightly lower but not significantly different ($p = 0.343$), reflecting subtle changes in the aromatic profile. These sensory alterations contribute to a modest reduction in overall acceptability, despite maintaining relatively comparable taste and acceptable texture. Previous studies support these observations: legume flours are prone to oxidation and thermal reactions, resulting in a more complex volatile compound profile with potentially stronger odor activity than wheat [42]. The characteristic flavor of legumes, including cowpea, can influence consumer acceptance of composite products [43]. Studies on the rheological properties, baking performance, and sensory quality of bread, chapatti, biscuits, and muffins replacing 5-25% wheat flour with cowpea flour indicated that incorporation above 15% reduced bread volume and sensory acceptability, whereas 5% addition improved sensory acceptability of muffins, bread, and chapattis [44].

Overall, these results indicate that enriching bread with 5% cowpea flour is feasible without significantly compromising taste or texture, although adjustments may be needed to enhance visual and olfactory appeal to optimize overall product acceptability.

4. Conclusion

This study demonstrated that Response Surface Methodology (RSM) is an effective tool for modeling and optimizing the formulation of bread enriched with cowpea flour. The optimization process identified an optimal substitution level of 5% cowpea flour, combined with specific processing conditions (14.66 g yeast, 7.07 g improver, and a 0.45 ice/water ratio), which enabled the production of bread with a specific volume and sensory acceptability comparable to those of the 100% wheat control, as confirmed by hedonic sensory evaluation. The optimized formulation exhibited a significant improvement in nutritional quality, notably through increased protein and dietary fiber contents, without compromising consumer acceptance. This 5% incorporation level represents a practical compromise between nutritional enhancement and technological feasibility. Overall, this work supports the use of cowpea flour as a locally available and sustainable ingredient to enhance food and nutritional security, particularly in the Senegalese context, where cowpea is widely produced and consumed.

As perspectives, further studies should focus on the selection of local cowpea varieties and the controlled production of cowpea flour, including systematic characterization of their physicochemical and functional properties. Such investigations would make it possible to assess the influence of cowpea variety and processing conditions (drying and milling) on flour composition and functional behavior, and consequently on dough rheology and bread-making performance. These future works would help to refine and generalize the present findings, which constitute a preliminary breadmaking trial using cowpea flour.

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Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

NFB: Methodology, Supervision, Writing-original draft, Writing-review and editing, Validation. **SC:** Experimentation, Methodology, Writing-original draft, and editing. **AS:** Methodology, Statistical analyses, Writing-original draft. **FNSV:** Writing-original draft, Writing-review, and editing. **SD:** Experimentation, Resources. **NCA:** Supervision. **CMD:** Supervision.

References

- [1] Bossou TK. Caractéristiques de production et de sécurité sanitaire du pain - une revue. *Eur Sci J.* 2022;18(8):129-157. doi:10.19044/esj.2022.v18n8p129
- [2] Sahel EG. Etat des lieux de la filière céréales locales au Sénégal. Gret, Enda Graf, SNC Lavalin, Cintech, MAE, CDE, ACIDI, MIA; 2006.
- [3] de Ubéda AA, Gourdon J. Conflit Russie - Ukraine : quelles conséquences sur les économies africaines? *FERDI Note Brève.* 2022;B233.

- [4] Abay K, Abdelfattah L, Breisinger C, Glauber J, Laborde D. La crise russo-ukrainienne constitue une grave menace pour la sécurité alimentaire en Égypte. *Food Security Portal*. 2022.
- [5] Mbengue M, Molczadzki D, Lullien-Pellerin V. La transformation du niébé au Sénégal : analyse des acteurs, opportunités et verrous pour la production d'aliments. *Innov Agron*. 2025;99:235-247. doi:10.17180/ciag-2025-vol99-art19
- [6] Potier de Courcy G, Frelut ML, Fricker J, Martin A, Dupin H. Besoins nutritionnels et apports conseillés pour la satisfaction de ces besoins. *Encycl Méd Chir*. 2023;10-308-A-10.
- [7] Dhingra S, Jood S. Physico-chemical and nutritional properties of cereal-pulse blends for bread making. *Nutr Health*. 2002;16(3):183-194. doi:10.1177/026010600201600304
- [8] Elharadallou S, Khalid I, Gobouri A, Abdel-hafez S. Amino acid composition of cowpea (*Vigna unguiculata* L. Walp) flour and its protein isolates. *Food Nutr Sci*. 2015;6:790-797. doi:10.4236/fns.2015.69082
- [9] Chivenge P, Mabhaudhi T, Modi AT, Mafongoya P. The potential role of neglected and underutilised crop species as future crops under water scarce conditions in Sub-Saharan Africa. *Int J Environ Res Public Health*. 2015;12(6):5685-5711. doi:10.3390/ijerph120605685
- [10] Agazounon C. Analyse des techniques de transformation de niébé en "atta" au Bénin. 2025.
- [11] Naiker TS, Gerrano A, Mellem J. Physicochemical properties of flour produced from different cowpea (*Vigna unguiculata*) cultivars of Southern African origin. *J Food Sci Technol*. 2019;56(3):1541-1550. doi:10.1007/s13197-019-03649-1
- [12] Timitey A, Adinsi L, Madode YEE, Cissé F, Hounhouigan D. Pratiques de production et caractéristiques physiques et chimiques du shô basi, un couscous de niebe (*Vigna unguiculata*) produit au Mali. *Afr J Food Agric Nutr Dev*. 2021;21:17509-17528. doi:10.18697/ajfand.97.19475
- [13] Monnet AF, Jeuffroy MH, Blumenthal D, Michon C. Associer blé et légumineuses, du champ aux gâteaux moelleux : variabilité matières premières / modification des procédés / ingénierie reverse. 2019.
- [14] Hallén E, İbanoğlu Ş, Ainsworth P. Effect of fermented/germinated cowpea flour addition on the rheological and baking properties of wheat flour. *J Food Eng*. 2004;63(2):177-184. doi:10.1016/S0260-8774(03)00298-X
- [15] Ali RS, Al-Obaidi LFH, Alssirag MA. Physical and nutritional properties of bread from wheat flour fortification with cowpea (*Vigna unguiculata*) flour. 2019.
- [16] Zaddem M. Application de la méthode des surfaces de réponse pour l'optimisation du blanchiment du son de blé par du peroxyde d'hydrogène et son incorporation dans une farine de pain. 2014.
- [17] Parenti O, Guerrini L, Zanoni B. Techniques and technologies for the breadmaking process with unrefined wheat flours. *Trends Food Sci Technol*. 2020;99:152-166. doi:10.1016/j.tifs.2020.02.034
- [18] Amjid M, Shehzad A, Hussain S, Shabbir MA, Khan MR, Shoaib M. A comprehensive review on wheat flour dough rheology. 2013;23:105-123.
- [19] Millar KA, Barry-Ryan C, Burke R, McCarthy S, Gallagher E. Dough properties and baking characteristics of white bread, as affected by addition of raw, germinated and toasted pea flour. *Innov Food Sci Emerg Technol*. 2019;56:102189. doi:10.1016/j.ifset.2019.102189
- [20] Cappelli A, Guerrini L, Cini E, Parenti A. Improving whole wheat dough tenacity and extensibility: A new kneading process. *J Cereal Sci*. 2019;90:102852. doi:10.1016/j.jcs.2019.102852
- [21] Chaurand M. Influence du type de mouture (cylindre vs meule) sur les teneurs en minéraux des différentes fractions du grain de blé en cultures conventionnelle et biologique. *Ind Céréale*. 2005;142:3-11.
- [22] Sreerama YN, Sashikala VB, Pratapa VM, Singh V. Nutrients and antinutrients in cowpea and horse gram flours in comparison to chickpea flour: Evaluation of their flour functionality. *Food Chem*. 2012;131(2):462-468. doi:10.1016/j.foodchem.2011.09.008
- [23] Rémésy C, Leenhardt F, Fardet A. Donner un nouvel avenir au pain dans le cadre d'une alimentation durable et préventive. *Cah Nutr Diététique*. 2014. doi:10.1016/j.cnd.2014.07.005
- [24] Mohamed B, Ghalem BR. Contribution à l'étude de l'influence d'intégration de la farine de pois chiche en panification. 2006.
- [25] Rizzello CG, Calasso M, Campanella D, De Angelis M, Gobetti M. Use of sourdough fermentation and mixture of wheat, chickpea, lentil and bean flours for enhancing the nutritional, texture and sensory characteristics of white bread. *Int J Food Microbiol*. 2014;180:78-87. doi:10.1016/j.ijfoodmicro.2014.04.005
- [26] Rostamian M, Milani JM, Maleki G. Physical properties of gluten-free bread made of corn and chickpea flour. *Int J Food Eng*. 2014;10(3):467-472. doi:10.1515/ijfe-2013-0004
- [27] Hung PV, Maeda T, Morita N. Dough and bread qualities of flours with whole waxy wheat flour substitution. *Food Res Int*. 2007;40(2):273-279. doi:10.1016/j.foodres.2006.10.007
- [28] Wang J, Rosell CM, Benedito de Barber C. Effect of the addition of different fibres on wheat dough performance and bread

- p>quality.
- Food Chem.*
- 2002;79(2):221-226. doi:10.1016/S0308-8146(02)00135-8
- [29] Anil M. Using of hazelnut testa as a source of dietary fiber in breadmaking. *J Food Eng.* 2007;80(1):61-67. doi:10.1016/j.jfoodeng.2006.05.003
- [30] Njintang N, Mbofung C, Waldron K. In vitro protein digestibility and physicochemical properties of dry red bean (*Phaseolus vulgaris*) flour: Effect of processing and incorporation of soybean and cowpea flour. *J Agric Food Chem.* 2001;49:2465-2471. doi:10.1021/jf0011992
- [31] Mohammed I, Ahmed AR, Senge B. Effects of chickpea flour on wheat pasting properties and bread making quality. *J Food Sci Technol.* 2014;51(9):1902-1910. doi:10.1007/s13197-012-0733-9
- [32] Wani IA, Sogi DS, Sharma P, Gill BS. Physicochemical and pasting properties of unleavened wheat flat bread (Chapatti) as affected by addition of pulse flour. *Cogent Food Agric.* 2016;2(1):1124486. doi:10.1080/23311932.2015.1124486
- [33] Sulieman AME, Sinada EA, Ali AO. Quality characteristics of wheat bread supplemented with chickpea (*Cicer arietinum*) flour. *Int J Food Sci Nutr Eng.* 2013;3(5):85-90.
- [34] Sharma S, Bajwa U, Nagi H. Rheological and baking properties of cowpea and wheat flour blends. *J Sci Food Agric.* 1999;79(5):657-662. doi:10.1002/(SICI)1097-0010(199904)79:5<657::AID-JSFA228>3.0.CO;2-3
- [35] Amjid M, Shehzad A, Hussain S, Shabbir MA, Khan MR, Shoaib M. A comprehensive review on wheat flour dough rheology. *Pak. J. Food Sci.* 2013;23:105-123.
- [36] Zhang Y, Hu R, Tilley M, Siliveru K, Li Y. Effect of pulse type and substitution level on dough rheology and bread quality of whole wheat-based composite flours. *Processes.* 2021;9(9):1687. doi:10.3390/pr9091687
- [37] Saraswath R, Hameed RS. Farinograph as a rheological tool to predict the quality characteristics for blend of wheat with pulse flour. *Int J Adv Agric Sci Technol.* 2018.
- [38] Meerts M, Ramirez Cervera A, Struyf N, Cardinaels R, Courtin CM, Moldenaers P. The effects of yeast metabolites on the rheological behaviour of the dough matrix in fermented wheat flour dough. *J Cereal Sci.* 2018;82:183-189. doi:10.1016/j.jcs.2018.06.006
- [39] Filipović VS. The effect of yeast extract addition on bread quality parameters. *J Serbian Chem Soc.* 2020;85(6):737-750. doi:10.2298/JSC191024137F
- [40] Pyler EJ. *Baking Science and Technology*. Vols I & II. Sosland Pub Co; 1988.
- [41] Hoque M, Biswas R, Alam M, Sarkar A, Haque MI, Hasan MM. Pulse fortified whole wheat bread: A review on dough rheology, bread quality, and sensory properties. *F1000Research.* 2022. doi:10.12688/f1000research.113421.1
- [42] Krause S. A product engineering approach to assess the reactivity of legume-based ingredients and its impact on the quality of processed foods such as cake [Theses]. Université Paris-Saclay; 2021.
- [43] Affrifah NS, Phillips RD, Saalia FK. Cowpeas: Nutritional profile, processing methods and products a review. *Legume Sci.* 2022;4(3):e131. doi:10.1002/leg3.131
- [44] Sharma S, Bajwa U, Nagi H. Rheological and baking properties of cowpea and wheat flour blends. *J Sci Food Agric.* 1999;79(5):657-662. doi:10.1002/(SICI)1097-0010(199904)79:5<657::AID-JSFA228>3.0.CO;2-3