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Optimization of complementary feed formulations from sprouted millet (*Pennisetum glaucum*) enriched with oyster mushroom (*Pleurotus geesteranus*) and cucurbit seeds (*Lagenaria siceraria*) using Central Composite Design

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Abstract

This study aims to optimize the formulation of a composite infant cereal made from sprouted millet and enriched with oyster mushrooms and cucurbit seeds, using a central composite design, in order to simultaneously achieve a maximum protein content in accordance with FAO/WHO recommendations and a satisfactory sensory quality of the resulting porridge. The independent variables selected were the amounts of sprouted millet flour (X_1), oyster mushroom powder (X_2), and cucurbit seeds powder (X_3). The results of the optimization, performed using R 4.5.2 and RStudio 2025.09.02+418, indicated that the target composite flour should contain 69.17% sprouted millet, 7.54% oyster mushrooms, and 23.29% cucurbit seeds in order to achieve the maximum protein content (Y_1) recommended for infants and ensure satisfactory sensory quality (Y_2) of the resulting porridge. Based on this, the infant flour formula developed, consisting of 80.17 g of millet, 8.75 g of oyster mushrooms, and 27 g of cucurbit seed, provides 13.85±0.0% protein, and the resulting porridge recorded an overall acceptability score of 5.80±0.61, indicating a good level of acceptability. These values are close to those predicted by the central composite design, with values of 13.77% and 5.74 for protein content and overall acceptability, respectively. Furthermore, this flour, which provided dry matter content of 91.96±0.05% and consists mainly of carbohydrates (65.47±0.09%) and fats (18.28±0.03%), nutrients that, along with proteins, contribute to caloric intake, could be proposed to combat childhood malnutrition, particularly protein-energy malnutrition in our countries.

Keywords: Central Composite Design; Childhood Malnutrition; Infant Flour; Sprouted Millet; Oyster Mushroom; Cucurbit Seeds

1. Introduction

A healthy diet ensures the survival, growth, and harmonious development of every child. This enables children to fully engage in age-appropriate activities by facilitating learning, the desire to explore, and, ultimately, the ability to participate and thrive in life in general. Conversely, malnutrition robs them of their future and plunges their lives into uncertainty [1]. Chronic malnutrition leads to stunted growth in height, weight, and cognitive development, while severe malnutrition causes wasting, emaciation, developmental delay, and immunosuppression [2]. In Côte d'Ivoire, the prevalence of stunting among children or chronic malnutrition is estimated at 22.4% according to the [3]. This chronic malnutrition, linked to food insecurity, is primarily due to the limited quality, quantity, and variety of the diet.

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According to Nguyen [4], the low energy density and poor nutritional quality of foods given to infants as a supplement to breast milk during the weaning period are the main causes of malnutrition. These foods are generally semi-liquid or liquid porridges made from starchy cereal flours that have not undergone any processing to increase their nutritional or energy value. In fact, the high starch content of these cereal-based preparations inevitably results in porridges with a thick consistency, forcing mothers to constantly add water to make them easier to digest. Consequently, these local cereals, ingredients high in starch and low in protein, which mothers use to prepare infant porridges, must not only undergo processes such as fermentation or germination to make them more digestible, but also be fortified in food formulations based on single-grain flours or mixtures of grains and tubers that are rich in carbohydrates but low in protein [5].

The benefit of sprouting is its ability to activate natural enzymes (amylases) that break down starch into easy-to-digest sugars. This not only increases the bioavailability of nutrients and neutralizes antinutritional factors, but also results in a much smoother, easier-to-swallow porridge, in which the amount of flour added to the water can be doubled without altering or affecting its consistency [6]. When enriching these flours with sprouted seeds (such as millet), it is important to use ingredients that can counterbalance the deficiencies or weaknesses of the seeds, primarily protein and fat. Thus, the addition of mushrooms and cucurbit seeds, both recognised sources of protein and fat will make it possible to create a highly nutritious complementary infant flour. This infant flour will be ideal for weaning, as this mixture will help address the deficiencies of traditional porridges by providing a concentrated source of nutrients in terms of protein, minerals, and energy [7]. A third and by no means least aspect is the infant's acceptance of the formulated baby food. Indeed, good acceptance of a food ensures that the infant actually consumes it, thereby helping to meet the infant's nutritional needs.

Thus, it appears essential to formulate infant flours using local raw materials that offer acceptable sensory qualities and good nutritional value to meet the needs of infants and young children, as recommended in [8]. To ensure that these two conditions are met, it is necessary to identify the optimal quantities of the formula's basic ingredients, such as sprouted millet flour, oyster mushroom and cucurbit seeds powders [9]. This study aims to formulate a flour blend that is both nutritious and palatable, through a central composite design. The influence of different amounts of flours or powders made from sprouted millet, mushrooms, and cucurbit seeds on the performance of the formulation is evaluated. The experimental design methodology for surface responses, using a central composite design, is applied during the enrichment process, in order to optimize the proportions of the various powders or flours to be included and to simultaneously maximize the protein content of the feed and the overall acceptability of the resulting porridge.

2. Material and methods

2.1. Material

Millet (*Pennisetum glaucum*), oyster mushrooms (*Pleurotus geesteranus*), and cucurbit seeds (*Lagenaria siceraria*) were all purchased directly from producers located in the cities of Niéllé (10°12'20''N ; 5°38'14''W), Abidjan (5°20'11''N; 4°1'36''W), and Arrah (6°35'55''N ; 3°58'20''W), respectively. The millet and cucurbit seeds were packaged separately in polypropylene bags, while the fresh mushrooms were stored in paper bags; all purchases were transported to the Laboratory of UPR of Biotechnologies (UFR Biosciences) at Félix Houphouët Boigny University.

2.2. Methods

2.2.1. Production of Flours and Powders

Soaking and sprouting millet grains

The millet grains were sprouted using a modified version of the method described in [10]. After removing impurities by manual winnowing and thoroughly washing 4 kg of millet grains (4 washes) in a gourd with tap water, the clean grains were soaked. This soaking was carried out at room temperature for 6 hours at a grain-to-water ratio of 1:3 (by weight). The soaking water was changed twice, then discarded, and the moist grains were recovered through a colander, where they were thoroughly rinsed, then spread out on thin layers of damp cotton placed in colanders for sprouting. These grains, left to sprout at room temperature for 48 hours, were sprayed with water at regular intervals.

Processing of Sprouted Millet Grains into Flour

After 48 hours of sprouting, the millet grains that had successfully sprouted were collected and dried in a ventilated oven at 50 °C for 48 hours. These grains were then ground using a blender (Silver Crest, China) and sieved through a

500 µm mesh sieve. The resulting fine flour was stored in sterile glass jars, sealed airtight, and kept at 4 °C for use in the various formulations.

Production of mushroom powder

The mushrooms were sorted to remove those damaged during transport and any substrate debris. After sorting, 5 kg were gently washed with tap water to remove impurities. The washed mushrooms were dried in a ventilated oven at 50 °C for 24 hours according to the modified method of [11]. Once dried, they were ground using a blender (Silver Crest, China) and sieved using a 500 µm sieve. The resulting fine powder was stored in sterile, airtight glass jars and kept at 4 °C for further work.

Production of cucurbit seeds powder

Cucurbit seeds were meticulously sorted to remove damaged seeds and sand. The selected seeds were washed with tap water and shelled. After shelling, 2 kg of the resulting kernels were roasted and then finely ground to obtain pistachio powder. This powder was subsequently stored in sterile glass jars at 4°C.

2.2.2. Formulation of infant flours by optimizing overall acceptability and protein content

The formulation of infant flours was carried out using the design of experiments method, specifically the central composite design, to determine the ideal proportion for each ingredient used. This will allow us to identify the best nutritional value of the flours in terms of protein, combined with good overall acceptability provided by their porridges.

We began by defining the experimental domain and the experimental design.

The experimental domain:

In this study, three factors were used for each flour formulation: millet (X_1), oyster mushrooms (X_2), and cucurbit seeds (X_3). The study domain (Table 1) was determined based on the levels (-1, +1) of the factorial design, ((-α) and (+α)) of the star designs, and level 0 of the middle trials. The coded values of these different levels are (-1) and (+1) for the factorial design trials, and (0) for the central trials. In contrast, those for the star trials (-α) and (+α) were determined using formula (1):

$\alpha = (Nf)\ 0.25$ (1)

Where Nf = (2 × number of factors) represents the number of points in the factorial design to be considered. In our case with 3 factors,

$\alpha = (2^3)^{0.25} = 1.682$

As for the actual values corresponding to the different coded values, they were determined using formula (2):

$x_k = x_{cent} + Z_k \times (x_{max} - x_{min} / Z_{max} - Z_{min})$ (2)

Where Z_k is the coded value for each factor level (-1.682; -1; 0; +1; 1.682).

x_k is the actual value of each factor within the study domain.

x_{cent} is the actual value of each factor at the center of the experimental domain.

Table 1 Experimental domain

Factors	**-1.682(-α)**	**-1**	**0**	**+1**	**+1.682(+α)**
X_1 : Millet (g)	65	72.1	82.5	92.90	100
X_2 : mushroom (g)	0	7.1	17.5	27.9	35
X_3 : cucurbit seeds (g)	0	6.08	15	23.92	30

Note: The extreme values (65 and 100 g), (0 and 35 g), and (0 and 30 g), respectively for X_1, X_2, and X_3, were determined from the literature [12-13].

Experimental matrix

Developing the experimental design requires determining the number of experiments to be conducted. This determination was made using the method described in [14]. According to this method, the total number of trials to be conducted is the sum of the trials in the factorial design (2^K), the star trials (2k), and the central trials (n_0), and is determined using the following formula (3):

$$N=2^k + 2k + n_0 \quad (3)$$

K represents the number of factors, 2K represents the number of trials in the factorial design, 2K represents the number of radial trials, and n0 represents the number of central trials within the experimental domain.

Regarding the number of central trials, [15] recommends using a number between 2 and 4 for central experiments. In our study, 3 central trials were selected, resulting in a total of 17 trials to be conducted for all factorial, central, and star trials (Table 2).

Table 2 Experimental matrix showing the different trials to be conducted

Trials		**Coded values**			**Actual values (g)**		
		X_1	X_2	X_3	x_1	x_2	x_3
1	Factorial trials	-1	-1	-1	72.5	7.1	6.08
2		1	-1	-1	92.9	7.1	6.08
3		-1	1	-1	72.5	27.9	6.08
4		1	1	-1	92.9	27.9	6.08
5		-1	-1	1	72.5	7.1	23.92
6		1	-1	1	92.9	7.1	23.92
7		-1	1	1	72.5	27.9	23.92
8		1	1	1	92.9	27.9	23.92
9	Star trials	-1.682	0	0	65	17.5	15
10		1.682	0	0	100	17.5	15
11		0	-1.682	0	82.5	0	15
12		0	1.682	0	82.5	35	15
13		0	0	-1.682	82.5	17.5	0
14		0	0	1.682	82.5	17.5	30
15	Central trials	0	0	0	82.5	17.5	15
16		0	0	0	82.5	17.5	15
17		0	0	0	82.5	17.5	15

X_1, X_2, and X_3 correspond to the coded values of the three formulation factors: sprouted millet, mushroom, and cucurbit seeds. x_1, x_2, and x_3 correspond to the actual values representing the quantities of each ingredient to be included in the formulation.

2.2.3. Analysis of the different formulations

Protein content of the different formulations

The determination of total protein in the different formulations was performed using the Kjeldahl method [16]. Thus, the total nitrogen obtained after sulfuric acid digestion of the plant matrix in the presence of a catalyst (selenium), distillation and capture of the distillate in boric acid, and titration with sulfuric acid, was converted to total protein using the nitrogen-to-protein conversion factor (6.25).

Sensory evaluation of the different formulations

- Preparation of the porridges

The porridges for the different formulations were prepared as described in [17] with slight modifications. An amount of 50 g of flour mixed with 100 mL of tap water was poured into 250 mL of boiling water in a stainless steel saucepan. The mixture was cooked over low heat for 15 min, stirring constantly to prevent the porridge from sticking. At the end of cooking, 8 g of sugar was added to the porridge.

- Presentation of the porridges and evaluation method

The sensory evaluation of the different porridges was determined through a hedonic test conducted according to the modified method of [18]. This test was conducted at the Community-Based Urban Health Center (CSU-BC) in Riviera Palmeraie, located in the city of Abidjan, Côte d'Ivoire, with a panel of 30 untrained nursing mothers. The porridges from the seventeen (17) formulations, coded with three-digit numbers, were prepared successively in a random and randomized manner. To do this, two days were required for the tasting of the porridges from the 17 trials (formulations), at a rate of 4 porridges per half-day with 5 porridges on the last half day.

The judges were asked to look at, taste, smell, touch, and rate their level of appreciation for each descriptor (colour, smell, taste, texture, and overall acceptability) on a linear rating scale ranging from 1 (lowest) to 9 (highest). On this scale, 1 indicates "I hate it," 2 "I don't like it," 3 "I neither like nor dislike it," 4 "I like it a little," 5 "I like it," 6 "I like it moderately," 7 "I like it quite a bit," 8 "I like it a lot," 9 "I like it extremely." The pleasure perceived by each panelist was evaluated on this 9-point hedonic scale, and the four three-digit-coded porridge samples from each session were presented to them one by one in a randomized order in identical dishes. Each taster was given a glass of water to rinse her mouth after tasting each sample.

2.2.4. Analysis of the biochemical components of the optimal flour

The methods described by AOAC [16] were used to determine the dry matter content as well as the total protein, total fat, ash, and carbohydrate contents of the optimal flour. The dry matter content was determined by drying at 105 °C to constant weight for 24 hours. The Kjeldahl method was used to determine the total protein content. The total fat content was determined using the Soxhlet method. The optimal flour was incinerated at 550 °C in a muffle furnace to determine the ash content. The total carbohydrate content was calculated based on the percentages of the aforementioned components. Crude fiber content was determined by AOAC [16]. As for energy value, it was determined according to the method [19], which stipulates that: Energy value (kcal/100 g) = (carbohydrates × 4) + (lipids × 9) + (proteins × 4)

2.2.5. Statistical Analyses

Statistical analyses, including regression, ANOVA, and optimization, were performed using R 4.5.2 and RStudio 2025.09.02+418 software.

The experimental data were fitted to the following second-order polynomial model:

$$\mathbf{Y_n = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X^2{}_1 + b_{22}X^2{}_2 + b_{33}X^2{}_3 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3}$$

Where Y_n is the experimental response; $b_0 \ldots b_{23}$ are the regression coefficients; X_1 represents the amount of millet, while X_2 and X_3 are the amounts of mushrooms and Cucurbit seeds, respectively.

3. Results and discussion

3.1. Results of the Experimental Matrix

The Central Composite Design was used to formulate infant flours based on sprouted millet, mushrooms, and cucurbit seeds. The overall responses obtained from the seventeen (17) trials of the experimental matrix are presented in Table 3. This table presents both the coded and actual values for each of the formulations produced, as well as the corresponding experimental responses. These experimental responses correspond to the protein content (Y_1) of the infant flours and the overall acceptability (Y_2) of their porridges, determined using the above described methods in [17] and [18].

The protein content of the different formulations ranges from 9.66% to 15.11%. The lowest protein content was observed for formulation 2, containing 92.9 g of sprouted millet flour, 7.1 g of mushroom powder, and 6.08 g of African pistachio powder. Meanwhile, trial 7, formulated with 72.1 g of sprouted millet flour, 27.9 g of mushroom powder, and 23.92 g of cucurbit seeds powder, had the highest protein content.

As for the scores assigned (Table 3) for overall acceptability by the panelists, they ranged from 4.88 for formulation 7 to the porridges of formulations with an acceptability level of 6, namely 6.28 (formulation 2), 6.14 (formulation 5), and 6.07 (formulation 11). Formulation 7 (72.1 g of sprouted millet flour; 27.9 g of mushroom powder, and 23.92 g of cucurbit seeds powder) was the porridge least appreciated by the panel (with a rating of 4, corresponding to "I like it a little"), despite its higher protein content (15.11%). In contrast, the porridges from formulations 2, 5, and 11 were the most liked, receiving a level 6 ("I like it") rating. Statistical analysis showed a significant difference in this level 6 rating, with the porridges from formulations 2 (6.28) and 5 (6.14) being the most liked (Table 3).

Table 3 Experimental design and experimental results

trials		Coded values			Actual values (g)			experimental results	
		X_1	X_2	X_3	x_1	x_2	x_3	Y_1	Y_2
1	Factorial trials	-1	-1	-1	72.1	7.1	6.08	10.22^{k}	5.71^{ab}
2		1	-1	-1	92.9	7.1	6.08	9.66^{m}	6.28^{a}
3		-1	1	-1	72.1	27.9	6.08	12.62^{g}	4.88^{b}
4		1	1	-1	92.9	27.9	6.08	11.76^{i}	5.29^{ab}
5		-1	-1	1	72.1	7.1	23.92	13.63^{e}	6.14^{a}
6		1	-1	1	92.9	7.1	23.92	12.57^{g}	5.04^{ab}
7		-1	1	1	72.1	27.9	23.92	15.11^{a}	4.88^{b}
8		1	1	1	92.9	27.9	23.92	13.99^{c}	5.15^{ab}
9	Star trials	-1.682	0	0	65	17.5	15	13.54^{f}	5.18^{ab}
10		1.682	0	0	100	17.5	15	11.91^{h}	5.96^{ab}
11		0	-1.682	0	82.5	0	15	10.83^{j}	6.07^{ab}
12		0	1.682	0	82.5	35	15	13.90^{d}	5.52^{ab}
13		0	0	-1.682	82.5	17.5	0	10.00^{l}	5.52^{ab}
14		0	0	1.682	82.5	17.5	30	14.59^{b}	5.73^{ab}
15	Central trials	0	0	0	82.5	17.5	15	12.60^{g}	5.96^{ab}
16		0	0	0	82.5	17.5	15	12.58^{g}	5.96^{ab}
17		0	0	0	82.5	17.5	15	12.61^{g}	5.92^{ab}

X_1 = coded value of millet sprouted for 48 hours; X_2 = coded value of mushroom; X_3 = coded value of cucurbit seeds; x_1 = actual value of millet; x_2 = actual value of mushroom; x_3 = actual value of cucurbit seeds; Y_1 = Protein (%); Y_2 = Overall acceptability

For a new food to gain acceptance among the target population, not only must its nutritional potential in this case, its protein content be sufficient to meet the needs of that target group, but it must also be accepted on a sensory level. This is to ensure that it is actually consumed by the target group to meet their nutritional needs. Thus, there is a need to perform an optimization that takes into account both the recommended protein intake for complementary foods and the maximum acceptability obtained. To do this, the second-order polynomial model defining the relationship between the various variables studied (X) and the experimental responses (Y) obtained must be readjusted in order to identify the best formulation in terms of the desired outcome.

3.2. Mathematical model of protein content in formulations and the resulting overall acceptability of the porridge

There is a relationship between the various parameters studied (X_1, X_2, and X_3) and the various experimental results obtained. This relationship is of the form:

$$\mathbf{Yn = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X^2_1 + b_{22}X^2_2 + b_{33}X^2_3 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3}$$

We used R version 4.5.2 and RStudio version 2025.09.02+418 to determine the various coefficients (b_0, b_1, b_2, b_3, b_{11}, b_{22}, b_{33}, b_{12}, b_{13}, and b_{23}) and their significance using the experimental design and the results of protein analysis of the formulations and sensory evaluation of their mash. The coefficients assigned to each parameter for protein content and the overall acceptability of their porridges, their linear, quadratic, and interaction effects, as well as the coefficient of determination R^2 and the *P-value* for the lack of fit, are listed in Table 4.

Table 4 Regression coefficients of the polynomial models

Coefficients	**Coefficients estimated**	
	Proteins	General acceptability
b_0	12.59***	5.96***
Linear		
b_1	-0.46***	0.11 ^{ns}
b_2	0.92***	-0.28*
b_3	1.37***	-0.04 ^{ns}
Quadratic		
b_{11}	0.04*	-0.18 ^{ns}
b_{22}	-0.08***	-0.10 ^{ns}
b_{33}	-0.11***	-0.16 ^{ns}
Cross product		
b_{12}	-0.04*	0.15 ^{ns}
b_{13}	-0.09***	-0.23^{ns}
b_{23}	-0.20***	0.08 ^{ns}
R^2	0.9997	0.7428
Fitting default (P-value)	2.097e-11^{ns}	0.1493^{ns}

*Significant at P = 0.05; ***Significant at P = 0.001; ns: not significant; R^2: Coefficient of Regression; *p-value* : Probability of misfit; b_1, b_2, and b_3 = linear regression coefficients corresponding to X_1, X_2, and X_3, respectively; b_{11} = quadratic regression coefficients of X_1; b_{22} = quadratic regression coefficients of X_2; b_{33} = quadratic regression coefficients of X_3; b_{12} = regression coefficients of the interaction between X_1 and X_2; b_{13} = regression coefficients of the interaction between X_1 and X_2; b_{23} = regression coefficients of the interaction between X_2 and X_3.

Two major findings emerge from the analysis of this table. First, the values of the coefficient of determination R^2 for the regression model of protein content (0.9993) and overall acceptability (0.7428), being close to 1, indicate that the second-order polynomial models accurately describe the responses within the chosen experimental range. Furthermore, the non-significance of the residuals for each response indicates a good overall fit of the models. Thus, the proportions of millet flour (X_1), mushroom powder (X_2), and cucurbit seeds (X_3) play a key role in protein content (Y_1) and overall acceptability (Y_2). This model can be used to optimize the factors.

3.3. Effect of factors on the protein content (Y_1) of the formulated flours

Table 4 above shows the multiple regression coefficients and the significant effects ($p \leq 0.05$) of the various factors studied on the protein content (Y_1) of the flours formulated from the 17 trials. This table allowed us to establish the following mathematical model based on the various coefficients:

$$Y_1 = 12.59 - 0.46\,X_1 + 0.92X_2 + 1.37\,X_3 + 0.04\,X^2_1 - 0.09\,X^2_2 - 0.11X^2_3 - 0.04X_1X_2 - 0.09X_1X_3 - 0.20X_2X_3$$

We observe that, overall, the coefficients related to the various effects (linear, quadratic, and interaction) are significant for protein content. Regarding the linear effect, the coefficients of all three factors have a highly significant effect ($p = 0.001$) on protein content. Thus, millet X_1 has a negative linear effect on protein content (-0.46), whereas oyster mushroom X_2 (+0.92) and cucurbit seeds X_3 (+1.37) have a positive linear effect.

Among the three factors, oyster mushroom X_{22} (-0.09) and cucurbit seeds X_{23} (-0.11) have a highly significant negative quadratic effect ($p = 0.001$) while millet X12 (+0.04) has a significant positive quadratic effect ($p = 0.05$) on protein content.

There is a highly significant negative interaction ($p = 0.001$) between millet and Cucurbit seeds (-0.09 for X_1X_3), between oyster mushrooms and Cucurbit seeds (-0.20 for X_2X_3), as well as between millet and oyster mushrooms (-0.04 for X_1X_2) ($p = 0.05$), which negatively impacts protein content.

These various effects are illustrated by the response surfaces presented in Figure (1 A-C):

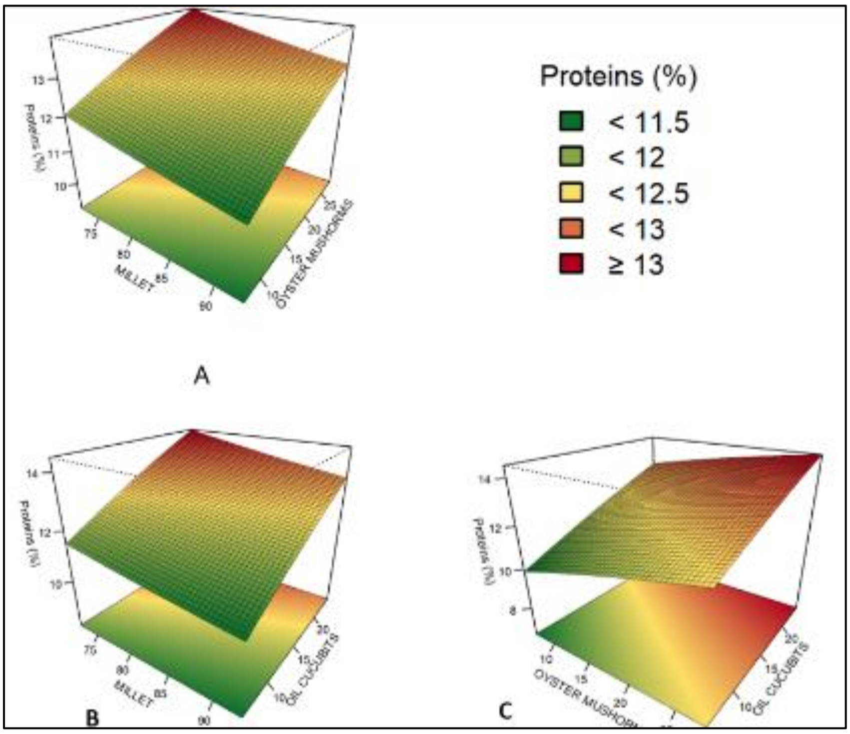

Figure 1 Response surfaces for protein content

X_1: millet — 1A: effect between X_1 and X_2 with X_3 set to 17.5 g

X_2: oyster mushroom — 1B: effect between X_1 and X_3 with X_2 set to à 15g

X_3: cucurbit seeds — 1C: effect between X_2 and X_3 with X_1 set to à 82.5g

Figure 1A shows the effect of millet and oyster mushrooms on the protein content of the formulations. We observe a flat surface that slopes along the millet axis with a slight curvature. This indicates that increasing the amount of mushrooms leads to a gradual increase in protein content, while increasing the proportion of millet results in a slight decrease in protein content. These same trends are observed in Figure 1B, which illustrates the effect of millet and cucurbit seeds on protein content. As for Figure 1C, it shows the effect of oyster mushrooms and cucurbit seeds on protein content. The upward slope indicates that the simultaneous increase in the proportions of these factors increases the protein content more than their separate increases.

The response surfaces show that oyster mushrooms and cucurbit seeds positively influence the protein content of the formulations, while increasing the amount of millet leads to a slight decrease in this response.

The negative effect of millet on protein content is due to its low protein content. In contrast, the positive effect of oyster mushrooms and cucurbit seeds s is a result of their high protein content. Enriching millet flour with oyster mushrooms and cucurbit seeds s promotes an increase in the protein content of infant formula made from millet, thereby highlighting the potential of these ingredients for the nutritional enrichment of millet-based infant formulas. Since this flour has a high protein content, it can be used to combat protein-energy malnutrition.

3.4. Effect of factors on the general acceptability of porridges made from the formulated flours

The regression coefficients presented in Table 4 indicate a significant negative linear effect ($p = 0.05$) of oyster mushrooms on the general acceptability of the porridges. This significant effect leads to the following mathematical model:

$$\mathbf{Y_2 = 5.96 - 0.28\, X_2}$$

Figure (2 A-C) presents the response surfaces related to general acceptability.

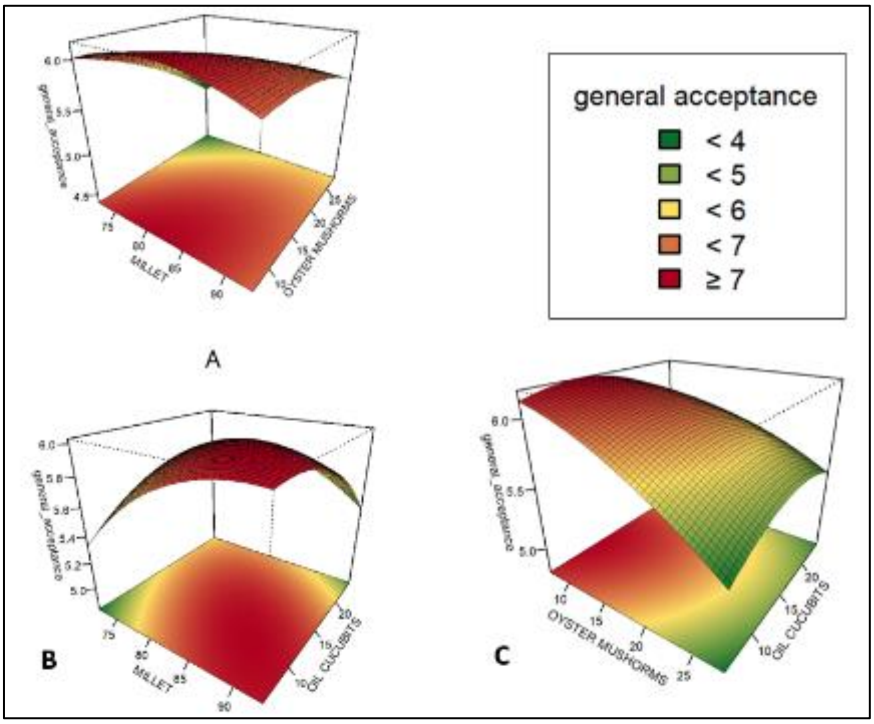

Figure 2 Response surfaces for general acceptability

X₁: millet — 2A: effect between X_1 and X_2 with X_3 set to 17.5 g

X_2: oyster mushroom — 2B: effect between X_1 and X_3 with X_2 set to à 15g

X_3: cucurbit seeds — 2C: effect between X_2 and X_3 with X_1 set to à 82.5g

Figure 2A shows the interaction between millet and mushrooms. A downward slope along the mushroom axis and a slight curvature are observed at this point. This indicates that an increase in the proportion of mushrooms tends to reduce the overall acceptability of the formulations. Regarding Figure 2B, which shows the effect of millet and cucurbit seeds, we observe a dome-shaped curve indicating that overall acceptability increases until it reaches an optimum near the central values for millet and cucurbit seeds and decreases as it approaches their extreme values. As for Figure 2C, it highlights the effect of mushrooms and cucurbit seeds. We observe a steep downward slope as the amount of mushroom increases, indicating a decrease in general acceptability for high and combined amounts of cucurbit seeds and mushroom.

In summary, the oyster mushroom is the factor with the most pronounced effect on general acceptability.

The negative effect of oyster mushrooms on acceptability is due to their slightly tart taste and high fiber content, which rapidly thickens the porridge [20]. The combination of sprouted millet, mushrooms, and cucurbit seeds s in intermediate quantities in this formulation is beneficial for improved general acceptability.

These results confirm the existence of a trade-off between nutritional enrichment and the sensory quality of the formulations, thus highlighting the importance of using an optimization approach.

3.5. Model Optimization and Validation

The optimization was performed using R 4.5.2 and RStudio 2025.09.02+418 via the desirability function, with the objective of targeting a protein content of 13% as recommended by the [21], while maximizing general acceptability. The optimal formula proposed by the mathematical model has the following composition: 80.17 g of millet, 8.75 g of oyster mushrooms, and 27 g of cucurbit seeds. The experimental phases determined a protein content of 13.85 ± 0.07% with a general acceptability of 5.80 ± 0.61. Statistical analysis showed that there is no significant difference ($p > 0.05$) between the values predicted by the model and the experimental values (Table 5).

Table 5 Experimental values and predicted values of the optimal flour

Reponses	Observed values	predicted values
Proteins (%)	13.85±0.07^{a}	13.77^{a}
general acceptability	5.80±0.61^{a}	5.74^{a}

Within the same row, values assigned the same letter are not significantly different at the 5% level according to Duncan's test.

Optimizing the formulation of millet flour enriched with edible mushroom and cucurbit seeds powder is advisable since it allows for the formulation of an infant cereal with a good protein content and a porridge that is accepted. This optimal cereal can be recommended to combat childhood malnutrition.

3.6. Nutritional Composition of the Optimized Formula

Table 6 presents the carbohydrate, total protein, fat, ash, crude fiber, and energy contents of the optimal formula compared to the recommended intake per 100 g of fortified infant cereal for infants aged 6 to 36 months [21-22]. The protein, fat, and ash contents of the optimal flour meet the levels recommended by [21-22]. These results are similar to those reported in [23], which found protein content ranging from 13.73 g to 15.27 g after adding mushroom powder to a flour blend of millet, cowpea, and peanut in a 1:1 ratio.

Table 6 Nutritional value of the optimal formula (100 g)

Nutrients (g/100 g)	Optimal composite flour	Ref. per 100 g
Dry matter	91.96±0.05	Nd
Carbohydrate	65.44±0.06	Nd
Total Proteins	13.85±0.04	8 - 22
Total fats	18.28±0.03	17.6 - 24
Crude fiber	5.19±0.01	3-6

Ash	2.39±0.02	Nd
Energy (Kcal)	461.12±0.01	400

± means standard deviation

This optimized flour dispached good nutritional potential. Its consumption could be highly beneficial for children aged 6 to 36 months. It could therefore promote these children's growth while preventing protein-energy malnutrition.

3.7. Sensory characteristics of the optimized flour porridge

Figure 3 presents the scores assigned to the various sensory characteristics of the optimal formula porridge, including colour, odour, taste, texture, viscosity, and overall acceptability. These scores show that all these aspects were accepted, with an average score ranging from 5.8 to 6.5.

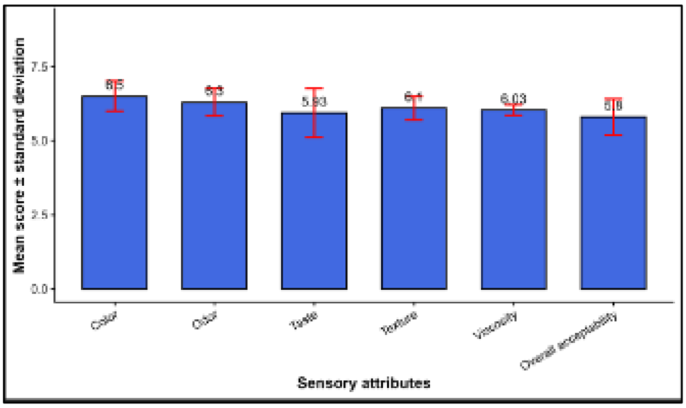

Figure 3 Average score for the sensory characteristics of the optimal flour porridge

The sensory acceptability of the porridge is very important for its consumption by children [24]. The tasters appreciated the attractive colour, pleasant smell, acceptable taste, smooth texture, and viscosity of the porridge. These factors led them to generally accept this porridge.

4. Conclusion

In this study, the central composite experimental design was successfully applied to optimize the fortification of a composite flour made from sprouted millet with oyster mushroom and cucurbit seed powders. The protein content of this composite flour and the overall acceptability of the resulting porridge were taken into account. The optimal enriched composite flour should contain 69.17% sprouted millet flour, 23.29% oyster mushroom powder, and 7.54% cucurbit seed powder. The flour and porridge prepared under these optimal conditions showed a protein content of 13.85% and an average score of 5.80±0.61 for overall acceptability. These characteristics are similar to the statistical predictions obtained from the desirability function derived from the R 4.5.2 and RStudio 2025.09.02+418 software packages. This flour could be used to address nutritional risks, particularly among children living in rural areas and could help reduce childhood malnutrition.

Compliance with ethical standards

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Disclosure of conflict of interest

Authors declare no conflict of interest.

Statement of ethical approval

Ethical approval was obtained from the Cocody Health District. Written and signed approval was obtained from the Cocody-Bingerville Departmental Director of Health. The study targeted wet nursing mothers attending the Community-Based Urban Health Center (CSU-BC) in Riviera Palmeraie, Cocody.

Statement of informed consent

The purpose of the study was explained verbally to the nursing mothers prior to their participation. Their informed consent was obtained.

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