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Optimization of Nutrient-Dense Plantain Dough Meals through Millet Bran Valorization and Defatted Soybean Fortification

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ABSTRACT

Unripe plantain is an important staple food in sub-Saharan Africa but is limited by its relatively low protein and fibre contents. This study investigated the potential of millet bran and defatted soybean flour to improve the nutritional, functional and sensory quality of plantain-based dough meals. Four optimized composite flour formulations selected using response surface methodology were processed into dough meals alongside a 100% plantain control and evaluated for proximate composition, mineral profile, pasting properties, colour characteristics, sensory quality and multivariate relationships. Enrichment significantly increased protein (9.01–21.40%), crude fibre (1.00–3.00%), ash, calcium and iron contents while reducing carbohydrate content ($p < 0.05$). Composite formulations also exhibited lower peak, breakdown, and setback viscosities, indicating that millet bran and soybean modified starch gelatinization and paste stability were enhanced through formulation interactions. Despite darker colour development, the enriched dough meals maintained acceptable sensory quality. Principal component analysis explained 80.2% of the total variation within the first two components. Clearly, it differentiated the formulations according to their nutritional, functional and sensory characteristics, identifying the enriched samples as mineral- and fibre-rich, while the control was primarily associated with superior sensory attributes. Collectively, these findings demonstrate that fortification of plantain flour with millet bran and defatted soybean flour enhances nutritional quality while maintaining acceptable functionality and consumer preference, highlighting millet bran as a promising value-added ingredient for developing more nutrient-dense and sustainable plantain-based staple foods.

KEYWORDS: Plantain flour; dough meal; Millet bran; Defatted soybean flour; Optimization; Principal component analysis

1. INTRODUCTION

Food systems worldwide face the dual challenge of providing nutritionally adequate diets while ensuring environmental sustainability for a rapidly growing population (Haddad et al., 2016; Egamberdiev et al., 2026). Despite improvements in global food production, a recent study by Elegbeleye et al. (2025) revealed that micronutrient deficiencies and protein inadequacy remain widespread, particularly in low- and middle-income countries where diets are predominantly based on starchy staples (FAO, IFAD, UNICEF, WFP, and WHO, 2023). Developing nutrient-dense staple foods from locally available crops and underutilized agricultural resources has therefore emerged as an important strategy for improving diet quality while supporting sustainable food systems (Hunter et al., 2019; Ndlovu et al., 2024). Composite flour technology, which combines complementary plant materials with different nutritional and functional attributes, provides an attractive approach for enhancing the nutritional value of traditional staple foods without substantially altering established dietary patterns.

Plantain (*Musa paradisiaca L.*) is one of the most important staple crops consumed in tropical and subtropical regions, particularly in sub-Saharan Africa (Pérez-Donado et al., 2023), which contributes significantly to household food security and energy intake. Immature plantain is valued for its high starch content, appreciable resistant starch fraction and relatively low glycaemic potential compared with ripe fruits, making it suitable for the preparation of traditional dough meals and other staple products (Oyeyinka and Afolayan, 2021; Pérez-Donado et al., 2023; Bhattacharjee et al., 2026). However, plantain flour is composed predominantly of carbohydrates and contains relatively low amounts of protein, crude fibre and several

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essential micronutrients (Anajekwu et al., 2020). These nutritional limitations reduce its capacity to provide balanced nourishment, especially among populations with limited access to animal-derived protein sources. Consequently, improving the nutritional density of plantain-based foods through strategic fortification has become an area of increasing research interest.

Soybean (*Glycine max L.*) is widely recognized as one of the richest plant sources of high-quality protein, providing a balanced amino acid profile that complements the lysine deficiency characteristic of many cereal- and tuber-based foods (Olanipekun et al., 2021; USDA, 2023; Siddique and Sana-e-Mustafa, 2024). Following oil extraction, defatted soybean flour retains a concentrated protein fraction together with minerals and bioactive compounds, making it particularly suitable for food fortification (Murtaza et al., 2024). One of the techno-functional important aspects of soybean reported by Zhang et al. (2025) is that the proteins influence the physicochemical behaviour of starch-based systems through protein–starch interactions that modify water absorption, gelatinization, gel formation and rheological properties. These interactions affect not only processing performance but may also influence starch digestibility and the structural characteristics of finished food products.

Millet bran represents another valuable yet underutilized food resource. Generated as a by-product during millet milling, bran is often diverted to animal feed despite being rich in crude fibre, minerals, phenolic compounds and other bioactive constituents (Tripathi et al., 2023; Ma et al., 2024). According to Galanakis (2022), the increasing interest in circular food systems and sustainable resource utilization has highlighted the potential of cereal by-products as functional ingredients capable of enhancing both nutritional quality and environmental sustainability. The high fibre content of millet bran can alter starch organization within composite flour systems by modifying water distribution, restricting starch granule swelling and influencing paste rheology (Dubey et al., 2025). These structural changes may subsequently affect textural properties, starch digestibility and consumer perception, thereby making millet bran an attractive ingredient for developing healthier staple foods.

Several studies have demonstrated that fortification of plantain flour with protein-rich legumes or fibre-rich plant materials improves its nutritional composition and selected functional characteristics. However, previous investigations have largely focused on individual fortifying ingredients, including soybean, rice bran, moringa, pigeon pea and tiger nut, with comparatively little attention given to the combined utilization of millet bran and defatted soybean flour. More importantly, the relationships among compositional changes, rheological behaviour and consumer acceptance in such composite systems remain insufficiently understood. Since the nutritional functionality of composite foods depends not only on ingredient composition but also on interactions within the food matrix, understanding these relationships is essential for designing formulations that achieve both nutritional improvement and desirable processing performance.

Response surface methodology (RSM) has become an effective statistical tool for optimizing composite food formulations because it enables simultaneous evaluation of multiple formulation variables while minimizing the number of experimental trials. Likewise, multivariate statistical approaches such as principal component analysis (PCA) provide a comprehensive framework for identifying the quality attributes that most strongly influence overall product performance and for visualizing relationships among nutritional, functional, and sensory characteristics. Integrating these complementary analytical approaches provides deeper insight into formulation optimization than conventional univariate analyses alone.

Therefore, this study investigated the effects of enriching plantain flour with finger millet bran and defatted soybean flour on the nutritional composition, mineral profile, pasting behaviour, colour characteristics and sensory quality of plantain-based dough meals. Formulations optimized using response surface methodology were further evaluated using principal component analysis to elucidate the multivariate relationships among nutritional, functional and sensory attributes. By integrating nutrient enhancement with the valorization of millet bran, this study provides a framework for developing nutrient-dense and functionally acceptable plantain-based staple foods from locally available agricultural resources.

2. MATERIALS AND METHODS

2.1 Source of Food Materials

Mature unripe fruits of plantain were obtained from Ilara market, Akure, Ondo State, Nigeria, while the finger millet was obtained from Oja-Oba market, Akure, Ondo State, Nigeria. The soybean meal used was obtained from JOF Ideal Family Farms, Benin-Owo road, Owo, Ondo State, Nigeria.

2.2 Sample Preparation

2.2.1 Processing of Food Materials into Flour

2.2.2 Plantain Flour Processing

The plantain flour was processed using the method described by Adegunwa et al. (2017) with slight modifications. The plantain heads were cut into separate bunches, which were subsequently defingered. The fingers were washed to remove adhering soil particles, peeled, cut into round slices of approximately 2mm thick, and soaked with ascorbic (10g) and citric

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acid (2g) g/L for 15 minutes and drained. The plantain slices were oven-dried at 65 °C for 48 hours using a hot-air oven model Grieve LW-201C. This was then milled with a laboratory Waring blender model 1186 S/N 8W 120V 50-60Hz and passed through a 60-mesh sieve (British Standard) to obtain plantain flour. The flour got was packed in an airtight plastic container and stored at room temperature until analysis.

2.2.3 Millet Bran Flour Processing

Millet bran was processed into flour using the method described by (Ji et al., 2019) with slight modification. Millet seeds were picked to remove dirt, stones, pebbles, and other foreign seeds. The millet seeds were milled once using a laboratory Waring blender model 1186 S/N 8W 120V 50-60Hz and sieved using a 60-mesh sieve to obtain the millet bran fraction (skin bran). The bran fraction was milled into flour and packaged inside an airtight container at room temperature until use.

2.2.4 Processing of Defatted Soybean Flour

The defatted soybean meal was processed by Jof Ideal Family Farms, Owo, Ondo State, Nigeria. The defatted soybean meal, a by-product of the soybean oil producing company, was oven-dried at 60^0C for 20 h using a hot-air oven model Grieve LW-201C. This was then milled using a laboratory Waring blender model 1186 S/N 8W 120V 50-60Hz and passed through a 60-mesh sieve (British Standard) to obtain defatted soybean flour. The flour was packed in an airtight container and stored at room temperature until analysis.

2.2.5 Preparation of Flour Blends

To optimize the formulation of the enriched flour blend, a Central Composite Design (CCD) from Response Surface Methodology was employed, resulting in 15 experimental runs. The independent formulation variables evaluated were plantain flour (70-80 g), soybean meal (15-20 g), and millet bran fraction (5-10 g) per batch quantity, weighed individually in grams. The evaluated responses were the resulting percentage protein and crude fibre of the blends. Four optimized flour blends were subsequently selected from the fifteen experimental runs (Table 1) for further physicochemical and nutritional analyses.

2.2.6 Reconstitution of Plantain Flour into Dough Meals

The following flour blends were selected; BTF -(plantain flour,78.00 g, millet bran flour,6.25 g, defatted soybean meal flour, 15.75 g); CNC-(plantain flour,70.00 g, millet bran flour,6.25 g, defatted soybean meal flour, 20.00 g); JMA-(plantain flour,72.99 g, millet bran flour,10.00 g, defatted soybean meal flour 17.01 g); KPA-(plantain flour,73.64 g, millet bran flour,7.82 g, defatted soybean meal flour 18.54 g) and control ANQ-(plantain flour100 g).

40g of enriched plantain flour blend was prepared into dough meal individually (four blends) and control by pouring each into the boiling water (130ml) and stirred continuously till it gelatinized into thick dough. A small quantity of water was added to allow the flour to cook properly; the paste was further stirred till thick dough was obtained.

2.3 Chemical Analyses

Determination of proximate composition, that is, moisture content, crude protein, crude fibre, total ash, and crude fat content of experimental food samples was determined using the standard methods (AOAC, 2023). Carbohydrate (CHO) content was determined by differences as follows;

CHO (%) = 100- (% moisture + % crude protein + % crude fibre + % total ash + % crude fat)

2.3.1 Determination of Mineral Content

Five grams (5g) of each sample was heated gently over a Bunsen burner flame until most of the organic matter was destroyed. This was further heated strongly in a muffle furnace for several hours until white-grey ash was obtained. The ash material was cooled. About 20ml of distilled water and 10ml of dilute hydrochloric acid were added to the ash material. This mixture was boiled, filtered into a 250ml volumetric flask, washed thoroughly with hot water, cooled, and made up to volume. Mineral content of each sample was analysed using an Atomic Absorption Spectrophotometer (PYE Unicorn, UK, model SP9) (AOAC, 2023). Some mineral elements determined include potassium(K), magnesium (Mg), phosphorus(P), calcium (Ca), and iron (Fe).

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Table 1. Experimental Runs

	Factor 1	Factor 2	Factor 3	Response 1	Response 2
Run	A: plantain flour	B: soybean meal	C: Finger millet bran	Protein	Fibre
1	78	15.75	6.25	15.75	2.6
2	78	15.75	6.25	15.75	2.6
3	75	13.9645	6.25	15.21	2.46
4	73.64	18.54	7.82	18.54	3
5	80	20	5	18.95	2.7
6	78	15.75	6.25	15.75	2.6
7	75	17.5	3.96447	17.6	2.26
8	70	20	10	18.95	3.4
9	78	15.75	6.25	15.75	2.6
10	80	15	10	15.1	3.3
11	72.99	17.01	10	17.01	3.28
12	70	15	5	15.4	2.2
13	70	20	6.25	18.69	2.73
14	78	15.75	6.25	15.75	2.6
15	74.0711	16	9.9289	17.33	3.23

2.3.2 Pasting Properties

The pasting properties of the flour samples were determined using a Rapid Visco Analyzer (RVA, Newport Scientific Pty Ltd., Warriewood, Australia) following the method reported by Dikibo et al. (2026). The sample weight was adjusted according to its moisture content to obtain an equivalent of 2.37 g (14% moisture basis), which was dispersed in distilled water to achieve a total suspension weight of 28 g. The slurry was thoroughly mixed in the RVA canister before analysis. The standard RVA heating and cooling profile was employed. The suspension was initially equilibrated at 50 °C, after which the temperature was increased to 95 °C over 4.73 min and maintained at 95 °C for 2 min. Subsequently, the paste was cooled to 50 °C over approximately 7 min and held at this temperature for a further 2 min before completion of the test. The RVA software automatically recorded the pasting parameters, including peak viscosity (PV), trough viscosity (TV), breakdown viscosity (BDV), final viscosity (FV), setback viscosity (SV), peak time (PT), and pasting temperature (PTemp). Trough viscosity was defined as the minimum viscosity attained during the holding period at 95 °C. All measurements were performed in triplicate, and the mean values were used for statistical analysis.

2.3.3 Colour Analysis

In the CIE L*a*b* uniform color space, the color coordinates are: L*, the lightness coordinate; a*, the red/green coordinate, with +a* indicating red, and -a* indicating green; and b*, the yellow/blue coordinate, with +b* indicating yellow, and -b* indicating blue. The L*, a*, and b*coordinate axis defines the three-dimensional CIE color space. Thus, if the L*, a*, and b* coordinates are known, then the color is not only described, but also located in a quadrant (Srivastav et al., 2023).

2.4 Sensory Evaluation

The organoleptic estimation for the quality attributes was carried out by thirty selected untrained panelists drawn among the students of the Department of Food Science and Technology, FUTA. Each sample was rated on perceived intensities of standard sensory attributes (taste, appearance, flavor, mouthfeel, texture, and overall acceptability) using a 9-point hedonic scale with 1 as disliked extremely and 9 as liked extremely.

2.5 Statistical Analysis

Sensory evaluation involved thirty panelists (n=30), while other parameters involved three independent replicates (n=3). The results were analysed using Analysis of Variance (SPSS17.0 version for Windows) and presented as means (±SEM). Comparisons between different groups were done using Analysis of Variance (ANOVA) and Duncan's Multiple Range Test (DMRT). Results were considered to be significantly different at $p \leq 0.05$. Principal Component Analysis was performed on the parameters. Component loadings were assessed to identify those variables contributing in a significant way to each PC and to understand how nutritional, antioxidant, colour, and sensory attributes covaried across samples. Score plots were generated to visualize sample clustering patterns and to evaluate the influence of formulation differences on multivariate positioning. All PCA procedures were performed using Minitab v21 (Minitab LLC, Pennsylvania, USA), using default convergence settings, and the results were exported as high-resolution figures for interpretation.

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3. RESULTS AND DISCUSSION

3.1 Optimization and ANOVA Results

The optimization study demonstrated that soybean meal was the principal determinant of protein enrichment in the optimized plantain dough meals. The linear regression model (Table 2a) showed that only soybean meal significantly influenced protein content ($p < 0.0001$), whereas plantain flour and finger millet bran had no statistically significant independent effects. This finding is expected because defatted soybean flour contains approximately 45–55% protein, considerably higher than plantain flour and millet bran, making it the dominant contributor to protein enhancement. The high coefficient of determination ($R^2 = 0.9251$), together with the adjusted R^2 (0.9047) and predicted R^2 (0.8464), indicates excellent agreement between the experimental and predicted values, confirming the reliability of the optimization model for predicting protein content.

Furthermore, the Adequate Precision value of 19.07, well above the minimum acceptable value of four, demonstrates that the model possesses an adequate signal-to-noise ratio and is suitable for navigating the experimental design space. These statistical indicators collectively suggest that the developed model can reliably predict protein content within the investigated formulation range.

The experimental model equation for protein is;

Table 2a. Linear model ANOVA for Protein (Response 1)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	27.46	3	9.15	45.29	< 0.0001	significant
A-plantain flour	0.1891	1	0.1891	0.9358	0.3541	
B-soybean meal	22.32	1	22.32	110.43	< 0.0001	
C-Finger millet bran	0.0915	1	0.0915	0.4528	0.5149	
Residual	2.22	11	0.2021			
Lack of Fit	2.22	7	0.3176			
Pure Error	0.0000	4	0.0000			
Cor Total	29.69	14				

$$\text{Protein} = 7.7709 - 0.0356A + 0.6788B + 0.0406C;$$

Where A = Plantain flour (%), B = Soybean meal (%), and C = Finger millet bran (%)

Unlike protein, crude fibre was influenced by all three formulation components as well as their interaction and quadratic effects. The quadratic model (Table 2b) indicated that the fibre content was significantly ($p < 0.0001$) affected by plantain flour, soybean meal, finger millet bran, their binary interactions (AB, AC, and BC), and quadratic terms (A^2, B^2, and C^2). This suggests that fibre development within the composite flour system was not simply additive but depended on synergistic interactions among the ingredients. The finger millet bran added more fibre content to the formulation since cereal brans represent the outer layers of kernels that contain insoluble crude fibre, along with plantain flour, which provided resistant starch and non-starch polysaccharides (Joye, 2020). The importance of the interaction terms reveals that a balance of ingredients rather than maximization of one ingredient is needed for optimization of crude fibre.

The experimental model equation for fibre is;

$$\text{Fibre} = -2.9407 + 0.1215A - 0.0982B + 0.0169C + 0.0009AB + 0.0018AC + 0.0007BC - 0.0009A^2 + 0.0026B^2 + 0.0012C^2$$

Where A = Plantain flour (%), B = Soybean meal (%), and C = Finger millet bran (%)

The contour and three-dimensional (3D) response surface plots further confirmed the dominant influence of soybean meal on protein enrichment (Figure 1 and 2). The contour plots showed closely spaced contour lines along the soybean meal axis, indicating a steep increase in protein content with increasing soybean meal concentration, whereas changes in plantain flour and finger millet bran produced relatively minor variations in protein levels. The elliptical contour pattern also suggested that the response was primarily driven by soybean meal rather than by strong interactions among the formulation variables. Similarly, the 3D response surface exhibited a pronounced upward slope as soybean meal increased, while the surface remained relatively flat across the ranges of plantain flour and finger millet bran. This observation is consistent with the ANOVA results, where soybean

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Table 2b. Quadratic model ANOVA for Fibre (Response 2)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	2.03	9	0.2261	2.268E+06	< 0.0001	significant
A-plantain flour	0.0106	1	0.0106	1.063E+05	< 0.0001	
B-soybean meal	0.0265	1	0.0265	2.654E+05	< 0.0001	
C-Finger millet bran	0.6826	1	0.6826	6.848E+06	< 0.0001	
AB	0.0004	1	0.0004	3821.64	< 0.0001	
AC	0.0004	1	0.0004	4168.77	< 0.0001	
BC	0.0000	1	0.0000	173.65	< 0.0001	
A^2	0.0004	1	0.0004	3787.56	< 0.0001	
B^2	0.0006	1	0.0006	5797.01	< 0.0001	
C^2	0.0002	1	0.0002	1737.89	< 0.0001	
Residual	4.984E-07	5	9.968E-08			
Lack of Fit	4.984E-07	1	4.984E-07			
Pure Error	0.0000	4	0.0000			
Cor Total	2.03	14				

Meal was the only significant linear factor ($p < 0.0001$), confirming that increasing soybean meal is the most effective strategy for improving the protein content of the composite flour. The smooth response surface without abrupt irregularities further demonstrates the adequacy of the fitted linear model in describing protein behaviour within the experimental region.

For the crude Fibre, the contour and 3D response surface plots (Figure 1 and 3) revealed a more complex relationship among the formulation variables for fibre than was observed for protein. The contour plots displayed curved and elliptical patterns rather than straight, parallel contours, indicating significant interaction and quadratic effects among plantain flour, soybean meal, and finger millet bran. These plots demonstrated that maximum fibre content could only be achieved through an appropriate balance of the three ingredients rather than by increasing a single component independently. The 3D response surfaces further illustrated this behaviour by exhibiting pronounced curvature, with fibre values increasing as finger millet bran increased but being simultaneously influenced by the proportions of plantain flour and soybean meal. The curved surfaces indicate the presence of nonlinear relationships among the variables, which agrees with the significance of the interaction terms (AB, AC, and BC) and quadratic effects (A^2, B^2, and C^2) obtained from the ANOVA. Importantly, the response surface analysis confirms that fibre optimization depends on synergistic interactions among the ingredients and validates the suitability of the quadratic model for predicting fibre content within the selected formulation range.

Run 1 (plantain flour,78.00%, millet bran flour,6.25%, defatted soybean meal flour, 15.75%), Run 9 (plantain flour,70.00, millet bran flour,6.25, defatted soybean meal flour, 20.00%), Run 11 (plantain flour,72.99, millet bran flour,10.00, defatted soybean meal flour 17.01%) and Run 4 (plantain flour,73.64, millet bran flour,7.82, defatted soybean meal flour 18.54%) from the experimental table were selected from the optimized runs and they were labelled as BTF, CNC, JMA and KPA respectively. 100% plantain flour was used as the control and labeled as ANQ

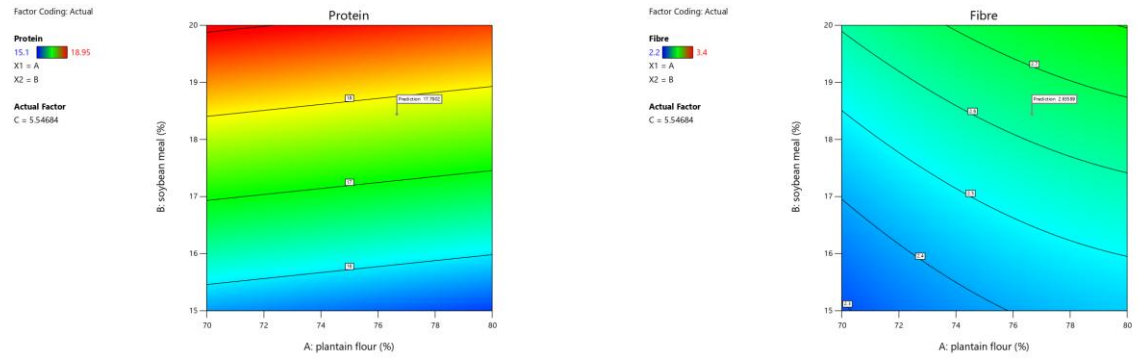


Figure 1. Contour plots for maximum Protein and Fibre in composite flour blends

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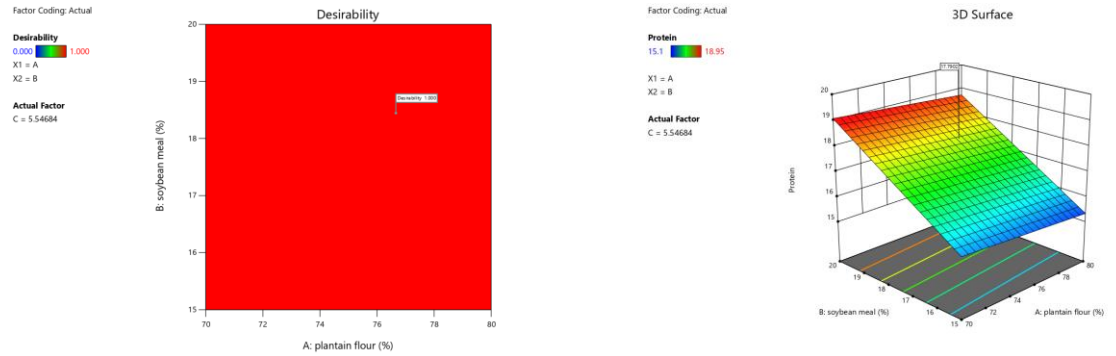


Figure 2. Contour Desirability and Surface plots for maximum Protein in composite flour blends

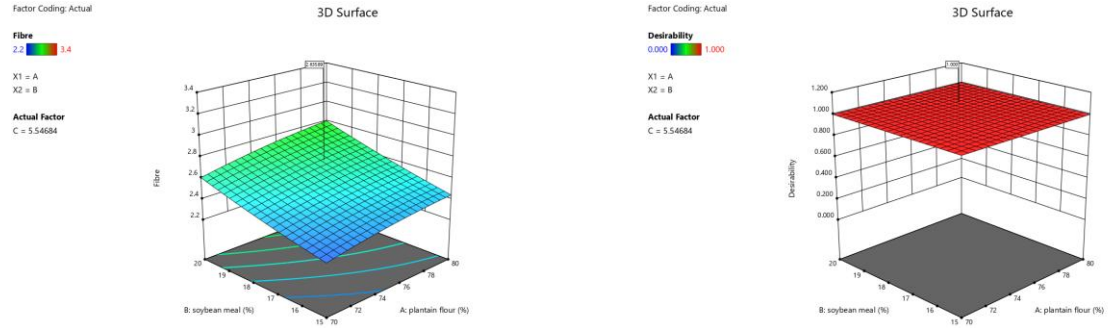


Figure 3. Surface plots for maximum Fibre and Desirability in composite flour blends

3.2 Nutrient Composition of Dough Meals from the Enriched Plantain Flour and the Control

The incorporation of millet bran and defatted soybean flour substantially improved the nutritional profile of the plantain-based dough meals (Table 3). Ash content increased in the enriched formulations relative to the control, reflecting the greater contribution of inorganic constituents from soybean and millet bran. Because ash serves as an indirect indicator of total mineral content, this increase suggests enhanced micronutrient density, consistent with previous reports on plantain-based composite flours enriched with nutrient-rich plant ingredients (Adegunwa et al., 2024). The enrichment therefore not only improved the macronutrient composition but also increased the mineral potential of the product.

Crude fibre increased progressively with the inclusion of millet bran, with KPA exhibiting the highest fibre content. This response is primarily attributable to the concentration of insoluble cell-wall polysaccharides, including cellulose, hemicellulose and lignin, in the bran fraction of millet. Beyond increasing total fibre, these structural polysaccharides can alter the food matrix by limiting starch swelling and reducing enzymatic accessibility during digestion (Zhuang et al., 2024). Such matrix effects have been associated with slower starch hydrolysis by Miao and Hamaker (2021), attenuation of postprandial glycaemic response and enhanced colonic fermentation by Grundy et al. (2016), thereby extending the physiological benefits of the product beyond simple fibre enrichment. The findings are consistent with previous studies on plantain-based composite flours enriched with fibre-rich ingredients (Adegunwa et al., 2017; Oluwajuyitan et al., 2021), while further supporting the valorisation of millet bran as a functional ingredient rather than an underutilized milling by-product.

Table 3. Proximate composition (g/100 g) of dough meals from plantain, millet bran and defatted soybean and control samples

Samples	Moisture Content	Crude Protein	Crude Fibre	Total Ash	CHO	Crude Fat	Energy (Kcal)
ANQ	17.33±0.95^{a}	9.01±0.01^{d}	1.00±0.02^{d}	1.34±0.01^{c}	69.59±0.01^{a}	1.33±0.58^{d}	326.37
BTF	15.33±0.61^{a}	18.67±0.85^{c}	2.00±0.02^{b}	2.83±0.01^{b}	54.50±0.01^{d}	6.67±0.58^{a}	352.71
CNC	19.13±0.81^{a}	21.40±0.90^{a}	1.52±0.02^{c}	3.04±0.01^{a}	49.91±0.01^{e}	5.00±0.00^{b}	330.24
JMA	14.80±0.53^{a}	19.50±0.01^{b}	1.50±0.02^{c}	2.11±0.01^{d}	58.26±0.01^{c}	3.83±0.29^{c}	345.51
KPA	15.03±4.00^{a}	15.87±0.00^{d}	3.00±0.02^{a}	2.33±0.01^{c}	59.79±0.01^{b}	3.98±0.02^{c}	338.46

Values represent the means of three replicates ± standard deviation. Mean values followed by different superscripts within columns are significantly different according to Duncan's Multiple Range Test ($p < 0.05$), represented with a-d. Repeated superscript letters indicate that the means were not significantly different ($p > 0.05$).

ANQ, control (100% plantain flour); BTF, CNC, JMA and KPA, composite flours of plantain, millet bran and defatted soybean flour (formulations given in Section 2.2.6).

Protein enrichment was principally driven by the inclusion of defatted soybean flour, resulting in protein contents that were nearly twofold higher than that of the control sample. The high protein concentration reflects both the intrinsic protein richness of soybean and the concentration of storage proteins following oil removal during defatting. From a nutritional

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perspective, soybean complements the amino acid limitations of plantain, particularly through its high lysine content (Medic et al., 2014), thereby improving protein quality rather than merely increasing crude protein concentration. Such protein complementation is particularly relevant in populations where plant-based staples predominate and access to animal protein remains limited. Similar improvements in protein content have been reported for soybean-enriched plantain formulations (Oluwajuyitan et al., 2021), reinforcing the effectiveness of legume fortification as a strategy to address protein inadequacy in cereal- and tuber-based diets (Oyeyinka and Afolayan, 2021).

Unlike the protein content, carbohydrate content declined with increasing soybean substitution, with CNC exhibiting the lowest value. This reduction is largely a dilution effect, whereby carbohydrate-rich plantain flour is progressively replaced by soybean flour, which contains proportionally higher amounts of protein and lipids. Importantly, this compositional shift may be advantageous because lowering the proportion of rapidly digestible carbohydrates while increasing protein and crude fibre has the potential to moderate glycaemic response (Pasmans et al., 2022), improve satiety (Chambers et al., 2015) and enhance the overall metabolic quality of the dough meal. Comparable reductions in carbohydrate content following soybean fortification have also been reported in soy-enriched gari and other composite flour systems (Anyaiwe et al., 2022)

3.3 Mineral Composition of Enriched Plantain Dough Meals and Control

The mineral composition of the enriched plantain dough meals (Table 4) demonstrated that supplementation with millet bran and defatted soybean flour enhanced the concentration of several essential minerals relative to the control. Calcium, sodium, and iron increased significantly ($p < 0.05$), whereas phosphorus remained statistically unchanged across the formulations. These findings indicate that the nutritional benefits of enrichment extend beyond macronutrient improvement to include enhanced micronutrient density.

The higher calcium content observed in the enriched formulations is attributable to the naturally greater mineral contribution of soybean and millet bran compared with plantain flour. Besides increasing total calcium concentration, soybean proteins may improve mineral retention within the food matrix through protein–mineral interactions formed during processing, although the actual bioavailability of calcium would also depend on the presence of mineral-binding compounds such as phytates. These interactions were described as important by Isanejad et al. (2017) because it is essential for nutrient absorption, bone and tissue formation, and enzyme function. Nevertheless, the increased calcium concentration agrees with Udomkun et al. (2022)'s study on plantain–soy composite products, where soybean supplementation improved the mineral profile while maintaining acceptable product quality. These researchers observed about an 8% increment between the control samples and the samples with 20 mg of soy flour/100 g. Given calcium's critical role in bone mineralization, neuromuscular function, and intracellular signaling (Hannan et al., 2019; Akinyede and Ajewole, 2026), the observed increase may enhance the nutritional value of the formulated dough meals, particularly in populations with inadequate dietary calcium intake. Additionally, the sample with the lowest value of 6.81mg/100 g is higher than the maximum 81.15 mg/kg reported for the optimized samples of Shakpo et al. (2025) enriched with moringa leaves.

Sodium and iron contents also increased with increasing soybean substitution, reflecting the relatively higher mineral content of defatted soybean flour compared with plantain. The increase in iron is particularly noteworthy because iron deficiency remains one of the most prevalent micronutrient deficiencies worldwide (Bailey et al., 2015). Although total iron content does not necessarily translate into greater physiological availability due to the potential inhibitory effects of phytates and crude fibre (Nikolaou et al., 2026), increasing the iron density of staple foods represents an important first step toward improving dietary iron intake. Although millet bran tends to contribute iron, the lower values observed in the samples with higher millet bran reflect that soybean is a major contributor and that there exists no linear relationship between higher bran content and iron content. Future studies incorporating in vitro mineral bioaccessibility or simulated gastrointestinal digestion would further clarify the nutritional significance of these increases.

Table 4. Mineral Composition (mg/100 g) of dough meals from plantain, millet bran and defatted soybean and control samples

Samples	Iron	Calcium	Phosphorus	Sodium	Potassium
ANQ	0.70±0.01^{d}	6.81±0.01^{e}	0.03±0.01^{a}	12.00±0.01^{c}	19.03±0.01^{b}
BTF	1.08±0.01^{b}	7.30±0.01^{c}	0.02±0.01^{a}	14.01±0.01^{bc}	19.02±0.01^{b}
CNC	1.39±0.01^{a}	7.12±0.01^{d}	0.01±0.01^{a}	18.08±0.01^{a}	19.00±0.01^{b}
JMA	0.87±0.01^{c}	7.59±0.01^{b}	0.01±0.01^{a}	14.67±2.66^{ab}	18.00±0.01^{c}
KPA	0.83±0.01^{c}	7.69±0.01^{a}	0.16±0.00^{a}	15.98±0.01^{ab}	20.06±0.08^{a}

Values represent the means of three replicates ± standard deviation. Mean values followed by different superscripts within columns are significantly different according to Duncan's Multiple Range Test ($p < 0.05$), represented with a-c. Repeated superscript letters indicate that the means were not significantly different ($p > 0.05$).

ANQ, control (100% plantain flour); BTF, CNC, JMA and KPA, composite flours of plantain, millet bran and defatted soybean flour (formulations given in Section 2.2.6).

In contrast, phosphorus content did not differ significantly among the formulations despite the inclusion of soybean and millet bran. This suggests that the substitution levels employed were insufficient to substantially alter the overall phosphorus concentration, or that the naturally occurring phosphorus contents of the constituent ingredients were

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comparable within the formulation range. The relatively stable phosphorus concentration also indicates that the observed improvements in mineral composition were primarily driven by changes in calcium, sodium and iron rather than broad increases across all mineral elements.

3.4 Pasting Characteristics of Enriched Plantain Flour and Control

The pasting properties of the composite flour (Figure 4) demonstrate that partial substitution of plantain flour with millet bran and defatted soybean flour substantially modified starch gelatinization behaviour and paste rheology. These changes reflect alterations in the composition and structural organization of the starch matrix arising from the incorporation of non-starch components, particularly crude fibre and soybean proteins, which influence water distribution, starch swelling and molecular interactions during heating and cooling.

Peak viscosity decreased progressively following enrichment, indicating a reduced capacity of starch granules to swell before rupture (Lacerda et al., 2024). This response can largely be attributed to two complementary mechanisms. First, replacing starch-rich plantain flour with soybean and millet bran diluted the overall starch fraction available for gelatinization. Second, soybean proteins and fibre-rich millet bran competed with starch granules for available water, thereby restricting granule hydration and swelling. Based on evidence from Masli et al. (2018), insoluble fibre particles may also physically disrupt the continuity of the starch matrix, further limiting viscosity development. Similar reductions in peak viscosity have been reported for fibre- and protein-enriched composite flours (Chen et al., 2022; Lin et al., 2023). From a processing perspective, lower peak viscosity may improve thermal stability during cooking while potentially contributing to slower enzymatic starch digestion through reduced starch accessibility.

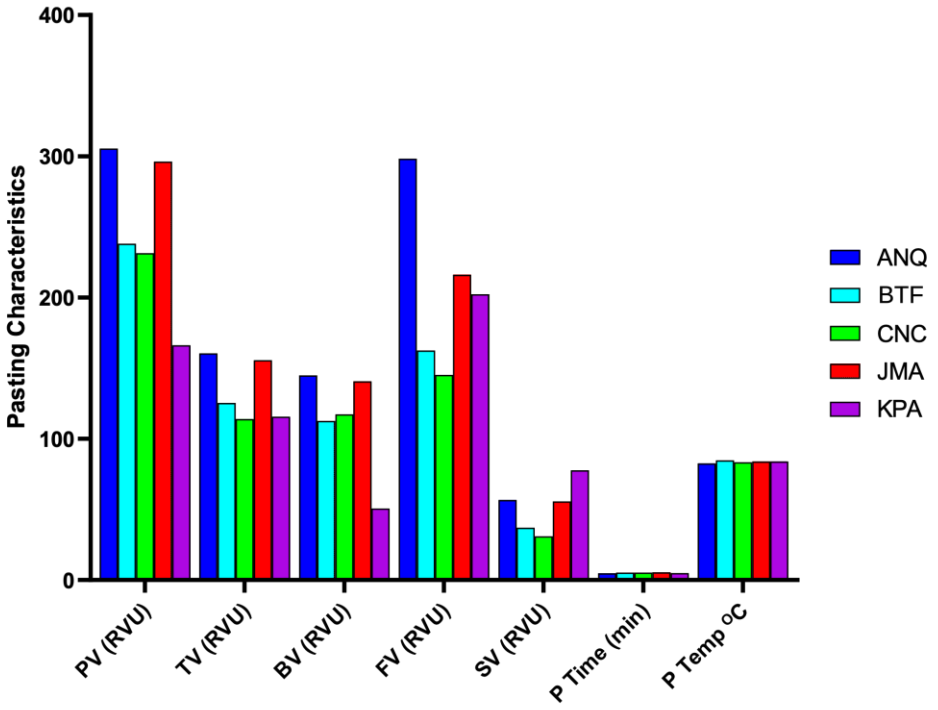


Figure 4. Pasting characteristics of flours from plantain, millet bran and defatted soybean and the control. PV, peak viscosity; TV, trough viscosity; BV, breakdown viscosity; FV, final viscosity; SV, setback viscosity; P Time, peak time; P Temp, pasting temperature. ANQ, control (100% plantain flour); BTF, CNC, JMA and KPA, composite flours of plantain, millet bran and defatted soybean flour (formulations given in Section 2.2.6).

A similar trend was observed for trough viscosity, suggesting that the enriched formulations possessed lower paste viscosity under prolonged heating and shear. Rather than reflecting inferior functional performance, this reduction indicates that the composite systems formed less swollen starch networks because non-starch constituents constrained gelatinization (Chen et al., 2025; Ye et al., 2025). The incorporation of soybean proteins and bran fibre likely altered the viscoelastic behaviour of the paste by reducing the proportion of freely gelatinizing starch while increasing the contribution of protein–polysaccharide interactions within the hydrated matrix. Evidence from the incorporation of wheat bran with arabinoxylan by Molina et al. (2021) and the incorporation of protein isolate into potato starch by Chakraborty (2024) reflects this.

Breakdown viscosity also decreased with increasing substitution, indicating improved resistance of the swollen starch granules to mechanical shear and thermal disintegration during heating (Sinhmar et al., 2023). Although native plantain flour exhibited greater swelling capacity, its larger breakdown value reflects increased susceptibility of swollen granules to

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structural collapse. In contrast, the lower breakdown values of the enriched formulations suggest that restricting starch swelling produced a more stable paste structure (Boonkor et al., 2022; Babatuyi et al., 2023). Such stabilization has been associated with protein-mediated reinforcement of the continuous phase and reduced granule fragility in composite flour systems by authors like Moniharapon et al. (2026).

Final viscosity likewise declined after enrichment, reflecting a reduced capacity of the starch paste to develop a highly viscous gel during cooling (Wu et al., 2022). This behaviour is consistent with dilution of the starch fraction and interference of fibre and proteins with amylose reassociation. The resulting weaker gel network may influence dough consistency and textural characteristics but could also contribute to improved handling properties by reducing excessive paste thickening during processing. This aligns with the review of (Chen et al., 2022) on starch modification by polysaccharides

Setback viscosity decreased consistently with increasing substitution, but according to Wang et al. (2015) and Liu et al. (2026), this indicates a lower tendency for amylose reassociation and starch retrogradation during cooling. Reduced retrogradation suggests that soybean proteins and millet bran interfered with the recrystallization of gelatinized starch chains by disrupting molecular alignment and limiting hydrogen-bond formation. In a recent study by Wang et al. (2025), the authors claimed that high fibre content in samples could limit water availability for starch-gluten network development. From a product quality perspective, lower setback values are generally associated with reduced staling, improved storage stability and maintenance of softer texture during storage (Saartrat et al., 2005; Wu et al., 2015; Ma et al., 2017). Furthermore, the modified starch organization may influence starch digestibility by altering enzyme accessibility, although direct digestibility measurements would be required to confirm this relationship.

Peak time and pasting temperature increased slightly in the enriched formulations. This delay indicates that greater thermal energy was required to initiate and complete starch gelatinization. This is also consistent with competition for water between starch, proteins and crude fibre, which reduces water availability for starch granules and consequently shifts gelatinization to higher temperatures (Nagy et al., 2020). Similar behaviour has been reported for plantain-based composite flours enriched with protein- and fibre-rich ingredients (Awolu, 2017). Although the increases were relatively modest, they suggest that formulation with millet bran and defatted soybean flour may require slightly longer cooking times, while simultaneously producing dough systems with improved thermal stability and modified functional behaviour.

3.5 Colour Profile

The incorporation of millet bran and defatted soybean flour significantly altered the colour characteristics of the dough meals (Table 5), resulting in lower L* and a* values but higher b* values relative to the control. These changes indicate that enrichment produced darker and more yellow products, reflecting modifications in both the intrinsic colour of the composite ingredients and the optical properties of the food matrix.

The reduction in lightness (L*) is primarily attributable to the higher proportion of bran particles, which contain naturally darker outer kernel tissues rich in phenolic compounds, pigments and fibre (Bhat et al., 2020). In addition, the increased protein content from defatted soybean flour may have promoted mild Maillard reactions during thermal preparation of the dough, generating brown-coloured melanoidins that further reduced product brightness. The combined effects of pigment incorporation and non-enzymatic browning therefore contributed to the darker appearance of the enriched formulations.

The increase in yellowness (b*) reflects the contribution of naturally occurring carotenoid pigments in plantain and soybean, together with coloured phenolic constituents present in millet bran. Because colour is strongly influenced by ingredient composition and matrix interactions (Trouillas et al., 2016; Giusti et al., 2023), the observed changes suggest that enrichment modified light scattering within the dough structure in addition to altering pigment composition. Similar increases in yellowness and reductions in lightness have been reported in fibre-enriched composite flour systems (Olumurewa et al., 2024), where incorporation of cereal bran and legume flours produced darker products because of their higher pigment and phenolic contents.

Table 5. Colour Profile of dough meals from plantain, millet and defatted soybean and control samples

SAMPLES	L*	a*	b*	Hue (h°)	Chroma
ANQ	55.34±0.01^{a}	55.32±0.02^{a}	9.08±0.01^{d}	0.20±0.00^{a}	22.62±0.01^{a}
BTF	54.07±0.01^{c}	47.30±0.01^{c}	9.11±0.01^{c}	0.19±0.02^{b}	22.33±0.01^{b}
CNC	54.19±0.01^{c}	54.19±0.01^{b}	9.35±0.01^{a}	0.19±0.00^{b}	22.22±0.00^{c}
JMA	53.69±0.01^{d}	46.88±0.01^{d}	9.25±0.01^{b}	0.19±0.01^{b}	21.94±0.01^{e}
KPA	54.88±0.11^{b}	46.88±0.02^{d}	9.25±0.00^{b}	0.91±0.00^{b}	21.98±0.02^{d}

Values represent the means of three replicates ± standard deviation. Mean values followed by different superscripts within columns are significantly different according to Duncan's Multiple Range Test ($p < 0.05$), represented with a-d. Repeated superscript letters indicate that the means were not significantly different ($p > 0.05$).

ANQ, control (100% plantain flour); BTF, CNC, JMA and KPA, composite flours of plantain, millet bran and defatted soybean flour (formulations given in Section 2.2.6).

Generally, moderate darkening represents an expected consequence of nutritional enhancement rather than a deterioration in quality. Indeed, colour changes frequently accompany the incorporation of whole-grain and fibre-rich

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ingredients that improve nutritional value. Consequently, balancing visual appeal with enhanced nutritional functionality remains an important consideration when developing composite plantain-based foods for consumer acceptance.

3.6 Sensory Evaluation of the Enriched Plantain Dough Meal Blends

The sensory evaluation (Table 6) demonstrated that incorporating millet bran and defatted soybean flour influenced several sensory attributes of the plantain dough meals, although the extent of these effects depended on the level of substitution. The control formulation received the highest scores for taste, aroma, and overall acceptability, reflecting the sensory characteristics traditionally associated with plantain dough meals. Nevertheless, the absence of significant differences in overall acceptability among most enriched formulations suggests that nutritional enhancement was achieved without substantially compromising consumer preference.

The slight decline in taste and aroma scores observed in the enriched samples is likely attributable to the characteristic flavour compounds of soybean and millet bran. Soybean contains lipoxygenase-derived volatile compounds that may impart a characteristic "beany" flavour (Kaczmarska et al., 2021; Shahidi and Hossain, 2022), while millet bran contributes cereal-like and slightly bitter notes arising from phenolic constituents and fibre-rich outer grain layers (Matías et al., 2024). These compositional changes can modify flavour perception, particularly in consumers accustomed to conventional plantain dough, although processing methods such as blanching or controlled heat treatment may reduce these sensory effects.

Texture scores were highest for the control and JMA formulations, suggesting that moderate substitution preserved the structural characteristics expected of plantain dough. In contrast, higher levels of millet bran and soybean flour slightly reduced texture ratings, probably because crude fibre and proteins interfere with the continuous starch gel network responsible for the smooth, cohesive texture of traditional dough meals (Zhou et al., 2025). Fibre particles may disrupt gel continuity, while protein–starch interactions modify water distribution during gelatinization, producing subtle changes in firmness and mouthfeel (Sun et al., 2023). These observations are consistent with the rheological changes reflected in the reduced peak and final viscosities of the enriched formulations.

Table 6. Sensory Evaluation of dough meals from plantain, millet, and defatted soybean and control samples

Samples	Taste	Aroma	Colour/Appearance	Texture	Mouth Feel	Acceptability
ANQ	6.90 ± 1.44^{a}	6.30 ± 1.70^{a}	6.40 ± 1.42^{a}	7.10 ± 1.28^{a}	6.80 ± 1.61^{a}	6.58 ± 1.34^{a}
BTF	5.30 ± 1.33^{d}	5.20 ± 2.04^{b}	5.60 ± 1.60^{ab}	5.10 ± 1.41^{b}	5.00 ± 1.41^{b}	5.12 ± 1.37^{b}
CNC	5.70 ± 1.25^{b}	5.30 ± 1.25^{c}	5.00 ± 1.41^{c}	5.30 ± 0.94^{c}	5.40 ± 0.84^{b}	5.34 ± 0.88^{b}
JMA	6.00 ± 1.24^{bc}	6.20 ± 1.03^{b}	5.80 ± 0.78^{ab}	6.20 ± 1.13^{a}	5.10 ± 1.28^{b}	5.86 ± 0.77^{ab}
KPA	5.70 ± 1.56^{bc}	6.10 ± 1.10^{b}	5.80 ± 0.82^{ab}	5.70 ± 0.82^{bc}	4.90 ± 1.79^{b}	5.60 ± 1.04^{ab}

Values represent the means of thirty panelists ± standard deviation. Mean values followed by different superscripts within columns are significantly different according to Duncan's Multiple Range Test ($p < 0.05$), represented with a-c. Repeated superscript letters indicate that the means were not significantly different ($p > 0.05$).

ANQ, control (100% plantain flour); BTF, CNC, JMA and KPA, composite flours of plantain, millet bran and defatted soybean flour (formulations given in Section 2.2.6).

Although the control sample achieved the highest overall acceptability, the comparable acceptance of the enriched dough meals indicates that the nutritional improvements did not result in a proportional decline in consumer preference. This finding suggests that moderate incorporation of millet bran and defatted soybean flour can enhance protein, crude fibre and mineral content while maintaining sensory properties within an acceptable range. Such a balance between nutritional quality and palatability is essential for the successful adoption of functional staple foods, as consumer acceptance ultimately determines their potential dietary impact.

3.7 Multivariate Analysis

The principal component analysis (PCA) was performed to evaluate the relationships among the nutritional composition, functional properties, processing characteristics, mineral composition, and sensory attributes of the optimized plantain dough meal samples. The eigenanalysis revealed that the first four principal components (PCs) had eigenvalues greater than one and together accounted for 100% of the total variation in the dataset. Specifically, PC1 explained 56.1%, PC2 explained 24.1%, PC3 explained 14.0%, and PC4 explained 5.8% of the total variance, while the remaining principal components contributed negligible variation. The cumulative variance of 80.2% explained by the first two principal components indicates that the biplot adequately summarizes the relationships among the measured variables and samples. This percentage is higher than 77% reported by Osanbikan et al. (2026) for their first two principal components.

The PCA biplot (Figure 5) clearly separated the five plantain dough meal samples according to their physicochemical, functional, and sensory characteristics. ANQ was positioned on the positive side of the first principal component (PC1) and closely associated with taste, aroma, appearance, texture, mouth feel, and overall acceptability, indicating that this sample possessed the most desirable sensory properties among all the formulations. ANQ was also positively associated with carbohydrate (CHO), Final Viscosity (FV), and trough viscosity (TV), suggesting that these attributes collectively

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contributed to its superior consumer acceptance. The proximity of these variables indicates strong positive correlations among them.

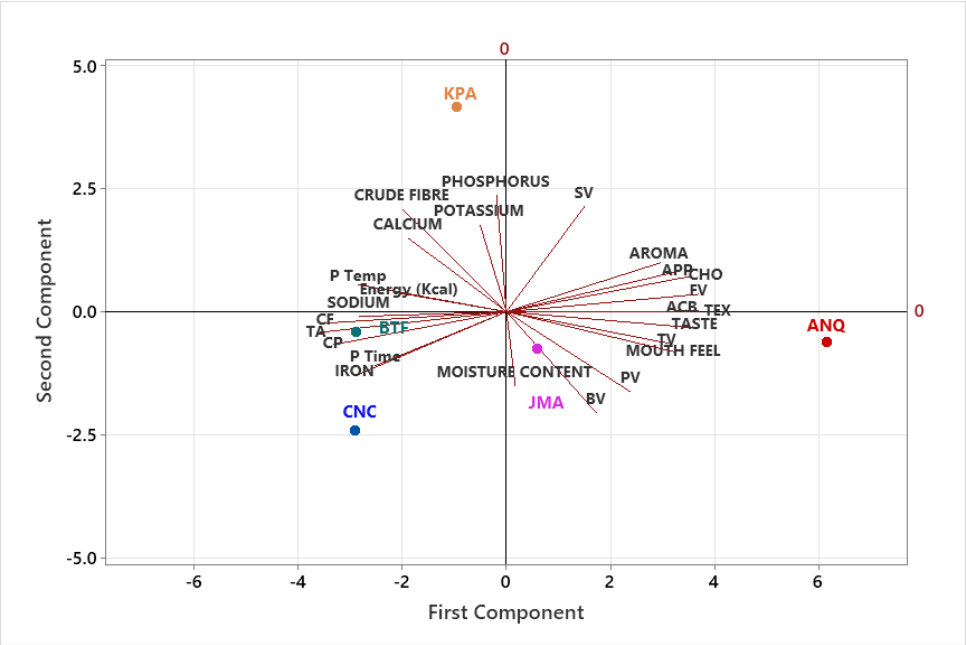


Figure 5. PCA Biplot of Nutritional and Sensory Properties of Dough Meal from Plantain, Millet and Defatted Soybean (This figure reveals the clusters between the samples and the measured parameters)

ANQ, control (100% plantain flour); BTF, CNC, JMA and KPA, composite flours of plantain, millet bran and defatted soybean flour (formulations given in Section 2.2.6).

Abbreviations: CP, Crude Protein; ACB, Acceptability; TEX, Texture; TV, Trough; TA, Total Ash; CF, Crude Fat; APP, Appearance

In contrast, BTF and CNC were located on the negative side of PC1 and were associated with crude protein, total ash, sodium, iron, processing time, and processing temperature. Their location opposite the sensory attributes indicates a negative relationship between these nutritional characteristics and sensory quality. The CNC sample, in particular, showed a stronger association with iron and processing variables, suggesting that it possessed comparatively higher mineral-related characteristics but lower sensory preference than ANQ.

The KPA sample was distinctly separated along the positive side of the second principal component (PC2), demonstrating a strong association with crude fibre, phosphorus, potassium, calcium and swelling volume (SV). This indicates that KPA possessed superior mineral composition and crude fibre compared with the other formulations. The strong loading of phosphorus (0.391), swelling volume (0.354), crude fibre (0.344) and potassium (0.291) on PC2 supports this observation, confirming that these variables were the major contributors to the separation of KPA from the remaining samples.

The JMA sample occupied the lower right quadrant of the biplot and was closely associated with moisture content, peak viscosity (PV), and breakdown viscosity (BV). The relatively close positioning of these variables suggests that JMA exhibited comparatively higher moisture content and oxidative stability-related properties than the other formulations. However, its separation from the sensory variables indicates that these properties contributed less to overall consumer preference (Jia et al., 2026).

The direction and length of the variable vectors provide additional information regarding the relationships among the measured parameters. Variables with vectors pointing in similar directions, such as taste, aroma, appearance, texture, mouth feel and acceptability, were positively correlated (Hamid et al., 2025), indicating that improvement in one sensory attribute was generally accompanied by improvement in the others. Similarly, calcium, phosphorus, potassium and crude fibre clustered together, demonstrating strong positive relationships among mineral and crude fibre contents. Conversely, variables located in opposite directions, such as sensory attributes and crude protein, total ash, sodium and iron, exhibited negative correlations, suggesting that increasing some nutritional components may adversely influence sensory perception.

4. CONCLUSION

Enrichment of plantain flour with millet bran and defatted soybean flour improved the nutritional profile of the dough meals by increasing protein, crude fibre, and selected minerals while modifying their functional and pasting characteristics. The altered rheological behaviour reflects changes in starch–protein–fibre interactions that may influence processing performance and product quality. Despite modest changes in colour and selected sensory attributes, the enriched formulations maintained acceptable consumer preference, demonstrating that nutritional enhancement can be achieved

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without substantially compromising acceptability. These findings highlight the potential of millet bran and defatted soybean flour as complementary ingredients for developing nutrient-dense plantain-based foods while promoting the utilization of underexploited agricultural resources. Future studies should evaluate starch digestibility, mineral bioaccessibility, and glycaemic response to establish the physiological relevance of these functional improvements.

Ethics Declaration

This study comprised the sensory testing of food products which were considered safe for human consumption. In compliance with the general ethical guidelines of the Ethical Committee of the School of Agriculture and Agricultural Technology, Federal University of Technology, Akure, Nigeria, for minimum risk sensory testing, approval was not sought before the sensory evaluation. However, all procedures adhered to the ethical standards. Voluntary participation, confidentiality, and the right to withdraw at any point in time were ensured by the verbal informed consent of all the individual participants before including them in the study. Five volunteers identified as being allergic to soybeans were excluded. A total of thirty volunteers performed the sensory evaluation.

Author Contributions

B.T.O: Conceptualization, Resources, Formal Analysis, Supervision, Writing - Original Draft, and Writing - Final Revision

D.S.A: Conceptualization, Resources, Investigation, Data Analysis, Writing - Original Draft, and Writing - Final Revision.

Data Availability

The raw data supporting the conclusions of this article will be made available by the authors on request.

Competing Interests

The authors declared that no competing interests exist.

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Informed Consent

The panelists gave verbal consent before sensory evaluation

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