Valorization of Brown Rice and African Yam Bean Flours in Reduced-Gluten Muffin Production: A Multi-Analytical Assessment of Nutritional, Functional and Sensory Quality

Dorothy Agamba[1*], Nafisatu Mahama[2], and Grace Efua Owusu Gyasi[3]

[1]Department of Hospitality Management, Bolgatanga Technical University, Ghana.
[2]Dr. Hilla Limann Technical University, Department of Hotel Catering and Institutional Management, Ghana.
[3]Department of Hospitality and Tourism, Koforidua Technical University, Ghana.
*Corresponding Author Email: dagamba@bolgatu.edu.gh

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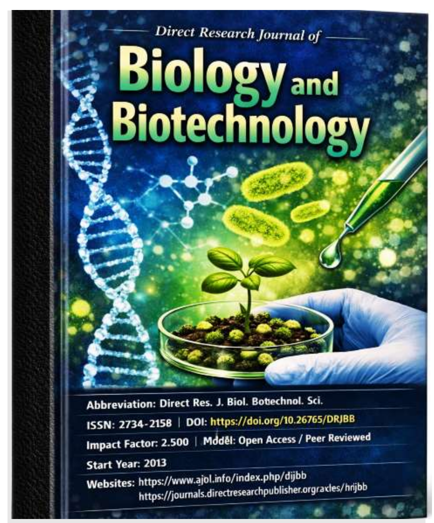
ABSTRACT

This study evaluated the valorization of brown rice and African yam bean flours in the production of reduced gluten muffins through functional, nutritional, physical, and sensory evaluation. Five blends consisting a 100% wheat control and four composite flour blends (30%, 40%, 50% and 60% brown rice and African yam bean flours) were used in a completely randomized design . Functional properties, gluten content, proximate analysis, mineral composition and physical properties were determined in triplicate according to standard methods. Sensory acceptability was evaluated by 100 consumers through a nine-point hedonic scale. Data were analyzed using analysis of variance and Tukey's test (p < 0. 05). Water retention, protein, fiber and ash contents were increased from 1. 35 to 1. 66 g/g, 8. 52% to 11 . 62%, 1. 12% to 2. 62% and 1. 34 to 2. 18%, respectively. The contents of calcium, iron and potassium were increased from 82. 40 to 115. 30 mg/100 g, 2. 10 to 3. 63 mg/100 g and 168. 40 to 264. 75 mg/100 g, respectively. In terms of gluten levels, the gluten concentration was reduced from 35620 mg/kg to 14280 mg/kg (59 . 9% reduction), whereas specific volume declined from 2. 57 cm³/g to 1. 97 cm³/g. However, the BRAYB1 (7. 98) scored likewise on overall acceptability to the wheat control (8. 18). The study concludes that Brown rice and African yam bean flour can be used to develop nutritionally improved, wheat-reduced muffins, and BRAYB1, made with 70% wheat, 20% brown rice and 10% African yam bean flour, is recommended for any further product development based on these criteria. Higher levels of substitute mean improved structural properties.

Keywords: *African yam bean-brown rice composite flour, muffin quality attributes, nutritional quality, low gluten muffins, sensory acceptability*



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INTRODUCTION

Due to interest in developing healthy, novel, and nutritionally improved baked goods, refined wheat flour is partially replaced with non-wheat cereal, legume, and plant flours in muffin formulations. Muffins are widely consumed for their soft texture, convenience, and consumer acceptance. Classic recipes predominantly use refined wheat flour, sugar and fat, resulting in low fibre, protein and micronutrient content. However, the overuse of these substitutes can result in reduced height, decreased volume, and compromised crumb quality (Kumar et al. , 2025). Reduced-gluten and gluten-free baked goods require careful formulation because gluten-free flours destabilise batter structure, alter gas retention, and affect the quality of the end product (Arif et al. , 2025). Muffins with reduced gluten are difficult to produce because gluten provides viscoelasticity, aeration, crumb structure and eating quality. Reducing the amount of wheat flour in muffins will produce dense or crumbly products because the functional properties of the alternative flour differ from those of wheat flour, including water absorption, starch and protein. Rice flour has been a major component of gluten-free systems due to its bland flavour, good color, and consumer acceptance. In many systems the performance of rice needs to be improved. More recently, research work has focused on ingredient and processing methods to improve the structure and nutritional value of rice-based baked goods (Gutiérrez et al. , 2026; Arif et al. , 2025). Brown rice flour, an unpolished rice flour, is a potential gluten-reduced cereal food. The bran and germ fractions, as a whole grain, can increase the amount of dietary fibre, minerals, lipids and bioactive compounds. Brown rice (Oryza sativa) flour is a starch-rich gluten-free flour with strong structuring properties. Low levels of gluten-forming proteins limit the potential use of rice flour in gluten-free formulations . The African yam bean (*Sphenostylis stenocarpa*), an underutilized African legume, can be a potential source of protein-dense and functional food components that can improve the nutrition and functionality of starchy food formulations without adversely affecting sensory acceptability when included at suitable concentrations (Elegbeleye & Sivakumar, 2026; Okorie et al. , 2026). Legume, and other plant protein, flours are well-known to improve the nutritional quality of gluten-free bread and cake products, but may cause disadvantages with respect to color, taste, hardness, springiness, texture and consumer acceptance. Other studies have explored mushroom powder as a protein-rich ingredient for use in gluten free bakery products including muffins (Noguera & Gigante, 2026). Chia and lentil flour effects on the physical, textural and sensory properties of cake systems suggested that legume-rich cake formulations be optimised (Kılıç et al. ,2025). Also, the fruit flour replacement of rice flour modified the physicochemical, bioactive, textural and sensory properties of gluten-free cakes, implying the need for the multi-quality evaluation of composite bakery products (Öncel et al. , 2025). Little is known about the strengths of brown rice- and African yam bean (AYB)-based flours in low-gluten muffins, as most studies have focused on the nutritional or sensory quality of muffins and have not examined flour performance, structural and textural characteristics, or consumer acceptability. Therefore, the aim of the present study was to develop low-gluten muffins supplemented with brown rice and AYB flour and to systematically analyse their nutritional, functional, structural, textural, and sensory quality. These findings may have implications for manufacturing nutritionally beneficial composite-flour muffins and for the targeted use of local and underexploited food resources.

MATERIALS AND METHODS

Research Design

The laboratory experimental design was adopted to determine the effect of partially substituting wheat flour with brown rice and African yam bean flour at different ratios on the nutritional, functional, structural, textural and sensory properties of reduced-gluten muffins. The completely randomized design (CRD) was used, with flour formulation as the main effect. Five flour blends were prepared: a control flour (100% wheat flour) and four experimental composite flours with varying proportions of wheat flour, brown rice and African yam bean flour. Each flour blend was prepared and analyzed in triplicate. Sensory analysis was conducted with 100 consumers.

Source of raw materials

The brown rice grains, seeds of African yam bean, refined wheat flour, granulated sugar, margarine, eggs, baking powder, milk, salt, and vanilla flavour were procured from a reputable food store in Rain in supermarket, Bolgatang. The chemicals and reagents used for laboratory analyses were of analytical grade. Brown rice flour was produced according to the modified and adapted from Yue et al. (2026). Brown rice grains were hand-sorted to remove stones, husks, immature grains and other foreign materials. The sorted grains were rinsed with drinking water, drained, and dried in a hot-air convection oven at 40-50 °C for 12 h or to constant weight. The dried grains were milled into flour using a lab mill or a hammer mill, passed through a 250 μm mesh sieve, transferred into sealable polythene bags, labelled, and stored in a refrigerator at 4 °C until used.

Preparation of African yam bean flour

Preparation of the African yam bean flour was undertaken according to a modified method of Beleya et al. (2026). The seeds were sorted by hand to remove stones, damaged seeds, dust and other extraneous materials. The seeds were then washed and soaked for 12 h at room temperature in potable water to soften the seed coats to allow hand dehulling and sieving. In a similar study on African yam bean seeds, Beleya et al. (2026) sorted and then soaked seeds in water for 12 hours before decorticating, drying and milling them into flour. Dehulled cotyledons were dried in a hot-air oven at 55-60 °C for 8-10 h (or as required) to reduce the moisture content to the desired level. The dried cotyledons were ground in a laboratory grinder, passed through a 250 µm mesh sieve, packed in sealable polyethene bags, and stored under dry, refrigerated conditions until formulation.

Formulation of Composite Flours

The composite flour was obtained by mixing wheat flour with varying proportions of brown rice flour and African yam bean flour. A 100% wheat flour control was prepared. The reduced-gluten composite flours were prepared by partially replacing wheat flour with blends of brown rice and African yam bean flours. The formulation approach was modified from the study of Majeed et al. (2025). Each flour blend was weighed accurately and mixed for 10 min using a laboratory mixer to ensure uniform distribution. The blends were packaged in airtight containers and stored under dry conditions before muffin production and laboratory analyses. Key: WF (100% wheat flour); BRAYB1 (70% wheat flour, 20% brown rice flour and 10% African yam bean flour), BRAYB2 (60% wheat flour, 25% brown rice flour and 15% African yam bean flour), BRAYB3 (50% wheat flour, 30% brown rice flour and 20% African yam bean flour) and BRAYB4 (40% wheat flour, 35% brown rice flour, and 25% African yam bean flour) respectively (Table 1).

Table 1: Muffin formulation for reduced-gluten muffin production

Ingredient	WF100	BRAYB1	BRAYB2	BRAYB3	BRAYB4
Wheat flour (g)	100	70	60	50	40
Brown rice flour (g)	0	20	25	30	35
African yam bean flour (g)	0	10	15	20	25
Total flour blend (g)	100	100	100	100	100
Sugar (g)	35	35	35	35	35
Margarine (g)	40	40	40	40	40
Whole egg (g)	45	45	45	45	45
Milk (mL)	50	50	50	50	50
Baking powder (g)	4	4	4	4	4
Salt (g)	1	1	1	1	1
Vanilla flavour (mL)	2	2	2	2	2

Muffin Formulation and Production

Muffin production was carried out using the creaming method adapted and modified from Abdul Majeed et al. (2025). For each formulation, the ingredients were measured based on 100 g flour blend. The basic formulation consisted of 100 g flour blend, 40 g margarine, 35 g sugar, 45 g whole egg, 50 mL milk, 4 g baking powder, 1 g salt and 2 mL vanilla flavour. Margarine and sugar were creamed together for 3–5 min until a light and fluffy mixture was obtained. Eggs were added gradually and mixed until uniform. The flour blend, baking powder and salt were mixed separately and added alternately with milk to the creamed mixture. Vanilla flavour was then added, and the batter was mixed gently until a homogeneous consistency was obtained. Approximately 50 g of batter was dispensed into paper-lined muffin cups. The muffins were baked in a preheated electric oven at 180 °C for 20 min. After baking, the muffins were cooled at room temperature for 30 min, packed in low-density polyethylene bags and used for subsequent analyses.

Functional properties of the flour blend

The functional properties of the flour blends were determined using the method of Olaitan et al. (2026). Bulk density was determined by filling a graduated measuring cylinder of known weight with known weight (W) of each flour blend. Bulk density was consequently recorded as the ratio of sample weight to volume. The water absorption capacity was determined by combining 1 g of flour with 10 mL distilled water. After one hour at room temperature, the mixture was then centrifuged, the supernatant was removed, and the residue was collected and weighed. Water absorption capacity was calculated as the amount of water that is absorbed by the flour. One hour was used instead of the original 30-minute standing period. Oil absorption capacity was measured in the same manner, but refined vegetable oil was used instead of distilled water . Swelling power and solubility were determined by heating a suspension of the flour in distilled water to 90 °C for 30 minutes, centrifuging, and estimating the swelling of the sediment from its weight. The supernatant was evaporated to dryness, leaving an insoluble residue, while the minimum gelation concentration was estimated by preparing flour suspensions, heating them to boiling point and cooling them to allow them to set. The minimum gelation concentration is the lowest concentration of flour at which the sample does not flow when inverted in a container.

Determination of Gluten Content

The gluten content of the muffins was analysed using the

R5 sandwich enzyme-linked immunosorbent assay (ELISA) gluten detection kit as per AOAC Official Method 2012. 01 and the collaborative study by Lacorn et al. (2022). The recommended cocktail extraction solution was used for the analysis of heated food samples. Samples were tested for the presence of gluten using the RIDASCREEN® Gliadin R5 ELISA kit according to the manufacturer's specifications or an equivalent validated R5 ELISA kit. Absorbance was measured with a plate reader and gluten concentration interpolated from the calibration curve. Results were reported in the amount of gluten, in milligrams per kilogram (mg/kg) of product.

Proximate composition of composite muffins

The proximate composition of composite muffins was determined by the official methods of the AOAC (AOAC International, 2023). Moisture content was determined by drying the sample to constant weight at 105 °C. The ash content was determined by dry ashing the sample in a muffle furnace at 550 °C. Crude protein was assessed by the Kjeldahl method, and nitrogen was converted to protein using the factor 6.25. Crude fat was determined by Soxhlet extraction with petroleum ether, crude fibre was determined by acid and alkaline digestion, and carbohydrate content was calculated by difference: The carbohydrate percentage (%) was calculated as 100 minus the sum of % moisture, % protein, % fat, % ash and % crude fibre. Energy value was calculated using Atwater conversion factors as follows: Energy value (kcal/100 g) = 4 × protein + 9 × fat + 4 × carbohydrate.

Mineral Analysis

Mineral determinations were conducted using methods adapted and modified from AOAC International (2023). One gram of dried and ground sample was ashed in a muffle furnace at 550 °C. The ash was leached with dilute hydrochloric acid and then made up to a known final volume with distilled water. Calcium, magnesium, iron and zinc in the extract were determined by atomic absorption spectrophotometry. Sodium and potassium were analysed using flame photometry. Mineral concentrations were reported as mg/100 g of sample.

Physical characteristics muffins produced

Physical parameters of the muffins (volume, specific volume) were measured according to an adjustment of the AACC Method 10-05. 01. Muffin volume was determined according to the seed-displacement method and the specific volume was calculated as the ratio between the volume and weight of the muffin following the method by Cifarelli et al. (2026). Muffin weight was determined using a digital weighing balance. Height and diameter were measured using a digital vernier calliper , and muffin volume was estimated by the rapeseed displacement method. Specific volume was calculated as: *Specific volume (cm³/g)* = muffin volume / muffin weight. Baking loss was calculated as the batter weight before baking minus the muffin weight after baking as follows: *Baking loss (%)* = (batter weight - muffin weight) / batter weight × 100.

Sensory Evaluation

The sensory evaluation was conducted using a consumer hedonic test in accordance with ISO 11136:2014. The hedonic evaluation was carried out with 100 selected muffin consumers. Prior to participation, panellists were screened for any known wheat, rice, legume, egg or milk allergy or intolerance. The muffins were assigned random three-digit codes and presented in a randomised order under controlled sensory evaluation conditions. Samples were rated for appearance, colour, aroma, taste, texture, mouthfeel, and overall acceptability on a 9-point hedonic scale (1 = dislike extremely, 9 = like extremely). Water was provided for rinsing mouths. Participation in the study was voluntary, and panellists were informed of the contents of the products prior to participation.

Data Analysis

The data were analysed using descriptive statistics and analysis of variance . Pearson's product-moment correlation analysis was used to evaluate the relationship between the nutritional, functional, physical, textural and sensory properties of the muffin samples. For the correlation values their direction, strength and importance ($p < 0.05$) were interpreted. Because the analysis of the principal components had not yet been done, it was not included in the statistical analysis. Care was taken to ensure that all equipment was calibrated and all chemicals used were of analytical grade. Flour and muffin blends were prepared in triplicate to minimise batch-to-batch variability during processing. All laboratory assays and analyses were performed in triplicate, with average values being used for statistical comparisons. Muffins were baked on the same day they were served for sensory analysis, to ensure that they were fresh.

RESULTS AND DISCUSSION

Demographic characteristics of respondents

Table 2 summarizes demographic data for the 100 panelists who conducted a sensory analysis of the reduced-gluten muffins, including sex, age, educational level, and frequency of muffin consumption. 58% of the respondents were female, and 42% were male, thus, both sexes were adequately represented in the respondents,

Table 2: Demographic characteristics of respondents (n = 100)

Demographic variable	Category	Frequency	Percentage (%)
Sex	Male	42	42.0
	Female	58	58.0
Age (years)	Below 20	18	18.0
	20-29	37	37.0
	30-39	25	25.0
	40-49	13	13.0
	50 and above	7	7.0
Education Level	No formal education	4	4.0
	Basic education	18	18.0
	Secondary education	38	38.0
	Tertiary education	40	40.0
Frequency of muffin consumption	Daily	8	8.0
	Two to three times weekly	28	28.0
	Once weekly	31	31.0
	Occasionally	26	26.0

although there were more respondents of the female sex Both men and women were studied since sensory preferences and consumption patterns may differ between men and women. The most common age group among respondents was 20-29 years (37%), followed by 30-39 years (25%). 18% were under 20 years old, 13% were 40-49 years old, and 7% were over 50 years old. Since most respondents are young adults, they are likely to have heard of muffins and other convenience bakery products. Tertiary education was the most common level of education, followed by secondary education (38%), basic education (18%), and no formal education (4%). Thus, the majority of participants had at least secondary education, so it is expected that they are capable of understanding the instructions for the sensory evaluation and the rating scale used with confidence. Consumption frequency was once a week (31%), two or three times a week (28%), occasionally (26%), daily (8%) and rarely (7%). In conclusion, the high percentage (67%) of study participants reporting muffin consumption at least once a week indicates that most had prior muffin experience and were able to properly evaluate the appearance, flavor, aroma, texture and acceptability of the lower gluten muffin samples.

Functional properties of wheat, brown rice and African yam bean composite flour blends

The functional properties of the wheat, brown rice, and African yam bean composite flour blends are presented in (Table 3). The various functional properties evaluated were considerably ($p < 0.05$) affected by partial substitution of wheat flour with brown rice flour and African yam bean flour, as shown by the different superscript alphabetic letters in the (Table 3). The bulk density of the WF (0.68 ± 0.01^{d} g/mL) was increased to 0.73 ± 0.02^{a} g/mL in the BRAYB4 composite flour. The densification of the composite flour increases with the increase in brown rice and African flours in the composite flour and can affect packaging, transportation, and batter thickness. Water absorption capacity differs considerably ($P < 0.05$): BRAYB4 (1.66 ± 0.05^{a} g/g) is much higher than WF (1.35 ± 0.04^{e} g/g). The proportion of the components of a composite flour blend can also have important effects on its water absorption capacity (WAC), oil absorption capacity (OAC) and swelling capacity (Owheruo et al., 2026). In this study, the oil absorption capacity of flour blends increased from 1.18 ± 0.03^{e} g/g in WF to 1.47 ± 0.05^{a} g/g in BRAYB4.

The oil absorption capacity of the flour blends considerably increased from 1.18 ± 0.03^{e} g/g in WF to 1.47 ± 0.05^{a} g/g in BRAYB4. This increase with a higher level of African yam bean flour may improve flavor retention, mouthfeel, and tenderness of the muffins. For 100% water swelling potential, the values also increased considerably from 5.42 ± 0.08^{d} g/g in the WF to 6.30 ± 0.10^{a} g/g in BRAYB4 (Table 3).

The means with the same superscript (a), (b), and (c) in the BRAYB3 and BRAYB4 groups were not considerably different because swelling plateaued at the higher substitution levels. Foaming capacity considerably increased ($P < 0.05$) from 8.40 ± 0.31^{e}% in WF to 15.72 ± 0.50^{a}% in BRAYB4. This could be due to the protein in the African yam bean (AYB) included in the mixtures reducing the surface tension and allowing air bubbles to stabilize within the foam. A study on the enrichment of the African yam bean concluded that hydration rate was highly dependent on hydrophilic compounds, and that the functional properties derived from the composition of the legume flour (Ohini et al., 2025). The least gelation concentration decreased from 12.00 ± 0.00^{a}% in the WF to 8.00 ± 0.00^{c}% in BRAYB3 and BRAYB4. This indicates that gelation occurs at lower flour concentration. The best performance occurs in BRAYB4, but values of water binding capacity and gelation strength are also higher, giving individual muffins a denser structure if uncontrolled.

Table 3: Functional properties of wheat, brown rice and African yam bean composite flour blends

Functional property	WF	BRAYB1	BRAYB2	BRAYB3	BRAYB4
Bulk density (g/mL)	0.68 ± 0.01^{d}	0.70 ± 0.01^{c}	0.71 ± 0.01^{bc}	0.72 ± 0.01^{ab}	0.73 ± 0.02^{a}
Water absorption capacity (g/g)	1.35 ± 0.04^{e}	1.44 ± 0.03^{d}	1.51 ± 0.05^{c}	1.58 ± 0.04^{b}	1.66 ± 0.05^{a}
Oil absorption capacity (g/g)	1.18 ± 0.03^{e}	1.25 ± 0.04^{d}	1.32 ± 0.03^{c}	1.39 ± 0.04^{b}	1.47 ± 0.05^{a}
Swelling capacity (g/g)	5.42 ± 0.08^{d}	5.71 ± 0.06^{c}	5.96 ± 0.07^{b}	6.18 ± 0.09^{a}	6.30 ± 0.10^{a}
Foaming capacity (%)	8.40 ± 0.31^{e}	10.65 ± 0.42^{d}	12.31 ± 0.38^{c}	14.08 ± 0.45^{b}	15.72 ± 0.50^{a}
Least gelation concentration (%)	12.00 ± 0.00^{a}	10.00 ± 0.00^{b}	10.00 ± 0.00^{b}	8.00 ± 0.00^{c}	8.00 ± 0.00^{c}

Note: Values are presented as mean ± standard deviation. Superscript letters a, b, c, d, and e within a row label statistical groups. Statistical importance (P < 0. 05) is indicated by different superscript letters. Values with a common superscript within the same row are not considerably different.

Gluten content of reduced-gluten muffins produced from wheat, brown rice and African yam bean composite flours

The gluten contents of reduced-gluten muffins made from wheat, brown rice and African yam bean composite flours are shown in (Table 4). It showed that increasing the proportion of brown rice and African yam bean flour, resulted in decreased gluten.

Table 4: Gluten content of reduced-gluten muffins produced from wheat, brown rice and African yam bean composite flours

Sample	Gluten content (mg/kg)
WF	35,620.00 ± 420.15^{a}
BRAYB1	24,850.00 ± 310.42^{b}
BRAYB2	21,170.00 ± 285.30^{c}
BRAYB3	17,760.00 ± 250.64^{d}
BRAYB4	14,280.00 ± 230.18^{e}

Note: Values are presented as mean ± standard deviation. Superscript letters a, b, c, d, and e within a row label statistical groups. Statistical importance (P < 0. 05) is indicated by different superscript letters. Values with a common superscript within the same row are not considerably different.

The WF control sample had the highest gluten content value of 35,620. 00 mg/kg while BRAYB4 had the lowest gluten content value of 14,280. 00 mg/kg. This means that the gluten content is reduced by 59. 9% from the wheat flour muffin to the highest composite flour formulation. The values in the (Table 4) were all statistically different (P < 0 . 05) because they have different superscript letters. These results indicate that all the samples with different replacements of wheat flour considerably differed in terms of gluten reduction. This may be due to the dilution of gluten-forming proteins (glutenin and gliadin) in the wheat flour which forms gluten when hydrated and combined with water. According to the Institute of Food Science and Technology, wheat flour contains glutenin and gliadin which when combined with water form gluten; thus, replacing wheat flour with other flours would reduce the gluten-forming protein fraction . These findings are consistent with those of Elegbeleye and Sivakumar (2026) that African yam bean is a protein-rich legume, and that fermented African yam bean can improve the protein digestibility and nutrient availability of wheat-based food products, thereby improving the nutritional quality of the food products. Therefore, the muffins generated are reduced-gluten products, but not gluten-free products. According to Codex Alimentarius, gluten-free food products must not contain more than 20 mg of gluten per kg of product, and food products specially processed to reduce gluten content must contain less than 100mg of gluten per kg of product. However, gluten amounts in this survey are far above levels a coeliac or gluten intolerant person can tolerate. In conclusion, increasing brown rice and African yam bean flour substitution can considerably reduce muffin gluten content, which can help in developing wheat-reduced bakery products . However, further improvement of the formulation is still required to achieve gluten-free or very low gluten standards.

Proximate composition of muffins made from reduced-gluten wheat, brown rice and African yam bean composite flour

Table 5 shows the proximate composition of muffins made from reduced-gluten wheat, brown rice and African yam bean composite flour. Partial substitution of wheat flour with brown rice and African yam bean flour led to considerable changes in the composition of the composite muffin. Moisture content of WF muffin was 22.10%, and BRAYB4 muffin was 24.05%. The treatments differed significantly (P < 0.05); the high water-absorption capacity of the composite flours, together with the protein and fibre fractions of the legume flour, may explain the higher moisture content of the baked muffins. Similar results have been obtained for composite flour systems, where non-wheat flours improved water absorption and other

Table 5: Proximate composition of reduced-gluten muffins produced from wheat, brown rice and African yam bean composite flours

Proximate composition	WF	BRAYB1	BRAYB2	BRAYB3	BRAYB4
Moisture (%)	22.10 ± 0.30^{e}	22.65 ± 0.28^{d}	23.05 ± 0.35^{c}	23.50 ± 0.32^{b}	24.05 ± 0.40^{a}
Crude protein (%)	8.52 ± 0.15^{e}	9.31 ± 0.18^{d}	10.02 ± 0.20^{c}	10.83 ± 0.22^{b}	11.62 ± 0.25^{a}
Crude fat (%)	15.85 ± 0.20^{a}	15.62 ± 0.18^{ab}	15.48 ± 0.21^{b}	15.31 ± 0.19^{b}	15.15 ± 0.22^{c}
Crude fibre (%)	1.12 ± 0.05^{e}	1.48 ± 0.06^{d}	1.78 ± 0.07^{c}	2.18 ± 0.08^{b}	2.62 ± 0.10^{a}
Ash (%)	1.34 ± 0.04^{e}	1.55 ± 0.05^{d}	1.72 ± 0.04^{c}	1.95 ± 0.06^{b}	2.18 ± 0.07^{a}
Carbohydrate (%)	51.07 ± 0.42^{a}	49.39 ± 0.39^{b}	47.95 ± 0.45^{c}	46.23 ± 0.41^{d}	44.38 ± 0.48^{e}
Energy value (kcal/100 g)	381.01 ± 1.15^{a}	375.38 ± 1.08^{b}	371.20 ± 1.22^{c}	366.03 ± 1.18^{d}	360.35 ± 1.30^{e}

Note: Values are presented as mean ± standard deviation. Superscript letters a, b, c, d, and e within a row label statistical groups. Statistical importance (P < 0. 05) is indicated by different superscript letters. Values with a common superscript within the same row are not considerably different.

Table 6: Mineral composition of reduced-gluten muffins produced from wheat, brown rice and African yam bean composite flours

Mineral composition	WF	BRAYB1	BRAYB2	BRAYB3	BRAYB4
Calcium (mg/100 g)	82.40 ± 2.10^{e}	91.75 ± 2.35^{d}	98.60 ± 2.52^{c}	106.85 ± 2.70^{b}	115.30 ± 2.88^{a}
Magnesium (mg/100 g)	28.65 ± 0.90^{e}	36.20 ± 1.05^{d}	42.55 ± 1.12^{c}	49.10 ± 1.20^{b}	56.35 ± 1.35^{a}
Iron (mg/100 g)	2.10 ± 0.08^{e}	2.48 ± 0.10^{d}	2.82 ± 0.11^{c}	3.20 ± 0.13^{b}	3.63 ± 0.15^{a}
Zinc (mg/100 g)	1.12 ± 0.04^{e}	1.32 ± 0.05^{d}	1.50 ± 0.06^{c}	1.69 ± 0.06^{b}	1.91 ± 0.08^{a}
Potassium (mg/100 g)	168.40 ± 4.20^{e}	194.55 ±5.00^{d}	216.35 ±5.40^{c}	239.10 ± 5.80^{b}	264.75 ± 6.10^{a}
Sodium (mg/100 g)	308.25 ± 6.30^{a}	305.80 ±5.90^{a}	304.60 ±6.10^{a}	303.25 ± 6.50^{a}	302.15 ± 6.25^{a}

Note: Values are presented as mean ± standard deviation. Superscript letters a, b, c, d, and e within a row label statistical groups. Statistical importance (P < 0. 05) is indicated by different superscript letters. Values with a common superscript within the same row are not considerably different.

functional properties (Ata et al. (2026). Crude protein content ranged from 8.52% for WF to 11.62% for BRAYB4. African yam bean, being a legume, is reported to be a good source of protein, ash, carbohydrate, fat, fibre and moisture content (Elegbeleye & Sivakumar, 2026). Therefore, it can be used to fortify cereal-based products. This supports the finding that African yam bean seed flour has functional and protein properties for use in the preparation of baked products (Beleya et al. (2026). The crude fibre and ash in the muffins increased from 1.12% to 2.62% and from 1.34% to 2.18%, respectively, due to dietary fibre and minerals from whole brown rice and African yam bean, which were used as non-starchy food materials in the refined wheat flour of the muffins. Overall, similar results have been recorded for such studies elsewhere. Gutiérrez et al., (2026), for example, found that whole brown rice flour contained more protein, ash, fibre, and fat than ordinary milled rice flour. Biscuits made from African yam bean composite flour had a better proximate composition than biscuits made from only wheat flour (Dada et al. 2023). Crude fat declined slightly from 15. 85% in WF to 15. 15% in BRAYB4. As noted above, there was no statistically significant difference (P = 0.05) between WF and BRAYB1, BRAYB1 and BRAYB2, or BRAYB2 and BRAYB3. Flour substitution caused a smaller decrease in fat than in protein, fibre, ash, carbohydrate, and energy contents; carbohydrate decreased from 51.07% to 44.38% and energy from 381.01 to 360.35 kcal/100 g due to the increase in moisture, protein, fibre and ash and the decrease in carbohydrate and fat content. In conclusion, fortified muffins with brown rice and African yam bean flour had higher protein, fibre and ash, with a concomitant decrease in carbohydrate and energy value. This suggests the potential use of BRAYB formulations for developing nutrient-dense bakery products with reduced gluten content.

Mineral composition of reduced-gluten muffins produced from wheat, brown rice and African yam bean composite flours

The mineral content of reduced-gluten muffins produced from wheat, brown rice composite flour and African yam bean composite flour is presented in (Table 6). The table indicates that substituting wheat flour with brown rice and African yam bean flour progressively improved the mineral content of the muffins. Calcium increased from 82. 40 to 115 . 30 mg/100 g in WF and BRAYB4 respectively, magnesium from 28. 65 to 56. 35 mg/100 g, iron from 2. 10 to 3. 63 mg/100 g, zinc from 1. 12 to 1. 91 mg/100 g and potassium from 168. 40 to 264. 75 mg/100 g. Superscript letters within the columns of the table show statistically meaningful differences in the calcium, magnesium, iron, zinc and potassium contents of muffin samples (p < 0. 05), confirming that the proportions of the composite flours had a meaningful effect on the micronutrient contents of the muffins. The increases in the mineral contents of muffins can be attributed to the contribution of minerals from brown rice and African yam bean flours. African yam bean has been reported to be a good source of minerals in food such as magnesium, iron, zinc, and potassium (Elegbeleye & Sivakumar, 2026). Besides, the whole brown rice flour contributed to the mineral content of the composite flour products in the form of an important amount of ash (the inorganic mineral content of the flour) (Gutierez et al., 2026). The increase in iron and zinc is nutritionally important, since both are required for hematopoiesis, immunity, growth and enzymatic activity. The increase in calcium and magnesium may confer benefits in bone health, muscle activity and metabolic processes. Increased potassium may also improve the nutritional quality of the muffins by contributing to fluid balance and normal functioning of the body. Similar results were observed in composite bakery products when wheat flour was supplemented with African yam bean (AYB) flour-based blends to improve the nutritional quality of biscuits (Dada et al., 2023). All other minerals were reduced except sodium, which decreased from 308. 25 mg/100 g in WF to 302. 15 mg/100 g in BRAYB4. However, the sodium values that share the same superscript are not considerably different from each other at $P < 0.05$. The sodium content in flour substitution products suggests that varying the flour does not greatly affect sodium content when sodium is contributed by fixed recipe components such as baking powder and salt. In conclusion, the addition of brown rice and African yam bean flour to the flour used for muffin preparation increased the calcium, magnesium, iron, zinc, and potassium contents of the muffin, while the sodium content was not considerably affected. This suggests that the BRAYB formulations can be used to fortify reduced-gluten muffins with micronutrients and help in the formulation of more nutritious bakery products.

Physical characteristics of muffins produced from wheat, brown rice and African yam bean composite flours

The physical properties of the wheat, brown rice, and African yam bean composite flour muffins are shown in (Table 7). A progressive increase in the substitution of wheat flour with brown rice and African yam bean flour had a meaningful effect on the weight, height, diameter, volume, specific volume, and bake loss of the muffins. The increase in muffin weight from 43. 80 g (WF) to 45. 58 g (BRAYB4) may be due to the composite flours' high water absorption and retention. The increased protein and fiber contents of the legume and other non-wheat flours compared to wheat flour may also contribute. Ata et al. (2026) showed that adding other non-wheat flours to wheat flour would improve water absorption-related functional properties. Beleya et al. (2026) reveal that African yam bean flour has high water holding capacities. The water absorption of unprocessed African yam bean flour was 2. 16 ± 0. 06 g/mL, while that of cracked and boiled flour was 2. 82 ± 0. 09 g/mL, indicating that processing increases the water holding capacity of African yam bean flour. The height of batter-specific muffins decreased from 5. 25 cm (WF muffins) to 4. 25 cm (BRAYB4 muffins) and the volume from 112. 40 cm^3 (WF muffins) to 89. 60 cm^3 (BRAYB4 muffins). Muffin specific volume also decreased from 2. 57 cm^3/g (WF muffins) to 1 . 97 cm^3/g (BRAYB4 muffins). Enhanced water binding ability of composite flour may change batter viscosity (flow behavior) and power (measured in terms of gas holding capacity) which may cause a collapse of gluten-based structure. These reductions suggest that increasing brown rice flour and African yam bean flour weakened the gluten matrix responsible for gas retention and oven spring, as wheat gluten retains CO_2 and steam during baking. Likewise, Silva et al. (2026) stated that excessive non-gluten flour could disrupt the viscoelastic matrix, promote the coalescence and collapse of gas cells, and then reduce gluten-free product specific volum. In a similar study, Kumbaji et al. (2026) reported a higher specific volume for the wheat-based control product because of its better gas retention and expansion properties as compared to the gluten-free composite products that were firmer and denser. The increased diameter of 6. 48 cm in WF to 7. 00 cm in BRAYB4 could be due to a weaker batter structure preventing a rise in height, but allowing a greater spread, during baking. This substitution is similar to other physical properties of composite bakery products from blends of African yam bean-based composites with wheat flour, where structure and other properties were observed to vary. The baking loss was considerably reduced from 12. 40% WF to 8. 84% in BRAYB4, as less moisture and volatile matter were lost during baking due to the improved water-binding capabilities of the composite flours. The superscript letters indicate that most of the recorded differences can be attributed to flour substitution. Replacement with brown rice and AYB flour increased weight retention and reduced baking loss; however, muffin height, volume, and specific volume were considerably reduced. Therefore, although a BRAYB formulation may increase nutritional quality, it may also be necessary to optimize structure-building ingredients to make muffins with a higher volume and a lighter colour.

Sensory evaluation of muffins produced from wheat, brown rice and African yam bean composite flours

The mean sensory scores of muffins prepared from wheat,

Table 7. Physical characteristics of muffins produced from wheat, brown rice and African yam bean composite flours

Physical characteristic	WF	BRAYB1	BRAYB2	BRAYB3	BRAYB4
Weight (g)	43.80 ± 0.45^{d}	44.25 ± 0.50^{cd}	44.71 ± 0.48^{c}	45.10 ±0.52^{b}	45.58 ± 0.55^{a}
Height (cm)	5.25 ± 0.10^{a}	5.02 ± 0.08^{b}	4.78 ± 0.09^{c}	4.50 ± 0.11^{d}	4.25 ± 0.10^{e}
Diameter (cm)	6.48 ± 0.07^{e}	6.60 ± 0.08^{d}	6.72 ± 0.09^{c}	6.86 ± 0.10^{b}	7.00 ± 0.11^{a}
Volume (cm³)	112.40 ± 2.15^{a}	106.85 ±2.00^{b}	101.20 ± 1.95^{c}	95.75 ± 1.88^{d}	89.60 ± 1.70^{e}
Specific volume (cm³/g)	2.57 ± 0.06^{a}	2.41 ± 0.05^{b}	2.26 ± 0.04^{c}	2.12 ± 0.04^{d}	1.97 ± 0.03^{e}
Baking loss (%)	12.40 ± 0.35^{a}	11.50 ± 0.30^{b}	10.58 ± 0.28^{c}	9.80 ± 0.25^{d}	8.84 ± 0.22^{e}

Note：Values are presented as mean ± standard deviation. Superscript letters a, b, c, d, and e within a row label statistical groups. Statistical importance ($P < 0.05$) is indicated by different superscript letters. Values with a common superscript within the same row are not considerably different.

Table 8: Sensory evaluation of muffins produced from wheat, brown rice and African yam bean composite flours

Sensory attribute	WF	BRAYB1	BRAYB2	BRAYB3	BRAYB4
Appearance	8.10 ± 0.72^{a}	7.95 ± 0.76^{ab}	7.70 ± 0.81^{b}	7.20 ± 0.88^{c}	6.65 ± 0.94^{d}
Aroma	7.85 ± 0.78^{a}	7.80 ± 0.80^{a}	7.55 ± 0.84^{ab}	7.15 ± 0.91^{b}	6.65 ± 0.97^{c}
Taste	8.15 ± 0.70^{a}	8.00 ± 0.74^{a}	7.70 ± 0.82^{b}	7.10 ± 0.90^{c}	6.40 ± 1.02^{d}
Texture	8.20 ± 0.68^{a}	7.90 ± 0.77^{b}	7.55 ± 0.83^{c}	6.95 ± 0.94^{d}	6.25 ± 1.05^{e}
Overall acceptability	8.18 ± 0.69^{a}	7.98 ± 0.73^{a}	7.68 ± 0.80^{b}	7.10 ± 0.89^{c}	6.48 ± 0.99^{d}

Note：Values are means with standard deviations per 100 participants on a nine-point hedonic scale ranging from 1 = dislike extremely to 9 = like extremely. Means with different superscript letters within a row are considerably different at $P < 0.05$. WF (100% wheat flour); BRAYB1 (70% wheat flour, 20% brown rice flour and 10% African yam bean flour), BRAYB2 (60% wheat flour, 25% brown rice flour and 15% African yam bean flour), BRAYB3 (50% wheat flour, 30% brown rice flour and 20% African yam bean flour) and BRAYB4 (40% wheat flour, 35% brown rice flour, and 25% African yam bean flour) respectively.

brown rice and African yam bean composite flour are presented in (Table 8). The sensory attributes evaluated by 100 respondents included the muffins' appearance, aroma, taste, texture and general acceptability / overall rating. In most instances the sensory scores decreased with increasing levels of brown rice and African yam bean flour substitution. The decline in the appearance, texture, taste and overall acceptability with increased levels of substitution of brown rice and African yam bean flour substantiates information obtained from earlier works. Ilyas et al. (2026) concluded that the sensory profile (color, appearance, aroma, texture, and taste) of biscuits with 5% non-wheat seed powder was similar to that of the control made from wheat flour, while the substitution of 10% and 20% non-wheat seed flours reduced sensory desirability due to increased bitterness and color darkening. Ata et al . (2026) also found that cakes with low concentrations of germinated legume flour were more favourable than those formulated at higher substitution levels, because the proportion of legume flour in the product negatively influences color, flavour, appearance, texture, and acceptability. It has been suggested that such poor sensory scores may be due to the effects of high concentrations of non-wheat flour on the flavour and other sensory characteristics of conventionally used wheat-based baked goods. The textural and appearance properties may have diminished as a result of a change in the structural matrix and gas-holding ability of the products, as indicated by Tyl et al. (2026), who found that the muffins with high flour substitution levels had lower specific volumes, heights, lightness, porosity and softness . Ata et al. (2026) also reported high gumminess and chewiness of legume-fortified cake products, particularly when a greater legume substitution level was used. It is possible that these changes render composite muffins denser, less aerated in texture, and less acceptable to consumers.

However, in the same study, one cowpea-based muffin formulation was found to be equally acceptable to a wheat control formulation. Thus, products containing legumes do not have to be unacceptable if the right variety and formulation are chosen. The substitution of wheat flour with flour from African yam bean and tiger nut had no negative effect on sensory attributes of composite flour biscuits. Dada et al. (2023) state that all biscuits made from wheat/African yam bean and tiger nut composite flour received noticeable sensory ratings by the sensory panel due to their acceptability. A 70% wheat flour, 15% African

Table 9: Pearson correlations between selected nutritional, functional, physical, and sensory properties of the muffin formulations

Property	Height	Volume	Specific volume	Sensory texture	Overall acceptability
Gluten content	0. 951	0. 957	0. 965	0. 902	0. 884
Crude protein	−1. 000	−1. 000	−0. 999	−0. 986	−0. 978*
Crude fibre	−0. 999	−0. 998	−0. 997	−0. 992	−0. 987
Ash	−0. 999	−0. 999	−0. 998	−0. 990	−0. 984*
Water absorption capacity	−0. 997	−0. 999	−1. 000	−0. 979	−0. 970*
Oil absorption capacity	−0. 999	−1. 000	−0. 999	−0. 987	−0. 980*
Swelling capacity	−0. 986	−0. 987	−0. 992	−0. 948	−0. 937*
Foaming capacity	−0. 996	−0. 997	−0. 999	−0. 973	−0. 963*

Note: Pearson correlation coefficients for the mean values of each of the five formulations (n = 5). Results were considered statistically important at p < 0. 05, p < 0. 01 and p < 0. 001 based on two-tailed tests. The values of |r| for n = 5 correspond to a critical correlation coefficient of |r| > 0. 878, |r| > 0. 959 and |r| > 0. 991 respectively. The sensory texture represents the mean texture liking score rated on the nine-point hedonic scale by the assessors, whereas instrumental texture is not measured. While sensory evaluation was performed with 100 assessors, correlation analysis was performed on the five formulation-level means rather than on any individual assessors' response. Thus, r=0. 957 is meaningful (one asterisk) because it is between 0. 878 and 0 . 959, and r=0. 965 is meaningful (two asterisks) because it is between 0. 959 and 0. 991.

yam bean flour and 15% tiger nut flour formulation was rated better than the wheat control in terms of appearance, aroma, taste, crispness and acceptability. According to Chompoarat et al. (2020), the addition of rice flour to red-kidney-bean cupcakes gave better flavor, taste, texture and overall quality than the control cupcakes; a 25% rice flour formulation had the best mean scores. Therefore, the reliability of these results should be further investigated. Weak gluten development, density, different color, and/or increased legume flavor perception may be factors for the lower scores of BRAYB3 and BRAYB4. However, it has been reported in the published literature that rice-legume blends can be as acceptable when compared with control wheat formulation. Thus, considering the sensory scores and statistically important differences, BRAYB1 may be the best formulation in the study of the blends, rather than the extrapolated data.

Pearson correlations between selected nutritional, functional, physical, and sensory properties of the muffin formulations

The Pearson correlation coefficients between nutritional and functional properties and physical and sensorial properties of five muffin formulations are presented in (Table 9). A positive correlation was observed between the gluten content and height, volume, specific volume, sensory texture, and overall acceptability. Protein, fibre, ash and functional properties were negatively correlated with these properties . There were strong positive correlations between gluten content and height (r = 0. 951), volume (r = 0. 957), specific volume (r = 0. 965), sensory texture (r = 0. 902) and acceptability (r = 0. 884). This indicates that as mixtures were fortified with gluten, muffins were taller and larger, closer to the control wheat muffin for texture and acceptability. As gluten forms a viscoelastic matrix that retains air and gases during baking, the dilution of the flours with brown rice and the African yam bean flour insufficiently supported vertical expansion . However, crude protein, crude fibre and ash were negatively correlated (from −0 . 997 to −1 . 000) with the height, volume, specific volume, sensory texture and overall acceptability. This indicated the nutritional-technological dilemma associated with increasing the density of nutrients while retarding the expansion, final volume and texture acceptability of the biscuits. The same trend was also reported by Ata et al. (2026) with legume-fortified cakes, where as the percentage of chickpea and kidney-bean flour substitution was increased, the protein and fibre increased while the specific volume, hardness, texture and overall-acceptability scores of the cake decreased at the highest substitution percentages. Water absorption, oil absorption, swelling capacity and foaming capacity correlated negatively with all physical and sensory properties.

Water absorption correlated perfectly negatively with specific volume (r = −1 . 000), and oil absorption with volume (r = −1. 000). Composite flours increased water and fat absorption and foaming capacity, but reduced gluten networks. Higher water absorption and swelling might have increased batter viscosity and therefore limited gas-cell formation. Feller et al. (2026) found that the viscosity of the fibre-containing ingredients and formulation influenced gas retention and specific volume in gluten-free baked products . Negative correlations between sensory texture and acceptability corroborate these findings. Pehlivan et al. (2026) indicated that the muffin formulation, moisture retention, and processing affected the firmness, chewability, and general acceptability.

Conclusion

The addition of Brown rice flour (BRF) and African yam bean flour (AYBF) improved the nutritional and functional properties of wheat flour muffins while lowering their gluten content. Water and oil absorption capacities, foaming capacity, protein, fibre, ash, calcium, magnesium, iron, zinc and potassium levels of the muffins all increased with increased BRF and AYBF levels. Conversely, carbohydrates and energy levels, as well as gluten content, decreased with increasing flour substitution. However, with a higher substitution, lower volume and specific volume were observed due to depletion of gluten proteins, weakening of batter structure, and reduced ability to retain gas. The increase in weight retention and reduction in baking loss demonstrated that the highest level of nutritional enrichment may not necessarily yield better physical and sensory properties. Pearson correlation coefficient analysis was also used. The gluten content was positively correlated with muffin height, volume, and specific volume, the sensory texture score and the overall acceptability score. The crude protein content, fibre content, ash content, water absorption capacity, oil absorption capacity, swelling capacity and foaming capacity were negatively correlated with the physical and sensory characteristics. Overall, this indicates a nutritional-technological trade-off, where the addition of BRF and AYBF, which increased the nutritional value and functional properties, was related to a reduction in expansion, texture and consumer acceptability, with caution that these associations are based on mean values of the five formulations and not a direct cause and effect. The mix of 70% wheat, 20% brown rice flour and 10% African yam bean flour (BRAYB1) was found to be the most appropriate for product development due to the balance it offered between nutrition, gluten reduction, physical quality and sensory acceptability. The use of brown rice and the African yam bean flour as an under-utilised crop offers a route to producing functionally improved and reduced gluten baked products. The study evaluated the functional, nutritional, mineral, physical properties, gluten and sensory characteristics of the muffins. Future studies need to focus on the shelf life, instrumental texture, crumb structure, antinutritional factors, and on the formulation strategies to improve gas retention and sensory properties at higher level of the replacement in the muffin formulation.

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