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Quality characteristics of sorghum–corn sourdough bread enriched with moringa leaf and duck meat

Karakteristik mutu roti sourdough berbasis tepung komposit sorgum–jagung yang diperkaya dengan daun kelor dan daging itik

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Abstract

Bread is widely consumed due to its affordability, convenience, and suitability as a vehicle for nutritional improvement. In Indonesia, reliance on imported wheat remains a concern, while commonly consumed white bread provides limited dietary fiber and micronutrients. Locally available crops such as sorghum and corn therefore offer potential alternatives for wheat-based bread formulations. This study aimed to evaluate gluten-free sourdough bread based on sorghum–corn composite flour enriched with moringa (*Moringa oleifera*) leaf powder and duck meat powder based on physicochemical, microbiology, and sensory. This study used a completely randomized design with variable, namely the concentration of moringa leaf (1%, 2%, 3%) and duck meat (10%, 20%, 30%) incorporated into the bread formulation. The incorporation of moringa leaf and duck meat powders significantly affected ($p < 0.05$) protein, iron, ash, moisture, and crude fiber contents, as well as selected sensory attributes, including taste, texture, and overall acceptance. In contrast, specific volume and aroma were not significantly influenced by formulation differences. Total plate count values of all samples remained below the maximum permissible limit, indicating acceptable microbiological quality at the initial storage period. Among the tested formulations, sample G exhibited the most balanced trade-off between nutritional enhancement, sensory acceptance, microbiological quality, and physical properties. These findings indicate that sorghum–corn sourdough bread enriched with moringa leaf and duck meat powders has potential as a nutritionally enhanced bread product derived from local resources.

INTRODUCTION

Bread is one of the most widely consumed cereal-based foods due to its affordability, convenience, and versatility as a carrier for nutritional enhancement (Aghalari et al., 2022). Global demand for bread and bakery products has resulted in a strong dependence on wheat-based raw materials. In many developing countries, including Indonesia, wheat is not produced locally in sufficient quantities, leading to a high reliance on imports and increased vulnerability to market and supply fluctuations, in 2024 Indonesia has imported 11,71 million tons (Badan Pusat Statistik, 2025). Dependence on importance wheat may poses economic and food security challenges, encouraging the utilization of locally available cereals for bread production.

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Sorghum (*Sorghum bicolor* (L.) Moench) has gained increasing attention in Indonesia due to its high tolerance to drought compared with other cereal crops, making it suitable for cultivation in expanding dryland areas across the country (Zubair, 2016). Sorghum is widely cultivated in several regions, including Java, East Nusa Tenggara, Sulawesi, and Sumatra. In addition to its agronomic advantages, sorghum is a gluten-free cereal with appreciable dietary fiber content (6–8%) and relatively high levels of iron and vitamins (Widowati & Luna, 2022). However, bread produced from sorghum flour is often characterized by poor gas retention, low loaf volume, and a dense crumb structure due to the absence of gluten (Adzqia et al., 2023). To improve dough handling and textural properties, sorghum flour is commonly combined with starch-rich ingredients such as corn starch to form composite flours (Canelo-Álvarez et al., 2023). Nevertheless, sorghum–corn composite flour remains limited in protein content and overall nutritional density, as both sorghum flour and corn starch are predominantly carbohydrate-based ingredients.

Ingredient enrichment has therefore been explored as an approach to improve the compositional quality of gluten-free composite flour bread. Moringa (*Moringa oleifera*) leaf powder has been widely studied as a nutrient-rich plant ingredient, containing high levels of protein and minerals such as calcium, iron, potassium, magnesium, and manganese (Peñalver et al., 2023). Several studies have reported increased ash and protein contents in bakery products following moringa leaf incorporation; however, higher inclusion levels are often associated with darker color, bitter taste, and reduced sensory acceptance, which limit its application in bread formulations (Koriyama et al., 2025; Ragal et al., 2025). Animal-derived protein ingredients have also been incorporated into bakery formulations to improve nutritional quality. Duck meat is characterized by a favorable essential amino acid profile, polyunsaturated fatty acids, and a balanced omega-6 to omega-3 ratio (Ismoyowati & Sumarmono, 2019), making it a potential protein source for composite flour bread. Previous studies have demonstrated the successful incorporation of animal-derived proteins into bakery products, such as the addition of chicken meat and fish protein to bread formulations, which significantly enhanced their protein content and overall nutritional profile (Bastos et al., 2014; Çakmak et al., 2013). However, its use in bread formulations remains limited and presents challenges related to dough structure and flavor development.

Sourdough fermentation has been recognized as an effective approach to enhance the quality of gluten-free bread by improving dough structure, flavor complexity, and overall product characteristics (Nionelli & Rizzello, 2016). The metabolic activity of lactic acid bacteria and yeast modifies the bread matrix through acidification and enzymatic reactions, potentially mitigating some technological shortcomings of gluten-free composite flours. While sourdough fermentation in sorghum-based bread has been widely studied, the combined incorporation of plant-based bioactive ingredients and animal-derived protein sources within a gluten-free sourdough system remains underexplored.

Therefore, this study aimed to evaluate the combined effects of moringa leaf powder and duck meat incorporation on the physicochemical characteristics of gluten-free sourdough bread produced from sorghum–corn composite flour.

METHODS

Tools

The equipment used in this study were glassware, oven, incubator, mixer, scales, baking pan, blender, and dough spatula.

Materials

Sorghum flour (Petani Muda) and corn starch (Kimia Market) were brought online from Jakarta, Indonesia while moringa leaf powder were procured from Malang, Indonesia. Duck meat, pineapple, yeast powder, salt, sugar, butter, and baking powder were sourced from Blitar,

Moringa leaves	0	0.9	0.9	0.9	1.8	1.8	1.8	2.7	2.7	2.7

Indonesia. The chemicals utilized for analysis included distilled water, hydrochloric acid, sodium hydroxide, sulfuric acid, Kjeldahl tablet, hexane solvent, and boric acid.

Research Design

This study used a completely randomized design with variable, namely the concentration of moringa leaf (1%, 2%, 3%) and duck meat (10%, 20%, 30%) incorporated into the bread formulation. The concentration percentages were calculated based on the total weight of sorghum flour and corn starch. All experiments were conducted in triplicate.

Preparation of sourdough starter

In preparing the starter used for gluten-free sourdough production, diverse microflora was sourced from pineapple juice and composite flour. The pineapple was peeled, diced, and blended with water at a 2:1 ratio. Composite flour (sorghum flour and corn starch, 1:1 ratio) was mixed with pineapple juice in a 1:1 ratio until homogeneous. The mixture was then incubated at 22 °C for 24 hours to activate the starter culture and initiate fermentation. After incubation, half of the starter was removed and replaced with water, followed by thorough mixing. On the second day, 50 g of flour was added to 50 g of pineapple juice and mixed thoroughly. This feeding process was repeated every 24 hours for a total of five days (Zaidiyah et al., 2020).

Process of Production Duck Meat

Duck fillets were washed, drained, and cooked with steam for 30 minutes to achieve a soft texture. The cooked duck meat was subsequently cooled and ground using a food processor (Philips HR-7310) to reduce particle size. The ground duck meat was subsequently oven-dried at 60 °C for 3 hours to lower the moisture content and ensure product stability. After drying, the meat was milled into a fine powder, packaged in airtight polyethylene pouches, and stored at –18 °C until further use in bread production (Mahmudah et al., 2024).

Process of Production Dough

Dough was formulated using two independent variables: moringa leaf powder concentration (1% w/w, 2% w/w, and 3% w/w) and duck meat concentration (10% w/w, 20% w/w, and 30% w/w), based on the total flour weight. A fixed dough formulation was used, consisting of 60 g sorghum flour, 30 g corn starch, 15 g sugar, 2 g salt, 1 g butter, 20 g

sourdough starter, 70 g water. All ingredients were mixed using a food processor (Philips HR-7310) until a smooth dough was obtained. The dough shaped into loaves, placed on baking sheets, and baked at 175°C for 45 minutes. The formulation of the various dough is presented in table 1.

Table 1. Formulation of Sourdough

Ingredient (g)	A (Control)	B	C	D	E	F	G	H	I	J
Sorghum flour	60	60	60	60	60	60	60	60	60	60
Corn starch	30	30	30	30	30	30	30	30	30	30
Sugar	15	15	15	15	15	15	15	15	15	15
Salt	2	2	2	2	2	2	2	2	2	2
Butter	1	1	1	1	1	1	1	1	1	1
Sourdough Starter	20	20	20	20	20	20	20	20	20	20
Water	70	70	70	70	70	70	70	70	70	70
Duck Meat	0	9	18	27	9	18	27	9	18	27

Quality assessment

a. Determination of physical properties

The physical parameters were evaluated for the bread products were color and spesific volume. Color indexes measurements, including (L*, a*, b*), were conducted using a Konica Minolta CR-410 colorimeter (Minolta Camera Co., Osaka, Japan). A DP-400 data processor (AQ Instrument) was used to measure crust color (CIE Lab* values). The L*, a*, and b* parameters represent lightness, redness/greenness, and yellowness/ blueness, respectively (Anggraeni et al., 2017). Spesific volume was obtained by dividing the sample volume by its weight (cm^3/g) (Curti et al., 2023).

b. Determination of chemical properties

The chemical parameters evaluated for the bread products included protein, lipid, ash, carbohydrate, moisture, crude fiber, and iron (Fe) content. Protein, lipid, ash, carbohydrate, moisture, crude fiber, and iron (Fe) content were analyzed using the AOAC method (AOAC, 2005). The total carbohydrate content was determined by difference. All results were expressed as grams per 100 grams of wet weight, except for iron content, which was expressed in parts per million (ppm).

c. Determination of sensory properties

Sensory analysis testing was conducted by modifying the method developed by S. A. Prayitno et al. (2021) A total of 30 semi-trained panelists was asked to evaluate the color, aroma, taste, and texture of samples by giving a liking rating from 1 to 5. A rating of 1 reflects

a strong dislike, while a rating of 5 reflects a strong liking. To neutralize their palates between samples, panelists were provided with water.

d. Determination of microbial properties

Each bread sample was weighed to 5 grams, mashed, and transferred to an Erlenmeyer flask containing 45 mL of sterile water. After homogenization with a cotton plug, serial dilutions were performed from 10^{-2} to 10^{-3}. One milliliter of each of the last two dilutions was transferred to separate Petri dishes, followed by the addition of 45 mL of molten Plate Count Agar (PCA) at 45°C. The plates were mixed thoroughly and allowed to solidify. The plates were then incubated at 37°C for 24 hours. Colony growth on each plate was observed, and the number of colonies was counted using the Standard Plate Count (SPC) method (Ojo et al., 2021).

e. Determination of the best treatment.

The optimal treatment was identified using the Zeleny method (Zeleny, 1998), which integrates multiple quality attributes, including physicochemical, microbiological, and sensory characteristics. In this approach, an ideal target value was first established for each parameter by defining whether a higher or lower value was preferable, depending on the specific attribute. To enable comparison among variables with different measurement units, all parameters were normalized to a scale ranging from 0 to 1. The relative closeness to the ideal solution was then assessed by calculating distance values using the L_1 (Manhattan), L_2 (Euclidean), and $L\infty$ (Chebyshev) metrics. All parameters were assigned equal weights to minimize subjectivity and ensure balanced consideration of each quality attribute. The treatment with the smallest distance values across all metrics was considered the closest to the ideal solution and was therefore selected as the best formulation by considering multiple quality attributes, including physicochemical, microbiological, and sensory.

Statistical analysis

All experiments were conducted in triplicate. Data were expressed as mean ± standard deviation. Analysis of variance (ANOVA) was performed using Minitab 18 (Minitab LLC, Pennsylvania) to analyze variations among samples. Tukey's multiple-range test was used for pairwise comparisons, with statistical significance set at $p < 0.05$.

RESULTS AND DISCUSSIONS

Physical Quality of Bread

Color and loaf expansion are critical physical quality attributes that strongly influence consumer perception and technological performance of bread products. In gluten-free sourdough systems, these parameters are particularly sensitive to ingredient composition and fermentation dynamics. Therefore, the effects of moringa leaf powder and duck meat powder incorporation on color characteristics was evaluated.

Table 2. Physical quality of bread

Parameters	A (control)	B	C	D	E	F	G	H	I	J
L*	48.20 ± 0.57^{a}	47.85± 0.21^{a}	46.30± 0.14^{bc}	46.25± 0.07^{bc}	46.80± 0.14^{b}	45.55 ± 0.21^{cd}	44.70 ± 0.14^{de}	45.45± 0.07^{cd}	45.80± 0.14^{c}	44.35± 0.07^{e}
a*	5.75 ± 0.49^{a}	5.45 ± 0.21^{ab}	5.45 ± 0.49^{ab}	5.45 ± 0.07^{ab}	4.25 ± 0.07^{c}	5.00 ± 0.00^{abc}	4.80 ± 0.14^{abc}	4.25 ± 0.07^{c}	4.50 ± 0.28^{bc}	4.05 ± 0.07^{c}
b*	18.95 ± 0.07^{a}	17.15± 0.07^{b}	15.25± 0.21^{e}	15.65± 0.21^{de}	15.20± 0.14^{e}	15.55± 0.07^{de}	15.40± 0.14^{de}	16.3 ± 0.14^{c}	15.95± 0.07^{cd}	14.45± 0.21^{f}
Specific volume (cm^3/g)	1.05 ± 0.03^{a}	0.96 ± 0.13^{a}	1.09 ± 0.03	1.11 ± 0.03^{a}	1.02 ± 0.03^{a}	1.02 ± 0.09^{a}	0.96 ± 0.03±	0.99 ± 0.10^{a}	1.09 ± 0.09^{a}	0.96 ± 0.03^{a}

Expressed values were mean±SD (n = 3); a same row containing means with the same superscript letters are notsignificantly different ($p < 0.05$)

Color was assessed using the CIE L*, a*, and b* parameters, where L* represents lightness (0 = black; 100 = white). As shown in Table 2, the control sample exhibited the highest L* value (48.20 ± 0.57), indicating the lightest crumb color. In contrast, enriched sourdough formulations showed significantly lower L* values, reflecting a darker appearance. This reduction in lightness can be attributed to the addition of moringa leaf powder and duck meat powder. Moringa leaf powder possesses a naturally dark green pigment, which has been reported to decrease lightness in bakery products (Kiranawati et al., 2021). In addition, duck meat contains relatively high levels of myoglobin, a heme protein responsible for red coloration in meat (Ruedt et al., 2023), which absorbs light and contributes to darker crumb color.

The a* and b* parameters describe color shifts along the red–green and yellow–blue axes, respectively. All formulations exhibited positive a* and b* values, indicating a reddish–yellowish hue. The reddish tone is primarily associated with myoglobin and oxymyoglobin pigments derived from duck meat, while the yellowish coloration may be attributed to the intrinsic color of sorghum flour and non-enzymatic browning reactions occurring during baking. Similar color trends have been reported in bread products enriched with plant powders and protein-rich ingredients (Čáslavková et al., 2014; Nakov et al., 2020), where ingredient composition and thermal processing jointly influence final product appearance.

The specific volume of all bread samples ranged from 0.96 to 1.11 cm^3/g and did not differ significantly among formulations ($p > 0.05$). This result indicates that the addition of moringa leaf powder and duck meat powder did not produce a statistically significant effect on loaf expansion as reflected by specific volume. Overall, the specific volume values obtained in this study were lower than those reported in previous studies on gluten-free and sourdough bread (Lupu et al., 2025; Ragal et al., 2025). The lower specific volume observed in the present study may be related to the relatively short fermentation time applied. Fermentation duration plays a crucial role in gas production, as longer fermentation allows lactic acid bacteria and yeast to generate more carbon dioxide, leading to greater dough expansion (Lupu et al., 2025). In addition, differences in starter culture characteristics, as well as the composition and type of

flour used, are known to influence gas retention and dough structure, thereby affecting the final specific volume of bread.

Chemical Composition of Bread

The chemical content of the bread products analyzed is protein, fat, moisture, carbohydrate, iron, and crude fiber contents, as presented in Table 3.

Table 3. Chemical composition of bread

Parameters	A	B	C	D	E	F	G	H	I	J
Protein (%wb)	3.46 ± 0.10^{e}	5.56 ± 0.50^{d}	7.07 ± 0.12^{c}	6.98 ± 0.31^{c}	5.47 ± 0.13^{d}	7.12 ± 0.47^{c}	8.11 ± 0.09^{b}	5.10 ± 0.20^{d}	5.83 ± 0.06^{d}	8.91 ± 0.42^{a}
Fat (%wb)	1.38 ± 0.06^{e}	1.48 ± 0.11^{e}	2.25 ± 0.02^{c}	2.53 ± 0.07^{b}	1.42 ± 0.07^{e}	2.24 ± 0.06^{c}	2.53 ± 0.09^{b}	1.43 ± 0.03^{e}	1.81 ± 0.06^{d}	2.82 ± 0.06^{a}
Moisture content (%wb)	34.10 ± 1.01^{bc}	35.70 ± 0.08^{ab}	37.18 ± 0.38^{a}	34.90 ± 0.35^{ab}	37.23 ± 0.43^{a}	35.72 ± 0.56^{ab}	37.30± 0.68^{a}	33.26± 1.09^{c}	33.60± 0.35^{c}	36.04± 0.69^{bc}
Ash (%wb)	0.49 ± 0.05^{f}	0.99 ± 0.01^{e}	1.49 ± 0.03^{c}	1.58 ± 0.02^{b}	1.30 ± 0.03^{d}	1.51 ± 0.02^{bc}	1.68 ± 0.04^{a}	1.34 ± 0.01^{d}	1.52 ± 0.05^{bc}	1.71 ± 0.03^{a}
Carbohydrate (%wb)	60.04 ± 1.04^{a}	55.72 ± 0.37^{cd}	51.42 ± 0.50^{fg}	53.34 ± 0.69^{ef}	54.01 ± 0.31^{de}	52.80 ± 0.20^{ef}	49.70 ± 0.81^{g}	58.29 ± 1.26^{ab}	56.63 ± 0.42^{bc}	49.84 ± 0.62^{g}
Iron (ppm)	37.41 ± 0.63^{e}	44.49 ± 1.24^{cd}	47.96 ± 0.66^{c}	55.86 ± 2.01^{d}	41.42 ± 0.47cd	55.44 ± 1.84^{b}	65.87 ± 0.67^{a}	41.72 ± 0.42^{d}	56.91 ± 2.58^{b}	64.23 ± 0.91^{a}
Crude fiber (%)	0.52 ± 0.03^{d}	0.56 ± 0.01^{cd}	0.60 ± 0.01^{bc}	0.66 ± 0.01^{a}	0.58 ± 0.02^{bc}	0.61 ± 0.01^{b}	0.67 ± 0.01^{a}	0.57 ± 0.01^{bcd}	0.61 ± 0.01^{b}	0.68 ± 0.03^{a}

Expressed values were mean±SD (n = 3); a same row containing means with the same superscript letters are not significantly different ($p < 0.05$)

The chemical composition of the gluten-free sourdough bread was markedly influenced by the incorporation of duck meat and moringa leaf powder. Changes observed in protein, moisture, ash, carbohydrate, iron, and crude fiber contents reflected formulation-driven effects associated with the replacement of starch-based ingredients with protein- and mineral-rich materials.

Protein content showed a clear increasing trend, ranging from 3.46% to 8.91%. The control bread, formulated without moringa leaf and duck meat addition, exhibited the lowest protein content. In general, higher levels of duck meat incorporation resulted in increased protein content, indicating that duck meat powder was the main contributor to protein enrichment in the sorghum–corn composite bread. A similar effect has been reported in other food products fortified with animal-derived ingredients (Moirangthem et al., 2022). When compared with previously reported protein levels in sorghum-based sourdough bread, which ranged from 4.55% to 5.55% (Olojede et al., 2022), the protein contents obtained in the present study were

notably higher. This result suggests that the observed increase in protein content was primarily driven by formulation composition.

Moisture content ranged from 34.10% to 37.30% across all formulations, with slightly higher values observed in samples containing greater amounts of duck meat powder and moringa leaf powder. This trend can be attributed to the water-binding capacity of proteins and fibrous components introduced through ingredient incorporation, which alters water distribution and retention within the dough and crumb structure. In gluten-free bread systems, such components are known to increase moisture retention by interacting with free water, although this effect does not necessarily translate into improved loaf expansion. The moisture values obtained in this study were lower than those reported by (Centeno et al., 2021) but comparable to ranges observed in other sorghum-based bread formulations (Mustika et al., 2015), indicating that variations in raw material characteristics, formulation composition, and baking conditions played a significant role in determining final moisture content (Centeno et al., 2021; Ibrahim et al., 2020; Rauf & Andini, 2019).

The fat content of the samples ranged from 1.38% to 2.82%, with Sample J exhibiting the highest fat content. This finding aligns with previous research indicating a fat content range of 2.53-3.61% in bread (Altiab et al., 2021). Factors such as flour type, added fats, and processing methods can influence fat content (Carocho et al., 2020; Scheuer et al., 2014). Additionally, a significant correlation exists between moisture content and fat content in bread, with higher moisture levels often associated with lower fat content (Xiao et al., 2013). This relationship is influenced by various factors affecting flour's baking quality and lipid composition.

The ash content ranged from 0.49% to 1.71%, with the highest value observed in sample J. A consistent increase in ash content was observed with increasing levels of moringa leaf powder and duck meat powder, indicating the contribution of mineral-rich ingredients to the bread formulation. Moringa leaf powder has been reported to contain appreciable amounts of minerals such as calcium, potassium, iron, zinc, and iodine, which can increase ash content when incorporated into food products (Anggraini et al., 2024). Similarly, duck meat has been reported to contain approximately 1.08–1.15% ash (A. H. Prayitno & Rahman, 2020), contributing additional minerals to the bread. The gradual increase in ash content across formulations suggests effective mineral incorporation into the bread matrix and highlights the compositional impact of ingredient selection on the mineral profile of gluten-free sourdough bread.

Carbohydrate content constituted the largest proportion of the bread composition, it has been reported that sorghum and corn starch are recognized as sources of carbohydrates (Nikolić et al., 2023; Widowati & Luna, 2022). Meanwhile, carbohydrate content of samples decreased slightly in formulations with higher levels of duck meat powder and moringa leaf powder. This reduction reflects partial substitution of starch-based ingredients by protein- and mineral-containing components rather than degradation of carbohydrates during processing.

Iron content increased markedly with higher inclusion levels of moringa leaf powder and duck meat powder. The observed trend demonstrates that both ingredients contributed effectively to the total iron content of the bread matrix. The higher the concentration of moringa leaves and duck meat, the higher the iron content. Moringa leaves are widely recognized for their rich iron content (Palanisamy et al., 2022) Moreover, duck meat, classified as red meat, is

also a source of iron, which is contributing to higher iron availability in the product matrix (Mafruchati, 2020).

Crude fiber content showed a moderate increase with increasing moringa leaf powder levels. Moringa leaf powder contain high of crude fiber (11,44%) (Astuti et al., 2025). In contrast, the lower crude fiber content in the samples might be attributed to minor degradation by sourdough lactic acid bacteria, potentially due to reduced fermentable sugar release by enzymes. Generally, crude fiber content declines during dough mixing and baking processes due to thermal conditions (Zaidiyah et al., 2020). It has been reported that crude fiber content in whole grain sourdough loaves ranging from 0.95% to 1.22%, significantly higher than that of wheat bread (0.00 ± 0.02) (Adepehin et al., 2023).

Sensory Evaluation of Bread

Sensory evaluation is an analytical approach that relies on human senses to determine consumer preferences toward food products. This method engages sight, smell, taste, and touch to assess attributes such as texture, appearance, aroma, and flavor (Hussain, 2020). Sensory evaluation of bread products can be seen in Table 4.

Table 4. Sensory of bread

Parameters	A	B	C	D	E	F	G	H	I	J
Taste	1.90 ± 0.76 ^{d}	2.10 ± 0.76^{cd}	2.23 ± 0.77^{bcd}	2.43 ± 0.90^{abcd}	2.43 ± 0.82^{abcd}	2.80 ± 0.92^{ab}	2.73 ± 0.78^{abc}	2.57 ± 0.90^{abcd}	2.97 ± 0.85^{a}	2.97 ± 0.89^{a}
Texture	2.47 ± 0.73^{b}	2.43 ± 0.77^{b}	2.73 ± 0.91^{ab}	2.77 ± 0.77^{ab}	2.60 ± 0.77^{b}	2.93 ± 0.69ab	2.83 ± 0.75^{ab}	3.00 ± 0.69^{ab}	3.37 ± 0.81^{a}	3.07 ± 0.98^{ab}
Color	2.80 ± 1.00^{a}	2.80 ± 1.00^{a}	3.00 ± 0.91^{a}	3.10 ± 0.76^{a}	2.73 ± 0.94^{a}	2.97 ± 0.81^{a}	3.03 ± 0.89^{a}	3.07 ± 0.94^{a}	3.43 ± 0.94^{a}	3.17 ± 0.79^{a}
Aroma	2.77 ± 1.07^{a}	2.60 ± 1.04^{a}	2.70 ± 0.84^{a}	2.63 ± 0.85^{a}	2.77 ± 0.82^{a}	3.03 ± 0.89^{a}	2.73 ± 0.98^{a}	2.77 ± 1.07^{a}	3.10 ± 0.96^{a}	3.00 ± 0.98^{a}
Overall appearance	2.40 ± 0.86^{d}	2.57 ± 0.73^{bcd}	2.50 ± 0.51^{cd}	2.50 ± 0.86^{cd}	2.53 ± 0.63^{bcd}	2.93± 0.69^{abcd}	2.87 ± 0.90^{abcd}	3.07 ± 0.74^{abc}	3.23 ± 0.82^{a}	3.13 ± 0.86^{ab}

Expressed values were mean±SD (n = 30); a same row containing means with the same superscript letters are not significantly different ($p < 0.05$).

Taste scores of the sourdough bread ranged from 1.90 to 2.97, with the highest score observed in sample J. Panelists mainly perceived sour and bitter taste notes across formulations. The sour taste is characteristic of sourdough products and is associated with the production of organic acids by lactic acid bacteria and yeast during fermentation, which leads to a decrease in pH (Clement et al., 2020). This characteristic sourness may require adaptation by consumers unfamiliar with sourdough-type bread. The bitter aftertaste became more pronounced with increasing levels of moringa leaf powder and is likely related to the presence of alkaloids and tannins (Salsabila et al., 2024). This finding aligns with several studies indicating that varying levels of moringa leaf powder can impact product acceptability (Hestiyawati et al., 2021; Indah Sari et al., 2019).

Texture scores ranged from 2.43 to 3.37, with sample I receiving the highest score. Formulations containing moderate levels of duck meat powder were perceived as softer and slightly chewy compared with other samples exhibiting harder textures. The absence of gluten in sorghum-based bread limits the formation of an elastic network, which commonly results in firmer crumb structures in gluten-free products. Variations in texture among formulations suggest that ingredient composition influenced crumb softness and chewiness (Gebremedihin & Abera, 2024; Saeed Omer et al., 2023).

No marked differences in color scores were observed among formulations. This may be attributed to the relatively small variations in moringa leaf powder and duck meat powder concentrations, as well as the dominant influence of sorghum flour, which naturally produces a brownish-yellow crumb. Thermal processing during baking further contributed to color development through Maillard reactions between reducing sugars and proteins (Khuenpet et al., 2020). Although the darker crumb color differed from that of conventional wheat bread, it did not substantially reduce panelist acceptance.

Aroma scores ranged from 1.60 to 3.10, with sample J achieving the highest score. The aroma profile was characterized by sour notes from fermentation, herbal notes from moringa leaf powder, and meaty notes from duck meat powder. Increasing moringa leaf powder levels tended to intensify herbal aromas, while higher duck meat concentrations contributed to a more pronounced characteristic meat odor. The sour aroma typical of sourdough bread results from volatile compounds produced during natural fermentation by lactic acid bacteria and yeast.

Overall appearance scores indicated moderate acceptance across formulations, with sample I rated most favorably. Although the sourdough bread exhibited a denser crumb structure and darker color compared with wheat-based bread, formulations with balanced ingredient levels were generally perceived as acceptable in terms of texture, aroma, and appearance. These findings suggest that sensory acceptance of gluten-free sourdough bread is strongly influenced by the balance between fermentation-derived attributes and the level of functional ingredient incorporation.

Microbiology Properties of Bread

The microbial load of food products serves as a critical determinant of microbiological quality and shelf-life, representing a fundamental quality parameter that reflects production hygiene, and raw material quality. In this study, total plate count (TPC) analysis was conducted on the first day after bread production. The results demonstrated that TPC values of bread samples ranged from 2.67 x 10^3 CFU/g to 4.67 x 10^4 CFU/g. All values were well below the maximum permissible limit for bread products established by the Indonesian National Standard (1 x 10^6 CFU/g; SNI 01-3840-1995), indicating that all formulations met microbiological quality standards. The relatively low initial TPC values suggest that appropriate sanitation practices and controlled processing conditions were applied during bread production. Nevertheless, microbiological analysis was limited to the initial storage period. Based on visual observations during storage at room temperature (25 °C), bread samples containing higher concentrations of duck meat powder (samples D, G, and J) showed visible mold growth on the third day of storage, whereas mold growth in the other samples became apparent on the fourth day. Although this observation was qualitative and not supported by quantitative microbial counts, it suggests that higher levels of animal-derived ingredients may accelerate microbial

spoilage under ambient storage conditions. Further studies involving extended storage and periodic microbiological analysis would be required to comprehensively evaluate the shelf-life and microbiological stability of the products.

Table 5. TPC of Bread

Parameters	A	B	C	D	E	F	G	H	I	J
TPC (CFU/g)	2.67 x 10^{3c}	1.27 x 10^{4c}	1.30 x 10^{4c}	3.83 x 10^{4ab}	2.93 x 10^{4b}	1.23 x 10^{4c}	4.67 x 10^{4a}	5 x 10^{3c}	9 x 10^{3c}	4.23 x 10^{4a}

Expressed values were mean±SD (n = 3); a same row containing means with the same superscript letters are not significantly different ($p < 0.05$).

The best treatments by Zeleny's Method

Using the Zeleny multi-criteria decision-making method, the optimal bread formulation was identified by integrating physicochemical properties, nutritional composition, sensory acceptance, and microbiological quality. Formulation G, with 30% duck meat and 2% moringa leaf powder, was selected as the best treatment because it demonstrated as the optimal. Rather than excelling in just a single aspect, this formulation provided the best balance between high nutritional content and acceptable sensory quality. Equal weights were assigned across all parameters to avoid subjective bias. However, because weighting was applied per parameter rather than per category, the final evaluation naturally leaned toward nutritional attributes. This occurred because chemical or nutritional parameters were the most numerous (7 tests), compared to sensory (5), physical (4), and microbiological (1) attributes. While this aligns with our primary research objective of nutritional enrichment, it represents a methodological limitation. Criteria weighting heavily influences the final outcome in food product optimization (Sari et al., 2026). Therefore, Formulation G represents the best nutritional compromise under equal parameter weighting; if sensory quality were prioritized (e.g., weighted at 40–50%), Formulations I or J would be favored instead due to their higher taste scores.

Table 6. The best treatment in this study

Formulation	L1	L2	L∞	Total	the best treatment
A	0.193	0.012	0.059	0.265	9
B	0.223	0.006	0.035	0.264	8
C	0.196	0.005	0.038	0.239	7
D	0.186	0.006	0.038	0.229	2
E	0.237	0.006	0.032	0.275	10
F	0.189	0.004	0.038	0.231	5
G	0.176	0.006	0.038	0.219	1
H	0.194	0.006	0.035	0.235	6
I	0.183	0.005	0.043	0.230	4
J	0.184	0.003	0.043	0.230	3

CONCLUSION

This study demonstrates that incorporation of moringa leaf powder and duck meat powder into sorghum–corn gluten-free sourdough bread effectively enhances nutritional composition, particularly protein and iron contents, while introducing formulation-related technological limitations. Among the evaluated formulations, sample G showed the most balanced trade-off

between nutritional enhancement, sensory acceptance, microbiological quality, and physical characteristics. These findings highlight the importance of formulation balance in developing nutritionally enriched gluten-free bread products derived from local resources.

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