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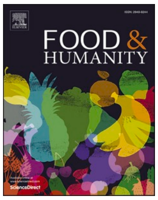

Development and evaluation of gluten-free rice bread formulated with hydrocolloid-protein additive systems

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ABSTRACT

The structural and sensory limitations of gluten-free bread remain a major challenge in baking, particularly in formulations based on rice flour. This study explored the effects of xanthan gum, egg powder and gelatin powder, both individually and in combination, on the rheological behaviour, structural quality and sensory acceptability of gluten-free rice bread. Five formulations (F1-F5) were developed, with F1 serving as the control. Key quality parameters, thus, including dough firmness, adhesiveness, cohesiveness, loaf volume, specific volume, bread density, moisture content, crumb texture, crust appearance and sensory attributes, were evaluated. The formulation containing all three additives (F5) exhibited the best performance across nearly all metrics. F5 recorded the highest loaf volume ($1295.7 \pm 21.8\ \mathrm{cm}^3$), the lowest bread density ($0.48 \pm 0.02\ \mathrm{g/cm}^3$), the highest moisture content ($36.8 \pm 0.5\ \%$) and the most preferred crust appearance (L* value = 42.3 ± 1.1; score = 8.0 ± 0.4). Rheological properties also showed significant enhancement, with F5 displaying the highest dough firmness (275.3 ± 4.2 g) and cohesiveness (93.1 ± 2.6). Principal Component Analysis (PCA) revealed strong positive correlations between F5 and key quality indicators such as crumb texture, overall acceptability and consistency. Mechanistic interpretation suggested that xanthan gum improved dough viscosity and water retention, egg powder contributed protein coagulation during baking and gelatin enhanced elasticity and moisture stabilisation. These synergistic effects resulted in gluten-free bread with structural, sensory and visual characteristics that closely approximate wheat-based bread. The results provide a strong formulation strategy for producing high-quality gluten-free bread with improved consumer appeal and functionality.

1. Introduction

The growing demand for gluten-free foods has emerged from both clinical necessity and rising consumer awareness of diet-related health issues. Individuals diagnosed with celiac disease, wheat allergy, or non-celiac gluten sensitivity must avoid gluten, a composite protein found in wheat, barley and rye, due to adverse immune or gastrointestinal reactions (Kumador et al., 2025; Singh et al., 2023; Vidaurre-Ruiz et al., 2019; Mahama et al., 2025). Additionally, a segment of the general population chooses gluten-free products in pursuit of perceived digestive and health benefits, further expanding the gluten-free market (Osei Tutu et al., 2019, 2024a).

Bread, a widely consumed staple, poses a major challenge in gluten-free product development. In wheat-based baking systems, gluten is essential for forming a viscoelastic dough network that traps gas during fermentation and supports expansion during baking (Osei Tutu et al., 2019, 2024a). The absence of gluten in alternative flours, such as rice flour, disrupts this structure-function relationship, leading to doughs with low elasticity and cohesiveness and breads with low volume, poor texture and rapid staling (Osei Tutu et al., 2024a; Arendt and Mester, 2009; Lazaridou et al., 2007; Kupkanchanakul et al., 2019). Rice flour, although naturally gluten-free and hypoallergenic, lacks the proteins and fibre necessary to support optimal bread structure and therefore often produces dense, crumbly loaves with limited consumer appeal when used alone (Marco & Rosell, 2008; Omran & Mahgoub, 2022; Wang et al., 2022; Mahama et al., 2025).

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To improve the quality of gluten-free bread, food scientists have explored the use of functional additives such as hydrocolloids, proteins and emulsifiers. Hydrocolloids like xanthan gum are commonly used to enhance dough viscosity, improve gas retention and stabilise crumb structure. Xanthan gum, a microbial exopolysaccharide, has been reported to increase the strength and cohesiveness of gluten-free doughs by forming viscous solutions that mimic the effects of gluten (Demirkesen et al., 2010; Acheampong et al., 2025). Egg powder provides structural proteins such as albumin that coagulate during baking, helping to reinforce the matrix and improve volume and crumb softness (Rosell et al., 2001). Gelatin, a protein derived from collagen, can bind water and contribute to the elastic and moist qualities of the crumb. Its thermoreversible gelling properties allow it to form a soft, flexible matrix that retains moisture during baking and storage, thereby extending the shelf life and freshness of gluten-free bread (Lafarga et al., 2017; Ozmen et al., 2025).

While individual studies have reported improvements in gluten-free bread quality through the use of xanthan gum, egg powder, or gelatin, there is limited research on the combined or synergistic effects of these ingredients. In practice, bread formulations often rely on multiple functional ingredients working together to replicate the structural integrity and mouthfeel of wheat bread. Understanding how combinations of hydrocolloids and proteins influence the rheological behavior of dough and the final structural and sensory properties of bread is essential for optimising gluten-free formulations.

Therefore, the objective of this study was to evaluate the synergistic effects of xanthan gum, egg powder and gelatin powder on the quality of gluten-free rice bread. Specifically, this study assessed how these ingredients influenced dough rheology, loaf volume, bread density, moisture content, crust and crumb characteristics and sensory acceptability. Structural properties were quantified through instrumental and visual methods, while multivariate relationships among quality attributes were analyzed using Principal Component Analysis (PCA). By linking ingredient functionality to bread structure and quality, this research provides new insights into the formulation of high-quality gluten-free bread that approaches the performance of traditional wheat-based products.

2. Materials and methods

2.1. Materials

Refined long grain rice flour (food grade; moisture ≤ 13.5 %; ash ≤ 0.6 %) was obtained from Tamanaa Company Ltd., Accra, Ghana. Xanthan gum (E415; food grade; purity ≥ 98 %) was supplied by Jungbunzlauer GmbH, Basel, Switzerland. Whole egg powder (spray dried; protein ≥ 45 %; fat ≈ 40 %; moisture ≤ 4 %) was supplied by Buxtrade GmbH, Germany. Gelatin powder (Type B; bovine origin; bloom strength 220; food grade) was supplied by Gelita AG, Eberbach, Germany. Granulated white sugar (Golden Tree brand), iodised table salt (U2 Company Limited), instant dry yeast (SAF Instant; active cell count $\geq 1 \times 10^9$ CFU g^{-1}) and vegetable oil (Fortune brand, refined, 100 % soybean oil) were procured from local vendors in Accra. Distilled water (conductivity < 1 μS cm^{-1}; pH 6.8–7.2) was used for dough hydration. All materials were food grade.

2.2. Dough formulation and experimental design

Five bread formulations were developed as shown in Table 1. F1 was the control without additives. F2 contained xanthan gum only. F3 contained xanthan gum and egg powder. F4 contained xanthan gum and gelatin powder. F5 contained all three additives.

Each formulation was expressed on a flour weight basis of 100 parts. Ingredients were standardised as follows: rice flour 100, water 65, sugar 4, salt 1.5, instant dry yeast 2 and fat (vegetable oil) 3. Additives were included at 1.5 % each. The selection of 1.5 % was based on preliminary trials and supported by previous studies which found this level effective in improving dough handling and bread quality without imparting undesirable off-flavours (Lazaridou et al., 2007; Marco & Rosell, 2008; Rosell et al., 2001).

Table 1
Formulation of gluten-free rice bread samples (flour basis = 100 parts).

Ingredient (%, flour weight basis)	F1 (Control)	F2 (Xanthan)	F3 (Xanthan + Egg)	F4 (Xanthan + Gelatin)	F5 (Xanthan + Egg + Gelatin)
Rice flour	100	100	100	100	100
Water	65	65	65	65	65
Sugar	4	4	4	4	4
Salt	1.5	1.5	1.5	1.5	1.5
Instant dry yeast	2	2	2	2	2
Fat (vegetable oil)	3	3	3	3	3
Xanthan gum	0	1.5	1.5	1.5	1.5
Egg powder	0	0	1.5	0	1.5
Gelatin powder	0	0	0	1.5	1.5

Each formulation was prepared in three independent baking trials and analytical measurements were performed in triplicate to ensure technical replication.

2.3. Proofing and baking procedure

Dough samples (450 g each) were shaped and placed in rectangular loaf pans (20 cm × 10 cm × 7 cm; aluminium alloy, non-stick coated). Proofing was conducted in a programmable proofing chamber (Sinmag SM-16FT, Wuxi City, China) at 35 ± 1 °C and 85 ± 2 % relative humidity for 60 min. Baking was carried out in a convection deck oven (Fornitalia 4 C, Italy) preheated to 180 °C for 30 min. Loaves were cooled on wire racks at ambient temperature (25 ± 2 °C) for 2 h before packaging in low-density polyethylene bags for evaluation within 24 h.

2.4. Rheological characterisation of dough

Rheological properties were measured using a TA.XTplus Texture Analyzer (Stable Micro Systems, UK) equipped with a 5 kg load cell and a back-extrusion cell (A/BE fixture, 5 cm diameter). Dough samples (50 g each) were subjected to a probe speed of 1.0 mm/s to a penetration depth of 5 mm. Parameters recorded included firmness (g), adhesiveness (g·s), cohesiveness and consistency (g). Each test was performed in triplicate and mean values were used for statistical analysis.

2.5. Structural observation and crumb evaluation

Internal crumb structure was evaluated two hours after baking. Each loaf was sliced at the geometric centre with a serrated stainless steel bread knife. Crumb characteristics that were assessed included porosity, gas cell size distribution, symmetry and elasticity. Visual assessment was undertaken by three trained evaluators using a five-point descriptive scale where one indicated poor structure and five indicated excellent structure. Panellists recorded their observations independently and photographic documentation was obtained for each loaf. Photographs were taken under standardised lighting conditions (5600 K softbox diffuser) with a Nikon D5600 digital camera. Images were used to support the visual scores and to allow for side-by-side comparisons.

2.6. Determination of loaf volume and specific volume

Loaf volume was determined using the standard rapeseed displacement method (AACC Method 10–05.01). A calibrated volume container was filled with polished rapeseeds (particle size < 2 mm) to establish a baseline volume. Each loaf was placed in the container and the displaced volume was measured in cm^3. Specific volume was calculated using the formula:

$$\text{SV}\left(\text{cm3}\middle/\text{g}\right) = \frac{\textbf{\textit{Volume of Bread}}}{\textbf{\textit{Loaf Weight}}}$$

$$\text{VB}\ (\text{cm}^3) = \text{VN} - \text{VM}$$

where;

VB = Bread Volume

VN = measured loaf volume plus millet displacement volume

VM = Volume of Millet

Measurements were performed in triplicate using a calibrated scale (Ohaus Scout Pro, ±0.1 g).

2.7. Determination of bread density

Bread density was calculated by dividing the loaf weight (g) by loaf volume (cm^3), using the following formula:

$$\textbf{Bread Density}\left(\textbf{g}\middle/\textbf{cm3}\right) = \frac{\textbf{\textit{Mass}}}{\textbf{\textit{Volume}}}$$

Measurements were done in triplicate using data obtained from the rapeseed displacement method and analytical weighing (2.6). This metric provides insight into crumb compactness and gas retention.

2.8. Determination of moisture content

Moisture content was determined using the **oven drying method** (AOAC 925.10) (AOAC, 2000). About 5 g of homogenised crumb from the central portion of each loaf was weighed into a pre-dried crucible and dried at 105 °C for 4 h in a laboratory oven (Memmert UF55, Germany). The percentage moisture content was calculated as:

$$\text{Moisture Content}(\%) = \frac{\textbf{\textit{Initial Dough Weight}} - \textbf{\textit{Final Dough Weight}}}{\textbf{\textit{Initial Dough Weight}}} \times \mathbf{100}$$

Measurements were conducted in triplicate and results are reported as mean ± SD.

2.9. Crust colour measurement and crust appearance scoring

Crust colour was measured instrumentally using a Minolta CR 400 Chroma Meter (Konica Minolta, Japan). Three readings were taken at different locations on the crust of each loaf and reported as L* (lightness), a* (redness) and b* (yellowness). Mean values and standard deviations are reported.

Crust appearance was also assessed by the sensory panel. To avoid confounding colour with other sensory attributes during tasting, the sensory evaluation of aroma, texture and flavour was carried out under red light. Crust appearance for visual appraisal was conducted separately under normal white light before samples were moved to the tasting booths. Panellists rated crust appearance on a nine-point hedonic scale with reference anchors where one indicates dislike extremely and nine indicates like extremely. This separate procedure allowed for objective instrumental colour measurement together with subjective visual appraisal by the panel.

2.10. Sensory evaluation

A panel of twelve trained assessors from the Department of Food Process Engineering conducted sensory evaluations. The panel comprised both male (6) and female (6) assessors between 22 and 45 years of age. All panellists provided written informed consent prior to participation. Training comprised three one-hour sessions in which attribute definitions were standardised, the use of the nine-point hedonic scale was practised and sample handling procedures were rehearsed. Bread samples were coded with random three digit numbers and presented in a balanced random order. For the sensory evaluation session, samples were served in individual booths at 25 ± 1 °C. Red lighting was used during tasting to mask colour differences when participants rated aroma, flavour, crumb texture and overall acceptability. Water and unsalted plain crackers were provided as palate cleansers between samples. Each assessor scored crust appearance, aroma, crumb texture and overall acceptability using a nine point hedonic scale. Panel data were collected for each assessor and used in the statistical analysis.

2.11. Statistical and multivariate analysis

All quantitative data were subjected to one-way analysis of variance (ANOVA) using IBM SPSS Statistics version 25.0 (IBM Corp., Armonk, NY, USA). Post hoc comparisons were performed using Tukey's Honest Significant Difference (HSD) test at a 5 % significance level ($p < 0.05$). Multivariate analysis was performed by principal component analysis. Prior to PCA, data were mean centred and scaled to unit variance to remove effects of differing units. PCA was implemented in Python using NumPy and scikit learn libraries and plots were generated with Matplotlib. Scores and loadings were plotted together in a biplot to facilitate interpretation of the relationships between formulations and quality attributes. The percentage of total variance explained by the principal components was reported.

3. Results and discussion

3.1. Rheological properties of dough

The rheological behaviour of the dough was evaluated through back-extrusion testing using the TA.XTplus texture analyser. The results are shown in Fig. 1. One-way ANOVA revealed significant differences among the formulations for all measured parameters ($p < 0.05$), confirming that the additives used had a notable effect on dough structure and mechanical strength.

Dough firmness increased consistently from 78.3 ± 2.4 g in the control (F1) to 275.3 ± 4.2 g in F5, and this difference was statistically significant ($F(4, 10) = 68.42$, $p = 0.0001$). Adhesiveness decreased from –118.1 ± 4.2 g·s in F1 to –82.2 ± 2.5 g·s in F5 ($F(4, 10) = 42.36$, $p = 0.0004$), indicating that the doughs with additives were less sticky and easier to handle. Cohesiveness and consistency also increased markedly, from 58.2 ± 3.1 and 104.5 ± 3.6 g in the control to 93.1 ± 2.6 and 297.8 ± 6.3 g in F5, respectively ($F(4, 10) = 55.21$, $p = 0.0002$; $F(4, 10) = 63.08$, $p = 0.0001$). These changes demonstrate that the composite additive systems strengthened internal bonding and improved resistance to deformation.

The control dough F1) had low firmness and poor consistency, showing weak structural integrity and high stickiness. With the inclusion of xanthan gum in F2, both firmness and consistency improved considerably. This is due to xanthan gum's capacity to bind water and increase viscosity, producing a more cohesive matrix. Similar observations were made by Rosell et al. (2001), Ayadi et al. (2021) and Apovian et al. (2019), who reported that xanthan enhances dough stability by forming viscous solutions that replicate gluten's elastic behaviour.

As more additives were introduced, the rheological properties improved progressively. F5, which combined xanthan gum, egg powder and gelatin, recorded the highest dough firmness (275.3 ± 4.2 g), lowest adhesiveness (-82.2 ± 2.5 g·s) and highest consistency (297.8 ± 6.3 g), indicating a strong, elastic dough capable of retaining gas during proofing. The cohesiveness value of F5 also improved significantly, showing better internal structure. These improvements can be attributed to the combined effects of xanthan gum's network-forming

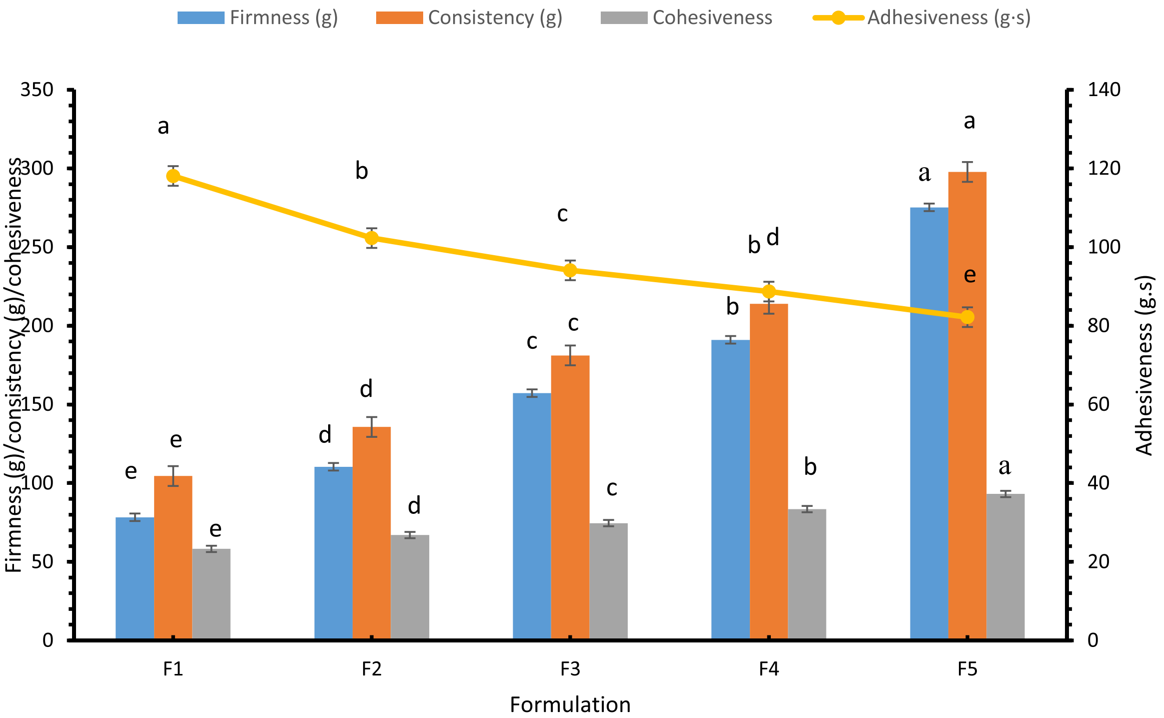

Fig. 1. Rheological parameters (Firmness, Consistency, Cohesiveness and Adhesiveness) of gluten-free rice doughs (F1–F5). Firmness, Consistency and Cohesiveness plotted on the left axis (g; Cohesiveness dimensionless); Adhesiveness plotted on the right axis (g·s). Different superscript letters above the bars indicate significant differences at $p < 0.05$.

behaviour, egg powder's heat-induced protein coagulation and gelatin's gel elasticity and moisture retention capacity (Ayadi et al., 2021; Lafarga et al., 2017; Marco & Rosell, 2008). Mechanistically, the increase in measured firmness and consistency with xanthan addition is attributable to the high-water binding capacity and viscosity of xanthan in aqueous systems. Xanthan forms an entangled polysaccharide network that increases continuous phase viscosity and slows bubble coalescence, thereby improving the apparent strength of the dough (Marco & Rosell, 2008; Ruiz, 2023; Sasaki, 2018, 2022). Egg powder contributes by supplying heat-settable proteins that denature and coagulate during baking to form a supporting protein film around gas cells; this action increases cohesiveness and helps to retain structure (Marco & Rosell, 2008; Pycarelle et al., 2021). Gelatin adds a thermoreversible gel component that swells with water and enhances elasticity; on heating it forms a denatured network that improves the dough's capacity to resist deformation (Lafarga et al., 2017; Rashid et al., 2018). When xanthan, egg powder and gelatin act together, the combined mechanisms produce a pseudo-network that more closely resembles the functionality of gluten. This synergy explains the markedly higher firmness and cohesiveness measured in F5 and its lower adhesiveness relative to the control.

The rheological improvements observed here agree with previous studies that report increased firmness and gas retention in gluten-free doughs containing hydrocolloids and proteins (Apovian et al., 2019; Demirkesen et al., 2010; Osei Tutu et al., 2019, 2024a, 2024b). The pattern of results also matches reports that single additives often give partial gains while blended systems give larger, synergistic gains in mechanical strength and handling properties (Marco & Rosell, 2008; Rosell et al., 2001). In practical terms, doughs with higher firmness and cohesiveness are better able to tolerate the stresses of proofing and oven spring and they are more likely to produce loaves with higher volume and finer crumb structure.

3.2. *Structural characteristics of bread*

Loaf volume and specific volume are fundamental indicators of bread quality. These parameters reflect the dough's ability to retain gas produced during fermentation and to expand properly during baking. The loaf characteristics for the five formulations are presented in Table 2. Loaf volume, specific volume and density are fundamental indicators of bread quality because they reflect the capacity of the dough to expand and retain gases during proofing and baking. Significant differences were found among the samples ($p < 0.05$). Loaf volume increased from 880 ± 15 cm^3 in the control (F1) to 1296 ± 22 cm^3 in F5, with a statistically significant difference (F (4, 10) = 73.56, p = 0.0001). Specific volume also rose from 2.10 ± 0.05 cm^3/g to 3.20 ± 0.08 cm^3/g (F(4, 10) = 58.49, p = 0.0002). In gluten-free systems, achieving acceptable loaf volume is often challenging due to the absence of the viscoelastic gluten network that typically traps gases and provides structural elasticity (Mir et al., 2021). In this study, the control sample (F1) exhibited the lowest loaf volume of 880 ± 15 cm^3 and a corresponding specific volume of 2.10 ± 0.05 cm^3 /g as indicated in Table 2. The low rise and dense crumb observed in this sample are characteristic of rice flour-based doughs that lack structural reinforcement. Without gluten or alternative matrix-forming agents, the dough structure collapsed easily under its weight and the gas produced during proofing escaped through weakened interstitial spaces (Mir et al., 2021; Osei Tutu et al., 2024a).

When xanthan gum was added to formulation F2, loaf volume increased modestly to 1016 ± 18 cm^3(Table 2). This improvement is attributable to xanthan gum's high viscosity and water-binding capacity. Mechanistically, xanthan forms entangled molecular networks that increase the dough's resistance to deformation while still allowing gas cell expansion. The thickened matrix supports a foam-like structure that holds CO_2 more effectively during fermentation and baking. Additionally, the presence of xanthan delayed starch gelatinisation, thereby allowing better dough expansion before structural setting occurred in the oven (AbuDujahn et al., 2022).

In formulation F3, the inclusion of egg powder resulted in a further

Table 2
Loaf characteristics (Mean ± SD; n = 3).

Formulation	Loaf Volume (cm^3)	Specific Volume ($cm^3\ g^{-1}$)	Density ($g\ cm^{-3}$)
F1 (Control)	880 ± 15^e	2.10 ± 0.05^e	0.66 ± 0.03^a
F2 (Xanthan)	1016 ± 18^d	2.35 ± 0.06^d	0.61 ± 0.02^b
F3 (Xanthan+Egg)	1150 ± 19^c	2.78 ± 0.07^c	0.56 ± 0.02^c
F4 (Xanthan+Gelatin)	1205 ± 20^b	3.05 ± 0.07^b	0.52 ± 0.02^d
F5 (Xanthan+Egg+Gelatin)	1296 ± 22^a	3.20 ± 0.08^a	0.48 ± 0.02^e

Values are means ± SD (n = 3). Different superscript letters in the same column indicate significant differences ($p < 0.05$).

rise in loaf volume to 1150 ± 19 cm^3(Table 2). This enhancement is due to the emulsifying and foaming properties of egg constituents. Egg proteins unfolded during dough mixing, exposing hydrophobic and hydrophilic domains that stabilised gas bubbles. Upon baking, these proteins coagulated to form a continuous film that helped set the structure around the expanded gas cells. The effect of lipids in the egg, which reduces surface tension, further contributed to the formation of smaller, more stable air cells, enabling the dough to expand more uniformly (Acheampong et al., 2024; Amjad et al., 2025; Pycarelle et al., 2021; Osei Tutu et al., 2023). This mechanism mirrors the role of gluten in wheat bread by offering thermal gelation and structure formation, as also reported by Xu et al. (2024).

The addition of gelatin in formulation F4 raised loaf volume to 1205 ± 20 cm^3(Table 2). Gelatin's contribution lies in its ability to form a gel matrix upon hydration, which integrates with starch granules and proteins to strengthen the dough framework. During baking, gelatin transitions from a hydrated gel to a denatured network that maintains elasticity, allowing the dough to stretch and expand while retaining its integrity. This behaviour enables better gas retention and reduced collapse during oven spring (Acheampong et al., 2025; Grenier et al., 2021; Akonor et al., 2023).

The optimised formulation (F5), which combined xanthan gum, egg powder and gelatin, yielded the highest loaf volume of 1296 ± 22 cm^3(Table 2) and a specific volume of 3.20 ± 0.08 cm^3/g (Table 2). This significant improvement reflects a synergistic interaction among the three additives. Xanthan gum contributed viscosity and delayed starch gelatinisation, egg powder provided protein coagulation and emulsification capacity, while gelatin added elasticity and water-binding strength (Grenier et al., 2021; Pycarelle et al., 2021; AbuDujahn et al., 2022). Together, these mechanisms created a composite matrix capable of withstanding the internal pressures of gas expansion during fermentation and baking. This network maintained dough stability while allowing vertical rise, mimicking the gas-retaining properties of gluten.

Compared to standard wheat bread, which typically exhibits specific volume values in the range of 3.5 and 5.0 cm^3/g (Arendt and Mester, 2009; Schopf and Scherf, 2021), formulation F5 falls within an acceptable and commercially viable range. This comparison confirms that properly formulated gluten-free bread can approach the performance of conventional wheat-based systems when mechanistically compatible ingredients are used.

The significant increase in loaf volume and specific volume from F1 to F5 demonstrates the crucial role of matrix-forming and gas-retaining ingredients in gluten-free baking. The results support the concept that functional hydrocolloids and proteins can, through water structuring, film formation and thermal gelation, replicate the physical behaviour of gluten and yield high-quality, aerated bread loaves (Goff & Guo, 2019).

Visual observations showed that F5 had a well-developed, aerated crumb with uniform gas cell distribution and soft, elastic texture. The structural improvements resulted from the pseudo-gluten matrix formed by the additives, where xanthan gum provided viscosity and gas retention, egg proteins formed a coagulated network upon baking and gelatin reinforced elasticity and retained moisture (Demirkesen et al., 2010; Pătraşcu et al., 2016).

3.3. *Bread density*

Bread density is a key indicator of crumb compactness and internal aeration. Lower density values generally signify better gas retention and lighter texture, while higher densities reflect compact structures with limited porosity (Dessev et al., 2020; Mir et al., 2021). The results, shown in Table 2, revealed significant differences among the five formulations (F(4, 10) = 58.21, p = 0.0001). Density decreased progressively from 0.66 ± 0.03 g/cm^3 in the control (F1) to 0.48 ± 0.02 g/cm^3 in the optimised formulation (F5).

The control bread (F1) exhibited the highest density, indicating minimal gas entrapment during proofing and baking. Mechanistically, the absence of gluten or any structural enhancer in F1 meant that gas cells could not be properly stabilised, leading to their collapse and subsequent compaction of the crumb. Rice flour, being primarily composed of starch and lacking extensible proteins, forms a brittle matrix incapable of maintaining gas bubble integrity under pressure (Demirkesen et al., 2010; Jan et al., 2022).

Formulation F2, with xanthan gum, had a reduced density of 0.61 ± 0.02 g/cm^3(Table 2). This reduction can be attributed to xanthan gum's ability to increase dough viscosity, thus slowing gas bubble coalescence and enabling the matrix to expand and hold shape during oven spring (Islam et al., 2015). Xanthan gum also delays water migration and starch gelatinisation, allowing the dough to remain flexible for longer during heating and giving gas bubbles more time to expand (Osei Tutu et al., 2024a). Recent studies have shown that xanthan gum enhances gluten-free dough structure by promoting a continuous, hydrated matrix capable of resisting gas diffusion (Encina-Zelada et al., 2019; Ruiz, 2023).

In formulation F3, the inclusion of egg powder lowered the density further to 0.56 ± 0.02 g/cm^3(Table 2). Egg proteins denature and coagulate upon heating, creating a thermo-set matrix that physically entraps gas cells and prevents their rupture. Furthermore, egg lipids improve gas distribution by stabilising foams during mixing. The resulting protein–lipid–starch matrix strengthens dough integrity and increases gas retention, thereby reducing loaf density. These effects have been supported by the findings of Lv et al. (2022), who noted that egg-based proteins in gluten-free formulations reduce density through heat-induced film formation and aeration support.

Gelatin incorporation in F4 reduced the density to 0.52 ± 0.02 g/cm^3(Table 2). Gelatin acts by forming a hydrated gel that swells and binds water, interacting with both starch granules and proteins to create a more cohesive dough. This gel network allows for better dough extensibility and elasticity, which prevents structural collapse during proofing and baking (Rashid et al., 2018). During thermal processing, gelatin transitions from a reversible gel to a denatured protein network that sets into a resilient structure capable of supporting the crumb (Rashid et al., 2018).

The lowest bread density was observed in F5, the synergistic formulation, at 0.48 ± 0.02 g/cm^3(Table 2). This formulation achieved optimal aeration due to the combined mechanisms of its additives. Xanthan gum provided the initial viscosity to trap water and support gas retention; egg powder contributed thermally coagulating proteins and emulsifiers; gelatin enhanced elasticity and reinforced the crumb network. Together, these ingredients created a dough system with controlled expansion, minimised gas loss and maximal structural resilience. Similar trends have been reported by Culetu et al. (2021), who demonstrated that hydrocolloid–protein interactions reduce crumb compactness by enhancing dough strength and elasticity in gluten-free systems. The cumulative effect was a lighter, more aerated loaf with density values approaching those of standard wheat breads, which typically range from 0.40 to 0.50 g/cm^3 depending on formulation and hydration level (Mir et al., 2021; Moazzam et al., 2025).

The progressive decline in bread density across formulations highlights the importance of additive functionality in replicating the aeration potential of gluten. These findings further confirm that density is not only a function of gas production, but more critically, of gas retention and structural setting, which depend on the rheological and thermal behaviours of the dough matrix. Incorporating functionally compatible ingredients like hydrocolloids and coagulating proteins can therefore significantly reduce crumb compactness and improve bread quality in gluten-free systems.

3.4. *Moisture content*

Moisture content is a key quality parameter influencing dough rheology, crumb texture, shelf life and consumer acceptability (Apovian et al., 2019; Kortei et al., 2024; Nyasordzi et al., 2025). In gluten-free bread systems, maintaining optimal moisture levels is challenging because the absence of gluten results in poor water-binding capacity and greater water migration during baking (Apovian et al., 2019). The results, presented in Table 3, showed significant variation among the five formulations ($p < 0.05$). Moisture content increased steadily from 29.2 ± 0.7 % in the control (F1) to 36.8 ± 0.5 % in the triple-additive formulation (F5) ($F(4, 10) = 19.87$, $p = 0.0003$).

The control bread F1) exhibited the lowest moisture content. This result is expected due to the lack of water-holding components in the formulation. Rice flour alone does not contain gluten-forming proteins or hydrophilic fibres and its starch granules lack the swelling and hydration capacity needed to retain moisture effectively during baking. The absence of a viscoelastic or gel-forming network in the dough resulted in greater water evaporation, producing a drier and more brittle crumb. Similar findings were reported by Culetu et al. (2021), who found that gluten-free breads without hydrocolloids or protein stabilisers suffer from poor moisture retention and rapid staling.

The inclusion of xanthan gum in F2 led to a notable increase in moisture content to 31.4 ± 0.6 %. Xanthan gum functions as a hydrophilic polysaccharide capable of forming viscous solutions and holding large amounts of water (Kurt, 2021). Mechanistically, its long-chain structure traps water through hydrogen bonding, forming a gel-like matrix that resists thermal dehydration during baking. This improved hydration also contributed to a softer crumb texture and better handling properties. Recent work by Kurt (2021), Matos and Rosell (2015) confirmed that xanthan gum enhances moisture retention in gluten-free baked products by delaying water migration and forming stable aqueous gels.

In formulation F3, which included egg powder, the moisture content increased further to 33.6 ± 0.5 %**.** This enhancement can be attributed to the water-binding ability of egg proteins, particularly albumin, which hydrates during mixing and coagulates during baking to trap water within the protein matrix. Additionally, the emulsifying properties of egg lipids improve fat–water interactions, helping to maintain a moist internal crumb. The coagulated proteins form a barrier that slows moisture diffusion from the bread's interior to the crust and the environment. Goff and Guo, (2019), Osei Tutu et al. (2024a, 2024b) similarly observed that egg inclusion increases water retention by creating a thermally stable matrix that reduces water loss during baking.

Table 3
Moisture content of gluten-free rice bread formulations.

Formulation	Moisture (%)
F1 (control)	29.2 ± 0.7^e
F2 (xanthan)	31.4 ± 0.6^d
F3 (xanthan + egg)	33.6 ± 0.5^c
F4 (xanthan + gelatin)	35.0 ± 0.4^b
F5 (xanthan + egg + gelatin)	36.8 ± 0.5^a

Values are means ± SD ($n = 3$). Different superscript letters in the same column indicate significant differences ($p < 0.05$).

In F4, the gelatin-containing formulation, the moisture content reached 35.0 ± 0.4 %**.** Gelatin acts as both a hydrocolloid and a protein-based gelling agent. It forms a three-dimensional network upon hydration that can bind water and restrict its mobility. During thermal processing, gelatin denatures and forms irreversible coils that further hold moisture within the dough (Lafarga et al., 2017; Osei Tutu et al., 2024a; Waseem et al., 2024). This mechanism reduces the rate of water evaporation and helps maintain crumb softness. Salehi (2019) noted that gelatin effectively improves water retention in gluten-free batters by forming a protein–starch network that swells and binds water during baking.

The highest moisture content was observed in F5, the optimised formulation, at 36.8 ± 0.5 %. The combined effects of xanthan gum, egg powder and gelatin resulted in superior hydration and moisture retention. Each ingredient contributed uniquely: xanthan gum created a highly viscous aqueous environment; egg proteins denatured and locked in water molecules; and gelatin formed a gel network that slowed moisture diffusion. Together, these mechanisms provided a synergistic effect that minimised moisture loss during baking and created a moist, palatable crumb. The observed levels were comparable to those reported for high-quality gluten-free breads with hydrocolloid–protein blends (Osei Tutu et al., 2024a; Ruiz, 2023).

The results demonstrate that increasing the functional water-binding capacity of gluten-free dough through targeted ingredient selection is essential for improving product texture, shelf stability and consumer appeal. Maintaining higher moisture content contributes to a fresher mouthfeel and delayed staling, which are critical quality determinants in gluten-free bread products.

3.5. *Crust colour and appearance*

Crust colour is an important visual attribute that influences a consumer's perception of bread quality, freshness, and flavour. It results mainly from Maillard reactions and sugar caramelisation that occur during baking. The colour parameters (L*, a*, and b*) for the various formulations are presented in Table 4. Significant differences were found among samples for all colour attributes ($p < 0.05$). The lightness value (L*) decreased from 48.6 ± 0.9 in the control (F1) to 42.3 ± 1.1 in the triple-additive formulation (F5) ($F(4, 10) = 27.62$, $p = 0.001$). Meanwhile, redness (a*) and yellowness (b*) increased from 6.8 ± 0.4–10.1 ± 0.5 and from 15.5 ± 0.6–19.8 ± 0.6, respectively ($F(4, 10) = 29.34$, $p = 0.001$; $F(4, 10) = 24.85$, $p = 0.002$). These changes indicate a darker, more golden crust as functional ingredients were

Table 4
L*a*b* Values of Gluten-Free Rice Bread. Different superscript letters indicate significant differences at $p < 0.05$.

Formulation	Additive Composition	L* (Lightness)	a* (Redness)	b* (Yellowness)
F1	Control (No Additives)	48.6 ± 0.9^a	6.8 ± 0.4^e	15.5 ± 0.6^e
F2	Xanthan Gum	46.8 ± 0.8^b	7.4 ± 0.3^d	16.2 ± 0.5^d
F3	Xanthan + Egg Powder	44.2 ± 0.7^c	8.9 ± 0.5^c	18.3 ± 0.4^c
F4	Xanthan + Gelatin Powder	43.1 ± 0.8^d	9.2 ± 0.4^b	18.9 ± 0.5^b
F5	Xanthan + Egg + Gelatin Powder	42.3 ± 1.1^e	10.1 ± 0.5^a	19.8 ± 0.6^a

introduced.

The control sample (F1) exhibited the highest L* value and the lowest a* and b* values, producing a pale, uneven crust. This is typical of rice-based gluten-free bread, which contains little protein and few reducing sugars necessary for Maillard browning (Khan et al., 2025; Obeng et al., 2025; Asiedu et al., 2025; Haider et al., 2025; Javed et al., 2025). The limited interaction between amino and carbonyl groups in the rice flour matrix results in weak colour development and a less appealing crust.

The control sample (F1) exhibited the highest L* value (48.6 ± 0.9), indicating a lighter, pale crust. Its low a* (6.8 ± 0.4) and b* (15.5 ± 0.6) values suggested minimal browning and colour development. Mechanistically, this result is due to the limited presence of proteins and reducing sugars in the rice flour matrix. Maillard reactions, which are primarily responsible for non-enzymatic browning, require both amino groups (from proteins or amino acids) and carbonyl groups (from reducing sugars). In the absence of sufficient protein content and emulsifiers, these reactions occur to a lesser extent, resulting in lighter crust colouration. This finding is consistent with Osei Tutu et al. (2019, 2024a, 2024b), who observed poor colour development in gluten-free breads made solely from starch-rich flours lacking reactive amino components.

The incorporation of xanthan gum in F2 significantly enhance the a* and b* values. While xanthan gum influences moisture retention and baking dynamics, it lacks proteinaceous components and therefore does not contribute directly to Maillard browning (Osei Tutu et al., 2024a; Pătraşcu et al., 2016). However, it modifies the thermal conductivity of the crust by retaining more moisture, thereby slightly increasing the crust's exposure to sustained heat, which may promote mild sugar caramelisation (Moazzam et al., 2025; Osei Tutu et al., 2024a).

A marked improvement in crust colouration was observed in F3, which included egg powder. The L* value decreased to 44.2 ± 0.7, while a* and b* increased to 8.9 ± 0.5 and 18.3 ± 0.4, respectively. These shifts reflect a browner and more appealing crust. Mechanistically, the increase is attributed to the presence of protein and lipid components in egg powder. During baking, egg proteins undergo Maillard reactions, while egg yolk lipids participate in oxidation and contribute to desirable pigmentation and flavour. The amino acids and peptides in egg white accelerate browning and the fat content improves surface heating and colour uniformity (Adil et al., 2025; Asiedu et al., 2026; Udayana et al., 2020; Adil et al., 2025; 2025). These mechanisms are in agreement with findings by Demirkesen et al. (2010), who reported enhanced browning and sensory appeal in gluten-free breads supplemented with egg derivatives.

In F4, gelatin addition resulted in further enhancement of crust colouration. The L* value declined to 43.1 ± 0.8, indicating darker colouration, while a* and b* increased to 9.2 ± 0.4 and 18.9 ± 0.5, respectively. Gelatin is a denatured form of collagen, composed of proteinaceous chains rich in glycine, proline and hydroxyproline. These amino acids react readily with reducing sugars during thermal processing, intensifying Maillard reactions. Additionally, gelatin increases surface viscosity, helping to retain heat and concentrate reducing sugars on the crust, thereby facilitating browning. Salehi (2019) reported similar effects when gelatin was used in gluten-free formulations, attributing deeper crust colouration to enhanced protein-sugar interactions.

The most intense browning occurred in the triple-additive formulation (F5), where L* dropped to 42.3 ± 1.1, while a* and b* reached 10.1 ± 0.5 and 19.8 ± 0.6, respectively. The darker and richer crust colour was visually more appealing and likely contributed positively to overall sensory ratings. This enhanced pigmentation results from synergistic Maillard and lipid oxidation reactions, supported by high protein content from egg and gelatin and optimal heat retention from xanthan gum. In addition, the emulsifying and stabilising actions of egg proteins and xanthan gum help distribute heat uniformly across the dough surface, promoting consistent browning.

Compared to standard wheat bread, which typically presents L* values ranging from 55 to 65 depending on baking temperature and flour type (Mir et al., 2021; Osei Tutu et al., 2024b; Suleman et al., 2025; Waseem et al., 2024), the F5 formulation falls within a desirable visual range. Its deep colour, supported by functional ingredient interactions, closely mimics the appearance of conventional wheat-based loaves, enhancing consumer acceptability.

Crust colouration in gluten-free bread can be significantly enhanced through the addition of proteinaceous and hydrophilic ingredients that promote browning reactions and heat transfer. The progression from pale, underdeveloped crust in F1 to the rich, golden-brown crust in F5 demonstrates the functional and aesthetic benefits of carefully selected additive combinations in gluten-free systems.

The darker, golden-brown crusts observed in these formulations aligned with consumer preferences, as evidenced by the sensory crust appearance scores (Fig. 2). Crust appearance also improved markedly, increasing from 5.3 ± 0.7 in F1–8.0 ± 0.4 in F5 (F(4, 55) = 35.26, $p = 0.0004$). F5 received the highest crust appearance rating (8.0 ± 0.4), indicating superior visual appeal and surface uniformity. F4 also performed well (7.5 ± 0.4), while F1 was rated the lowest (5.3 ± 0.7), reflecting its uneven browning and unappealing finish.

3.6. Sensory evaluation

Sensory evaluation provides a direct measure of consumer perception and satisfaction. In this study, twelve trained panellists assessed the bread samples for crust appearance, aroma, crumb texture, and overall acceptability using a nine-point hedonic scale. The results are presented in Fig. 2. Significant differences ($p < 0.05$) were found among all formulations for each attribute evaluated.

Aroma scores increased progressively from 5.0 ± 0.6 in the control (F1) to 7.8 ± 0.3 in the triple-additive formulation (F5) (F(4, 55) = 31.42, $p = 0.0006$). Crust appearance also improved significantly, increasing from 5.3 ± 0.7 in F1–8.0 ± 0.4 in F5 (F(4, 55) = 35.26, $p = 0.0004$). Crumb texture ratings rose from 5.1 ± 0.5–8.5 ± 0.3 (F(4, 55) = 38.15, $p = 0.0003$), while overall acceptability increased from 5.0 ± 0.6–8.6 ± 0.4 (F(4, 55) = 41.09, $p = 0.0002$). These results indicate that the use of functional additives significantly improved the sensory quality of gluten-free rice bread.

The control sample (F1) received the lowest overall acceptability score of 5.0 ± 0.6, falling into the "neither like nor dislike" to "dislike slightly" range. Panellists described its crust as pale and uneven, the aroma as weak and the crumb as dry and gritty. Mechanistically, the absence of gluten or functional additives resulted in poor dough structure, rapid moisture loss and limited Maillard reaction products, all of which compromised flavour and mouthfeel. The lack of proteins reduced the extent of browning and flavour precursor formation, leading to a bland and visually unappealing loaf. These observations are consistent with Hidas et al. (2020), who found that rice-based gluten-free breads without additives suffer from poor flavour and texture perception due to limited chemical reactions during baking.

In formulation F2, which included xanthan gum, acceptability improved modestly to 6.3 ± 0.6. The enhanced appearance, smoother surface and slightly better crumb softness contributed to improved perception. Xanthan gum increased water retention and promoted a more cohesive crumb, reducing dryness and making the bread easier to chew. However, since xanthan gum lacks aromatic or taste-enhancing properties, its effect was confined primarily to textural improvements. Encina-Zelada et al. (2019) noted that while hydrocolloids like xanthan improve moisture and elasticity, they do not substantially enhance flavour unless paired with proteins or lipids.

F3, with added egg powder, showed notable sensory improvement, achieving an overall score of 7.1 ± 0.6. Panellists praised its golden crust, mild eggy aroma and soft, springy crumb. Mechanistically, egg proteins contributed to improved gas retention and crumb softness, while lipids promoted emulsification and flavour dispersion. The

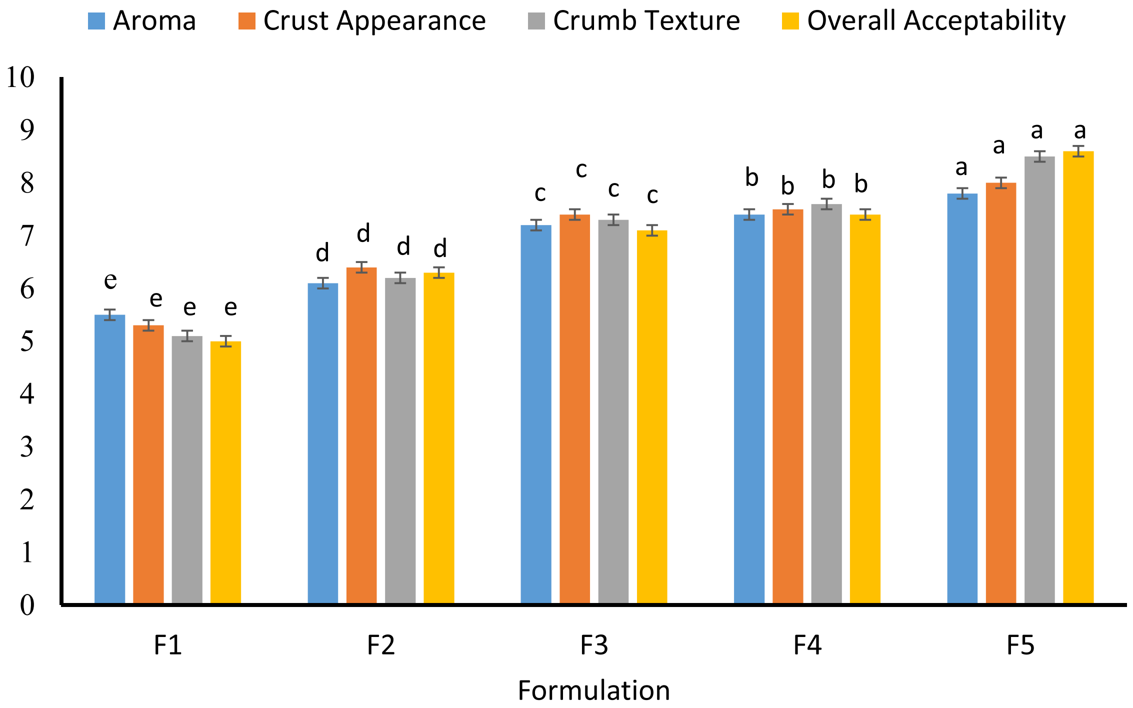

Fig. 2. Sensory Evaluation Scores of Gluten-Free Rice Bread. Different superscript letters above the bars indicate significant differences at $p < 0.05$.

Maillard reaction between egg proteins and reducing sugars generated aromatic compounds, improving crust flavour and internal aroma (Osei Tutu et al., 2024a). Moreover, the richness introduced by egg yolk lipids imparted a creamy mouthfeel, enhancing overall satisfaction (Osei Tutu et al., 2024a). Hidas et al. (2020) found that egg inclusion improves sensory quality in gluten-free systems by offering multiple functional benefits, including aroma enhancement and taste complexity.

The gelatin formulation (F4) received an overall acceptability score of 7.4 ± 0.5, slightly higher than F3. The bread was described as moist, elastic and visually appealing with a rich yellow crust and well-developed crumb. Gelatin enhanced chewiness and gave the crumb a slightly elastic bite that resembled that of wheat bread (Osei Tutu et al., 2024a; Acheampong et al., 2025). Mechanistically, gelatin's ability to bind water and form gel networks improved juiciness and prevented crumb drying during mastication (Osei Tutu et al., 2019; Zhao et al., 2021). This created a more satisfying mouthfeel and reduced staling, both of which contributed to favourable sensory impressions. Tóth et al. (2022) reported that gelatin improves the moistness and chewability of gluten-free breads, thereby enhancing consumer satisfaction.

The highest sensory scores were recorded for the optimised formulation (F5), which achieved 8.6 ± 0.4 in overall acceptability. Panellists rated it favorably across all parameters, particularly for crust colour, aroma, crumb softness and cohesive mouthfeel. This formulation presented a golden-brown crust, mild eggy-sweet aroma, soft and elastic crumb and a balanced, mildly sweet taste. Mechanistically, the synergy among xanthan gum, egg powder and gelatin produced a dough system that retained moisture, trapped gas effectively and underwent optimal browning during baking. Xanthan gum ensured internal softness and plasticity, egg contributed rich flavour and foaming capacity and gelatin enhanced chewability and crumb coherence. These combined mechanisms produced a gluten-free bread that closely mimicked the sensory attributes of wheat bread, confirming the additive triple functional synergy.

Compared to wheat bread controls documented in literature, which typically score between 7.5 and 8.5 in hedonic scales (Encina-Zelada et al., 2019; Mir et al., 2021), the F5 formulation approaches commercial standards of acceptability. The combination of colour development, structural softness and balanced flavour composition resulted in a gluten-free product that could compete favourably with conventional loaves in terms of sensory quality.

The incorporation of functional additives not only improved the physical and structural characteristics of the bread but also significantly enhanced sensory appeal. The findings affirm that formulating gluten-free bread with structurally and chemically active components is essential for achieving consumer-acceptable products that meet both functional and sensory expectations.

The panel size of twelve trained assessors is modest for hedonic evaluations but sufficient for descriptive testing. While this may limit the generalisation of findings to wider consumer populations, the consistent patterns observed suggest that the additive system offers real potential for consumer acceptance. Larger-scale consumer tests are recommended for future studies.

Overall, the sensory evaluation confirms that hydrocolloid–protein systems substantially enhance consumer-perceived quality, with the combined system (F5) delivering the best results. This aligns with the instrumental measurements of volume, density, moisture and colour and demonstrates that both technological and sensory improvements can be achieved when hydrocolloids and proteins are used together.

3.7. Principal component analysis (PCA)

Principal Component Analysis (PCA) was used to summarise the multivariate relationships among the measured rheological, sensory, physical and colour attributes of the gluten-free rice bread formulations. All parameters evaluated in the study thus, firmness, adhesiveness, cohesiveness, consistency, aroma, crust appearance, crumb texture, overall acceptability, loaf volume, specific volume, moisture, and colour values (L*, a*, and b*), were included in the analysis. The results are presented in Fig. 3, which displays both the score plot (formulation distribution) and loading vectors (variable contribution).

The first two principal components accounted for 99.27 % of the total variance, with PC1 explaining 97.76 % and PC2 explaining 1.51 %. As PC1 accounts for nearly all the variance, the separation among formulations occurs primarily along this axis. The variables that loaded strongly and negatively on PC1 include firmness, consistency, cohesiveness, loaf volume, specific volume, moisture content, and all sensory

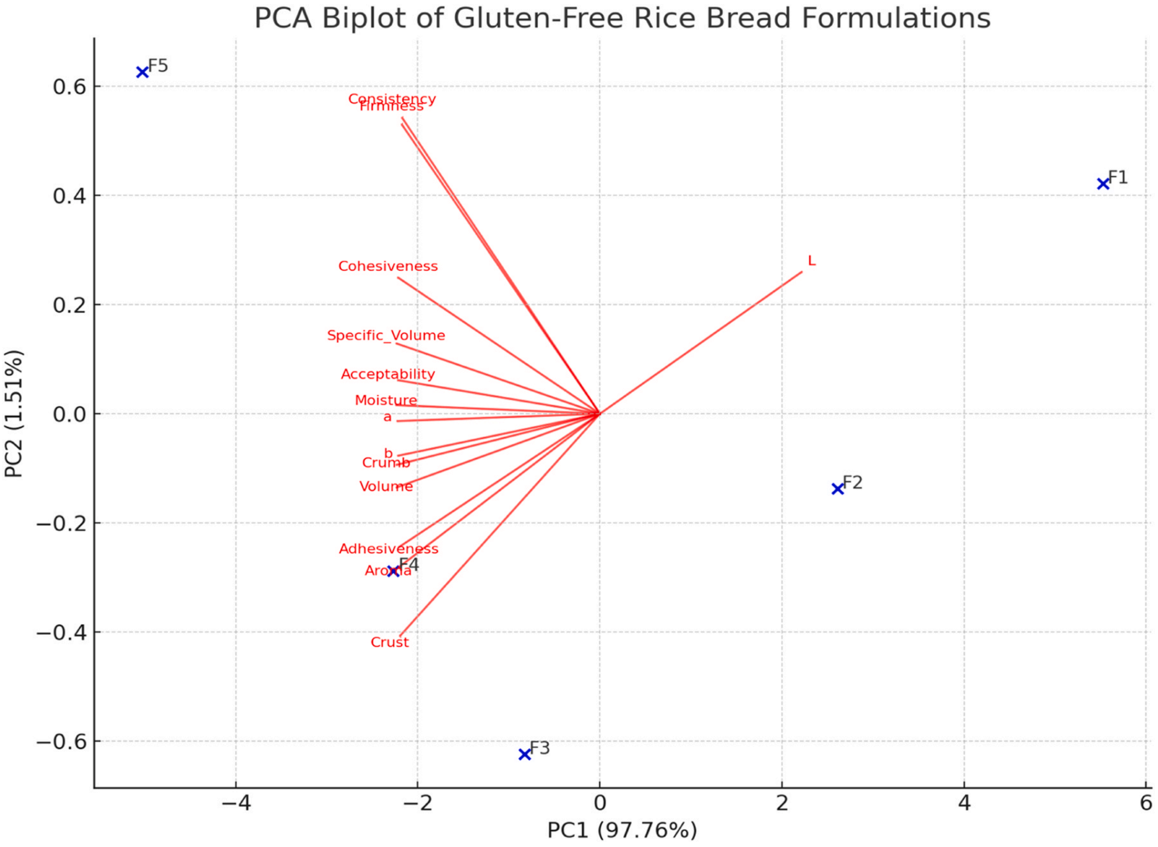

Fig. 3. PCA biplot (scores + loadings).

attributes (aroma, crust appearance, crumb texture, and overall acceptability). In contrast, lightness (L*) loaded positively on PC1, indicating a clear inverse relationship between a pale crust and all other desirable quality attributes. The positive correlation between the rheological properties of the dough and the structural and sensory quality attributes demonstrates that doughs with better rheological properties produced loaves with superior structural and sensory quality (Apovian et al., 2019; Demirkesen et al., 2010; Jan et al., 2022; Osei Tutu et al., 2024a).

PC2, which explained only a minor proportion of the total variance (1.51 %), separated the samples slightly based on contrasts between crust appearance, adhesiveness, and aroma versus firmness, consistency, and cohesiveness. The colour parameters a and b were positioned close to the x-axis, indicating that they contributed little to classifying samples across PC2. However, because PC2 contributed minimally to the total variance, its interpretation is considered secondary.

The score plot in Fig. 3 shows a clear separation among the formulations. The control sample (F1) lies on the positive side of PC1, associated with higher lightness (L) but lower firmness, cohesiveness, moisture, and sensory scores. Formulation F2 (xanthan gum alone) occupies an intermediate position, reflecting modest improvements in texture and volume. The formulations containing combined additives (F3, F4, and F5) cluster towards the negative side of PC1, near the vectors for firmness, consistency, cohesiveness, loaf volume, specific volume, moisture, and sensory acceptability. Among these, F5 (xanthan + egg + gelatin) lies furthest on the negative end of PC1, indicating the highest overall quality and strongest association with desirable attributes.

It is noted that in the biplot, F4 appears slightly closer to the "overall acceptability" vector than F5. This can be attributed to the fact that F4 (xanthan + gelatin) already provides excellent structural and textural properties, particularly moisture and elasticity, which are key drivers of sensory acceptance. However, F5, which incorporates egg powder in addition, achieves a more balanced and superior profile across a wider range of attributes, including the highest loaf volume, specific volume, and enhanced aroma, as confirmed by the univariate sensory scores where F5 scored highest (8.6 ± 0.4). Therefore, while F4 is a highly viable formulation, F5 represents the optimal synergistic combination.

The close proximity of the sensory vectors (aroma, crumb texture, and acceptability) to the mechanical and structural vectors (firmness, cohesiveness, consistency, and loaf volume) indicates that sensory perception in these formulations is largely governed by the rheological and textural properties of the dough. The alignment of these vectors reflects the positive effect of the combined use of xanthan gum, egg powder, and gelatin on the integrated quality of gluten-free rice bread. Similar findings were reported by Marco & Rosell (2008), who noted that hydrocolloid–protein interactions contribute to improved gas cell stability and sensory quality.

The PCA results confirm that formulation F5 offers the most balanced combination of rheological strength, moisture retention, and sensory acceptance. The alignment of multiple attributes along PC1 underscores the integrated nature of dough and bread quality. This multivariate analysis supports the univariate ANOVA results and provides a graphical representation of the strong positive interactions among hydrocolloid–protein ingredients in optimising gluten-free bread performance.

4. Conclusion

The results of this study provide compelling evidence that the combined application of xanthan gum, egg powder and gelatin significantly improves the structural, functional and sensory properties of gluten-free rice bread. Among the five formulations tested, the triple-additive combination (F5) achieved superior outcomes across multiple parameters, including the highest loaf volume and specific volume, the lowest bread density and the highest moisture content. These improvements translated into a softer crumb, more appealing crust and better sensory acceptance by panellists.

Mechanistically, the observed enhancements can be attributed to the distinct but complementary roles of each additive. Xanthan gum increased dough viscosity and gas retention, egg powder provided coagulating proteins that reinforced the matrix upon baking and gelatin contributed moisture binding and elasticity. The synergy between these components mimicked gluten's functionality, leading to better gas retention during fermentation and structural stability after baking. Crust colour and uniformity were enhanced through Maillard browning facilitated by protein-rich additives, while moisture retention helped preserve bread softness and delay staling.

Principal Component Analysis confirmed the multivariate alignment between F5 and the most desirable quality indicators. Compared to typical gluten-free alternatives, this optimised formulation offers a practical and mechanistic path to improving gluten-free bread.

In conclusion, this study demonstrates that a strategic combination of functional additives can overcome the structural and sensory limitations of rice-based gluten-free bread. The insights gained here support the development of commercial gluten-free bakery products with enhanced quality and consumer acceptability and lay a foundation for future work exploring shelf life, nutritional fortification and process scalability.

CRediT authorship contribution statement

Papa Toah Akonor: Writing – review & editing, Validation, Resources, Project administration, Methodology, Investigation, Conceptualization. **Justice Owusu-Bempah:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Investigation. **Bernard Kwabena Asiedu:** Writing – review & editing, Visualization, Resources, Project administration, Methodology, Investigation. **Helena Opoku Adusei:** Methodology, Investigation, Data curation, Conceptualization. **Firibu Kwesi Saalia:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization. **Paul Osei Mensah:** Writing – original draft, Resources, Project administration, Investigation, Data curation, Conceptualization. **Crossby Osei Tutu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Ethical approval

All participants provided their informed consent before taking part in the sensory evaluation. Measures were carefully observed to safeguard the rights, dignity and privacy of those involved. The food samples presented were confirmed to be safe for consumption. Conducting the sensory evaluation with trained assessors was covered under clearance by the Ethics Committee of the College of Basic and Applied Science (ECBAS), University of Ghana, Legon, Accra, Ghana.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data associated with this work are included/referenced within the article.

References

AbuDujayn, A. A., Mohamed, A. A., Alamri, M. S., Hussain, S., Ibraheem, M. A., Qasem, A. A. A., … Alqahtani, N. K. (2022). Relationship between dough properties and baking performance of panned bread: The function of maltodextrins and natural gums. *Molecules, 28*(1), 1.

Acheampong, R., Osei Tutu, C., Akonor, P. T., Asiedu, B. K., Mahama, S., Owusu-Bempah, J., Appiadu, D., Koranteng, A. F., Kumador, D. K., Andoh-Odoom, A. H., & Saalia, F. K. (2025). Effect of conventional and emerging thawing technologies on drip loss, microstructure and post-thaw quality of frozen fruits and vegetables: A review. *Applied Food Research.* , Article 101323. https://doi.org/10.1016/j.afres.2025.101323

Acheampong, R., Osei Tutu, C., Akonor, P. T., Asiedu, B. K., Owusu-Bempah, J., Mahama, S., … Saalia, F. K. (2025). Edible insects for food security: Overcoming cultural, legal and tech barriers to wider adoption. *Food and Humanity, 5*(2025), Article 100778. https://doi.org/10.1016/j.foohum.2025.100778

Acheampong, R., Osei Tutu, C., Amissah, J. G. N., Danquah, A. O., & Saalia, F. K. (2024). Physicochemical and sensory characteristics of a breakfast cereal made from sprouted finger millet-maize composite flour. *Cogent Food and Agriculture, 10*(1), Article 2363003. https://doi.org/10.1080/23311932.2024.2363003

Acheampong, R., Osei Tutu, C., Owusu-Bempah, J., Kumador, D. K., Mahama, S., Kortei, N. K., Wiafe-Kwagyan, M., Akonor, P. T., & Ayim-Akono, M. (2025). Underutilised Legumes in Regenerative Agriculture: Implications for Food and Nutritional Security – A Review. *Applied Food Research.* , Article 101313. https://doi.org/10.1016/j.afres.2025.101313

Adil, M., Xinbo, G., Cai, J., Waseem, M., Manzoor, M. F., & Osei Tutu, C. (2025). Investigating the role of Lactococcus lactis D1813, salinity, and dissolved oxygen on the nutritional, chromatic, and textural profile of Litopenaeus vannamei. *Food Chemistry: X, 27*, Article 102404. https://doi.org/10.1016/j.fochx.2025.102404

Adil, M., Xinbo, G., Cai, J., Waseem, M., Manzoor, M. F., Hussain, A., & Osei Tutu, C. (2025). Data-independent acquisition-mass spectrometry proteomic insights into nutritional metabolism of *Litopenaeus vannamei* exposed to *Lactococcus lactis* D1813, varied salinity, and dissolved oxygen. *International Journal of Food Science and Technology, 60*(1), Article vvaf067. https://doi.org/10.1093/ijfood/vvaf067

Akonor, P. T., Osei Tutu, C., Affrifah, N. S., Budu, A. S., & Saalia, F. K. (2023). Kinetics of β-Carotene Breakdown and Moisture Sorption Behavior of Yellow Cassava Flour during Storage. *Journal of Food Processing and Preservation.* , Article 2155029. https://doi.org/10.1155/2023/2155029, 9 pages.

Amjad, A., Syed, A., Waseem, M., Alshammari, J. M., Kamal, M. M., Akram, S., … Osei Tutu, C. (2025). Effect of apple peel powder and pomace extract on hyperlipidemic health indices of albino Wistar rats. *Journal of the Science of Food and Agriculture.* , Article 70242. https://doi.org/10.1002/jsfa.70242

AOAC (2000). Official Methods of Analysis. 17th edition. Association of Official Analytical Chemists, Gaithersburg, MD, USA.

Apovian, A. C., Batista, A. P., Souza, V. M., Santos, M. D. O., & Mendes, R. C. (2019). Effect of xanthan gum concentration on quality characteristics of gluten-free bread produced from rice flour and cassava starch. *Food Science and Technology, 39*(2), 238–245. ⟨https://www.sciencedirect.com/science/article/abs/pii/S0963996918304381⟩.

Arendt, E. K., & Mester, A. (2009). Gluten-free bread: A review. *Trends in Food Science Technology, 20*(1), 1–9.

Asiedu, B. K., Afoakwa, E. O., Osei Tutu, C., Obeng, R., Kortei, N. K., Akonor, P. T., Budu, A. S., & Saalia, F. K. (2025). Effect of roasting on flavonoids, phenolics, and antioxidant activity of industrial-pulped and fermented cocoa beans. *Food Chemistry Advances, 6*, Article 100925. https://doi.org/10.1016/j.focha.2025.100925

Asiedu, B. K., Osei Tutu, C., Akonor, P. T., Acheampong, A., Owusu-Bempah, J., Frimpong, R. Y., … Kortei, N. K. (2026). Momoni as a Model for African Fermented Fish: Nutritional Composition, Bioactive Metabolites and Safety Perspectives. *Journal of Food Composition and Analysis, 149*(2026), Article 108612. https://doi.org/10.1016/j.jfca.2025.108612

Ayadi, M. A., Maarouf, A. E., Fleury, C., Chekki, R., Bellakhdar, M., & Sahli, F. (2021). Impact of hydrocolloids on dough rheology, bread quality and potential health benefits of gluten-free bread. *Food Bioscience, 43*, Article 101180.

Culetu, A., Duta, D. E., Papageorgiou, M., & Varzakas, T. (2021). The role of hydrocolloids in gluten-free bread and pasta; Rheology, characteristics, staling and glycemic index. *Foods, 10*(12), 3121.

Demirkesen, C., Sumnu, G., & Sahin, S. (2010). Hydrocolloid effects on rheological properties of rice flour doughs. *International Journal of Food Science Technology, 45*(10), 2068–2073.

Dessev, T., Lalanne, V., Keramat, J., Jury, V., Prost, C., & Le-Bail, A. (2020). Influence of baking conditions on bread characteristics and acrylamide concentration. *Journal of Food Science and Nutrition Research, 3*(4), 291–310.

Encina-Zelada, C. R., Cadavez, V., Teixeira, J. A., & Gonzales-Barron, U. (2019). Optimisation of quality properties of gluten-free bread by a mixture design of xanthan, guar and hydroxypropyl methyl cellulose gums. *Foods, 8*(5), 156.

Goff, H. D., & Guo, Q. (2019). *The role of hydrocolloids in the development of food structure* (pp. 1–28). The Royal Society of Chemistry eBooks. https://doi.org/10.1039/9781788016155-00001

Grenier, D., Rondeau-Mouro, C., Dedey, K. B., Morel, M. H., & Lucas, T. (2021). Gas cell opening in bread dough during baking. *Trends in Food Science Technology, 109*, 482–498.

Haider, M. W., Abbas, S. M., Saeed, M. A., Farooq, U., Waseem, M., Adil, M., … Osei Tutu, C. (2025). Environmental and Nutritional Value of Fruit and Vegetable Peels as Animal Feed: A Comprehensive Review. *Animal Research and One Health, 3*(2), 149–164. https://doi.org/10.1002/aro2.7000, 70002.

Hidas, K. I., Visy, A., Csonka, J., Nyulas-Zeke, I. C., Friedrich, L., Pásztor-Huszár, K., & Gere, A. (2020). Development of a novel gluten-free egg Pie product: effects of sensory Attributes and storage. *Sustainability, 12*(24), 10389.

Islam, M. T., Ganesan, P., & Cheng, J. (2015). A pair of bubbles' rising dynamics in a xanthan gum solution: A CFD study. *Rsc Advances, 5*(11), 7819–7831.

Jan, N., Naik, H. R., Gani, G., Bashir, O., Amin, T., Wani, S. M., & Sofi, S. A. (2022). Influence of replacement of wheat flour by rice flour on rheo-structural changes, in vitro starch digestibility and consumer acceptability of low-gluten pretzels. *Food Production, Processing and Nutrition, 4*(1), 9.

Javed, M. A., Suleman, R., Waseem, M., Ismail, T., Alsulamin, T., Sattar, Dur-e-S., Siddiqui, N., Muzamil, M., Zahoor, M. A, Adil, M., & Osei Tutu, C. (2025). Novel Colocasia esculenta Starch-Clove Extract Packaging Films for Enhanced Oxidative Stability, Microbial Quality, and Sensory Acceptability of Chicken. *Journal of Food Processing and Preservation*, 14. https://doi.org/10.1155/jfpp/556360, 5563606.

2025 Khan, W. A., Waseem, M., Yasmin, I., Wadood, S. A., Qamar, A., Javed, M. R., … Osei Tutu, C. (2025). Effect of dietary proteins on mayonnaise techno-functionality and rheology: A review. *Food and Humanity, 5*(2025), Article 100665. https://doi.org/10.1016/j.foohum.2025.100665

Kortei, N. K., Ahlidobu, O., Asante-Donyinah, D., Boadi, M., Zaazie, P., Pobee, N. O., … Osei Tutu, C. (2024). Consumer food safety knowledge in the homes of residents of Ho municipality, Ghana. *Ghana Journal of Science, 65*(1), 17–33. https://www.ajol.info/index.php/gjs/article/view/277479.

Kumador, D. K., Opoku-Mensah, A., Tackie-Ofosu, V., Mahama, S., Owusu-Bempah, J., & Osei Tutu, C. (2025). Preterm delivery in Ghana: challenges and implications for maternal mental health trajectories. *PLoS ONE, 20*(3), Article e0317147. https://doi.org/10.1371/journal.pone.0317147.

Kupkanchanakul, W., Yamaguchi, T., & Naivikul, O. (2019). Gluten-free rice breading using composited rice flour and pre-germinated brown rice flour for health benefits. *Journal of Nutritional Science and Vitaminology, 65*(ement), S206–S211. https://doi.org/10.3177/jnsv.65.s206

Kurt, A. (2021). Synthesis, characterization and rheological properties of modified xanthan gum. *International Journal of Current Naturalscience and Advanced Phytochemistry, 1*(1), 1–11.

Lafarga, T., Rai, D., & O'Kane, F. (2017). Replacing wheat flour with alternative proteins in gluten-free bread: Influence on dough rheology and bread quality. *Journal of Cereal Science, 77*, 130–138.

Lazaridou, A., Duta, D., Papageorgiou, M., Belc, N., & Biliaderis, C. G. (2007). Effects of hydrocolloids on dough rheology and bread quality parameters in gluten-free formulations. *Journal of Food Engineering, 79*(3), 1033–1047.

Lv, X., Huang, X., Ma, B., Chen, Y., Batool, Z., Fu, X., & Jin, Y. (2022). Modification methods and applications of egg protein gel properties: A review. *Comprehensive Reviews in Food Science and Food Safety, 21*(3), 2233–2252.

Mahama, S., Ackom, J. A., Agyeku, B. A., Osei Tutu, C., Kumador, D. K., & Owusu-Bempah, J. (2025). Beyond the observed: Postpartum posttraumatic stress symptoms and mother-child bonding in Ghana. *Midwifery, 148*, Article 104470. https://doi.org/10.1016/j.midw.2025.104470

Mahama, S., Osei Tutu, C., & Owusu-Bempah, J. (2025). Rethinking Entrepreneurship Modules in Ghanaian Tertiary Institutions: Perspectives of Graduates Transitioning into the Labour Market. *F1000Research, 14*(268). https://doi.org/10.12688/f1000research.157505.1

Marco, C., & Rosell, C. M. (2008). Effect of different hydrocolloids on dough rheology and bread quality of frozen bread. *Food Science and Technology International, 14*(2), 145–151.

Matos, M. E., & Rosell, C. M. (2015). Understanding gluten-free dough for reaching breads with physical quality and nutritional balance. *Journal of the Science of Food and Agriculture, 95*(4), 653–661.

Mir, M. B., Mir, S. A., Rajput, R., & Sablania, V. (2021). Challenges in development of gluten-free breads. *In Gluten-Free Bread Technology* (pp. 15–28). Cham: Springer International Publishing.

Moazzam, M., Ali, S., Khan, M. A., Waseem, M., Javed, M. R., Rajput, N., … Osei Tutu, C. (2025). Impact of Soy Protein Concentrate and Storage on the Safety, Quality and Shelf Stability of Beef Patties. *Food Science & Nutrition 13, 12*, Article e71327. https://doi.org/10.1002/fsn3.71327

Nyasordzi, J., Awude, S., Kortei, N. K., Kpodo, F. M., Osei Tutu, C., & Annan, T. (2025). Evaluation of safety and health risk characterization of some baby foods in Ghana. *Scientific Reports, 15*, Article 42289. https://doi.org/10.1038/s41598-025-21731-x

Obeng, R., Osei Tutu, C., Afoakwa, E. O., Asiedu, B. K., Kongor, J. E., Owusu-Bempah, J., … Saalia, F. K. (2025). Fat and Conching Time Optimisation for Melanger-Processed Artisanal Chocolate Spreads: A Physicofunctional and Rheological Study. *Translational Food Sciences, 1*(1), Article vxaf010. https://doi.org/10.1093/trfood/vxaf010

Omran, A., & Mahgoub, S. (2022). Quality evaluation of gluten-free flat bread prepared by using rice and millet flour. *British Food Journal, 124*(12), 4406–4419. https://doi.org/10.1108/bfj-11-2021-1215

Osei Tutu, C., Amissah, J. G. N., Akonor, J. N., Budu, A. S., & Saalia, F. K. (2024b). Physical, chemical and rheological properties of flour from accessions of Frafra potato (Solenostemon rotundifolius). *Journal of Agriculture and Food Research, 15*, Article 100974. https://doi.org/10.1016/j.jafr.2024.100974

Osei Tutu, C., Amissah, J. G. N., Amissah, J. N., & Saalia, F. K. (2019). Physicochemical and Sensory Characteristics of Bread Made from Wheat-Frafra Potato (Solenostemon rotundifolius) Composite Flour. *Science and Development, 3*, 20–29.

Osei Tutu, C., Amissah, J. G. N., Amissah, J. N., Akonor, P. T., Arthur, W., Budu, A. S., & Saalia, F. K. (2023). Physicochemical and microstructural characteristics of Frafra potato (Solenostemon rotundifolius) starch. *International Journal of Food Properties, 26*(1), 1624–1635. https://doi.org/10.1080/10942912.2023.2228513

Osei Tutu, C., Amissah, J. G. N., Amissah, J. N., Akonor, P. T., Budu, A. S., & Saalia, F. K. (2024a). Application of Frafra potato (*Solenostemon rotundifolius*) flour in the development of gluten-free bread. *Heliyon, 2024, 10*(2), Article e24521. https://doi.org/10.1016/j.heliyon.2024.e24521

Ozmen, D., Demircan, H., Yildirim, R. M., Waseem, M., Basdogan, H., Toker, O. S., & Osei Tutu, C. (2025). Influence of seed concentration and storage time on the rheological, textural, and microscopic crystallization attributes of Apis mellifera honey. *Food Chemistry: X, 28*, Article 102634. https://doi.org/10.1016/j.fochx.2025.102634

Pătraşcu, L., Tanta, M. F., & Amariei, S. (2016). Influence of different additives on quality characteristics of gluten-free bread. *Journal of Agroalimentary Processes and Technologies, 22*(2), 142–148. 〈https://ajfand.net/Volume24/No4/index.html〉.

Pycarelle, S. C., Bosmans, G. M., Pareyt, B., Brijs, K., & Delcour, J. A. (2021). The role of intact and disintegrated egg yolk low-density lipoproteins during sponge cake making and their impact on starch and protein mediated structure setting. *Foods, 10*(1), 107.

Rashid, T. U., Sharmeen, S., Biswas, S., Ahmed, T., Mallik, A. K., Shahruzzaman, M., … Rahman, M. M. (2018). Gelatin-based hydrogels. *In Cellulose-based superabsorbent hydrogels* (pp. 1–41). Cham: Springer.

Rosell, C. M., Rojas, J. A., & Benedito de Barber, C. (2001). Influence of hydrocolloids on dough rheology and bread quality. *Food Hydrocolloids, 15*(1), 75–81.

Ruiz, F. (2023). Development of gluten-free bread using teosinte (Dioon mejiae) flour in combination with high-protein brown rice flour and high-protein white rice flour. *Foods, 12*(11), 2132. https://doi.org/10.3390/foods12112132

Salehi, F. (2019). Application of hydrocolloids in gluten-free bread making: Technological and functional viewpoints. *Critical Reviews in Food Science and Nutrition, 59*(18), 2923–2939. 〈http://ukm.my/jsm/pdf_files/SM-PDF-53-2-2024/7.pdf〉.

Sasaki, T. (2018). Rheological properties of rice flour dough with different hydrocolloids. *LWT - Food Science and Technology, 90*, 563–568. 〈https://www.sciencedirect.com/science/article/pii/S0260877403001699〉.

Sasaki, T. (2022). Recent developments in gluten-free bread making: Technological and functional perspectives. *Trends in Food Science Technology, 121*, 435–448. 〈https://www.scielo.br/j/cta/a/t7pCYHztMcGkfMXjyKmwTsb/〉.

Schopf, M., & Scherf, K. A. (2021). Water absorption capacity determines the functionality of vital gluten related to specific bread volume. *Foods, 10*(2), 228.

Singh, S., Singh, J., & Jakhar, D. (2023). Development of Gluten-Free Bread Production Technology. *Foods, 13*(2), 271. 〈https://www.mdpi.com/2304-8158/13/2/271〉.

Suleman, R., Choudhary, H., Waseem, M., Alshammari, J. M., Muzamil, M., Liu, H., Ismail, T., Khan, M. A., Qamar, M., & Osei Tutu, C. (2025). Nutritional and antioxidative characterization, antimicrobial and sensorial stability of flaxseed powder supplemented mutton patties. *Food Chemistry: X, 25*, Article 102098. https://doi.org/10.1016/j.fochx.2024.102098

Tóth, M., Kaszab, T., & Lambert-Meretei, A. (2022). Case study of commercially available gluten-free bread products: Texture changes during storage and sensory analysis. *Progress in Agricultural Engineering Sciences, 18*(1), 1–13.

Udayana, S., Reddy, C. V., Sogi, D. S., & Singh, N. (2020). Effect of different types of flours and egg components on physicochemical and functional properties of muffins. *Food Science and Technology International, 26*(2), 535–547.

Vidaurre-Ruiz, N., Sánchez, P., & Valencia, C. (2019). Gluten-free bread: Formulation, functional properties and health benefits. *Journal of Food Science, 84*(11), 2646–2656. 〈https://www.sciencedirect.com/science/article/pii/S0023643823001457〉.

Wang, J., Sun, Q., Zhu, F., Li, C., & Xu, X. (2022). Effects of rice bran dietary fiber and gelatin on quality characteristics of gluten-free rice bread. *Food Science and Technology International, 28*(4), 1222–1233.

Waseem, M., Akhtar, S., Ismail, T., Alsulami, T., Qamar, M., Sattar, D-e-s., Suleman, R., Saeed, W., & Osei Tutu, C. (2024). Effect of thermal and non-thermal processing on Technofunctional, nutritional, safety and sensorial attributes of potato powder. *Food Chemistry: X, 24*, Article 101896. https://doi.org/10.1016/j.fochx.2024.101896

Xu, K., & Kuang, J. (2024). Effects of thermal treatment on the physicochemical and structural properties of wheat gluten proteins: Insights from gluten, glutenin and gliadin fractions. *International Journal of Food Science and Technology, 59*(4), 2275–2285.

Zhao, F., Li, Y., Li, C., Ban, X., Cheng, L., Hong, Y., … Li, Z. (2021). Co-supported hydrocolloids improve the structure and texture quality of gluten-free bread. *LWT, 152*, Article 112248.