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Functional properties of chicken meat for incorporation in gluten-free breadstick formulation

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Abstract

The absence of gluten in breadsticks reduces gas retention during leavening, resulting in inferior texture. This challenge can be mitigated by incorporating hydrocolloids or alternative protein sources. Chicken meat, a high-biological-value protein with low lipid content and a neutral organoleptic profile, enhances the nutritional quality and palatability of food products without significantly altering their original flavour. Therefore, the present work aimed to characterise gluten-free breadsticks incorporated with varying levels of chicken meat (0, 20, 30, 40, 50, and 60%) as a protein source. Breadstick quality was evaluated through physical property analysis, proximate composition, porosity assessment, and sensory evaluation. Increasing chicken meat levels led to significant increases ($p < 0.05$) in moisture content, ash, protein content, hardness, bulk density, and yellowness, while lightness, redness, total colour difference, and porosity decreased significantly. Sensory evaluation indicated that chicken meat incorporation enhanced all sensory attributes up to 40% level, after which acceptability decreased. X-ray diffraction analysis revealed progressively pronounced V-type crystallinity peaks with higher meat content. In conclusion, chicken meat can be incorporated at levels up to 40% in gluten-free breadstick formulations to improve both physicochemical and sensory properties. These findings would support chicken meat as a promising functional protein source for developing high-protein, gluten-free baked products.

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Introduction

Bakery products are consumed globally, and serve as effective vehicles for incorporating functional ingredients and delivering health-promoting components to a broad population (Kadam and Prabhasankar, 2010). Breadsticks, originating in north-western Italy, are slender, pencil-shaped baked goods commonly served as appetizers. Traditionally, these products are made using wheat flour, which contains gluten as the primary structural component (Rodríguez-Carrasco *et al.,* 2014). The development of gluten-free products is essential for supporting individuals with celiac disease and non-celiac gluten sensitivity, who must strictly avoid gluten to prevent intestinal damage and systemic complications (Di Liberto *et al.,* 2020). Moreover, gluten-free diets are increasingly embraced by health-conscious consumers seeking alternatives for digestive well-being and lifestyle preferences (Knežević *et al.,* 2024). Achieving gluten-free products with acceptable texture, structure, and nutritional quality requires innovative formulation strategies to compensate for gluten's viscoelastic and functional properties (El Khoury *et al.,* 2018). Numerous studies have demonstrated that the incorporation of hydrocolloids, such as proteins and polysaccharides, can enhance the quality of gluten-free bakery products (Bize *et al.,* 2017). Additionally, the use of fibres, proteins, lipids, and alternative starches and flours has been explored to improve both the technological performance and nutritional profile of gluten-free breads.

Hydrocolloids have been widely studied as gluten substitutes in bakery products, as evidenced by the reviews conducted by Roman *et al.* (2019). Commonly used types include hydroxypropyl methylcellulose, locust bean gum, guar gum, and xanthan gum. These compounds improve moisture retention, and reduce crumbliness in gluten-free bread. They also form thermally reversible gels that strengthen during baking, stabilising the crumb

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structure (Crockett *et al*., 2011). Thus, hydrocolloids play a key role in improving texture and structural integrity. In order to achieve daily nutritional consumption needs, food scientists are currently researching the development and design of novel food products employing enrichment techniques. They specifically seek to prevent illnesses linked to protein deficiency. Snacks have been created by incorporating useful elements into the current formulation. The ideal ratio of necessary amino acids found in animal-based proteins such as eggs, milk, meat, and fish makes them complete proteins. To increase the protein level, researchers also add plant-based protein sources including lupin seed and brewer's waste grain. However, in comparison to animal-based proteins, plant-based proteins have far lower nutritional quality and availability (Cakmak *et al*., 2016).

A common practice in gluten-free bakery products is the use of proteins such as egg protein which improves crumb elasticity, and soy protein for promoting a more homogeneous cell structure, albeit with reduced bread cohesiveness (Storck *et al.,* 2013; Sahagún and Gómez, 2018). These protein additives not only increase the overall protein content but also contribute to the Maillard reaction by reducing sugar levels, enhancing crust colour formation, and improving the aroma of the final product (Roman *et al.,* 2019). Previous nutritional analyses have shown that gluten-free bakery items generally contain less protein than their gluten-containing counterparts (Roman *et al.,* 2019). This protein deficit can be attributed to two main factors: wheat flour naturally contains higher protein levels compared to alternative cereal sources, and gluten-free formulations often rely on starches rather than flour. Among available protein sources, chicken meat offers superior nutritional value, and is more affordable than other meats while containing higher total protein and lower total lipid content compared to beef and pork (Cakmak *et al.,* 2016). Its protein composition mainly consists of myofibrillar proteins (*e.g*., actin and myosin), sarcoplasmic proteins, and connective tissue proteins. Myofibrillar proteins are especially valuable in food applications due to their ability to form heat-induced gels, which enhance firmness and structural cohesion in food matrices. When incorporated into carbohydrate-based bread systems, these proteins improve water-holding capacity, enhance textural properties, and aid in forming a cohesive crumb structure in the absence of gluten (Barbut, 2023). According to Cakmak *et al.* (2013), incorporating chicken meat and chicken meat powder into white and whole wheat breads increased the protein content by up to 18.7%. Moreover, consumers are becoming increasingly aware of the health benefits of chicken meat, particularly skinless chicken breast, which is perceived as a healthier alternative to red meat. Recently, there has also been growing interest in incorporating chicken meat into gluten-free breadsticks to enhance their nutritional profile.

Chicken meat is a promising alternative to conventional hydrocolloids in gluten-free breadstick formulations due to its high content of functional myofibrillar proteins, which provide essential water-holding, emulsifying, and gelling properties (Hailemariam *et al.,* 2022). These proteins enhance dough cohesiveness and elasticity, partially replicating the viscoelastic structure typically contributed by gluten and hydrocolloids (Day *et al.,* 2022). Moreover, chicken meat improves its nutritional profile by supplying complete, high-quality proteins, helping to address common nutritional deficiencies in gluten-free baked products (Marti and Pagani, 2021). This dual functionality supports its use as a single-ingredient substitute for synthetic or plant-based hydrocolloids.

Therefore, the present work aimed to address the protein deficiency commonly found in gluten-free breadsticks by incorporating minced chicken breast meat as a functional ingredient to develop protein-enriched gluten-free breadsticks. This approach leverages chicken meat, a highly nutritious protein source, to create value-added food products. The present work focused on improving both the nutritional profile and physicochemical quality of gluten-free breadsticks formulated with chicken meat.

Materials and methods

Breadstick preparation

Gluten-free breadsticks were formulated by substituting tapioca flour with minced chicken meat at levels of 0 (control), 20, 30, 40, 50, and 60% based on total flour weight. Six formulations were prepared: BC00 (control, 100% tapioca flour), BC20, BC30, BC40, BC50, and BC60, containing 20, 30, 40, 50, and 60% minced chicken meat, respectively. The dough was prepared using the straight dough method. For the control, 400 g of tapioca flour, 20 g of salt, 20 g of sugar, 50 g of emulsified bread fat, 15 g of milk powder, 10 g of xanthan gum, 10 g of guar gum, and 25 g of fresh yeast were mixed with 355 g of water. In the experimental formulations, minced chicken meat partially replaced tapioca flour at specified levels (Table 1). All dry ingredients were premixed and combined with hydrated yeast solution using a Kenwood Chef Mixer (speed 3) to ensure uniform mixing, and prevent lumps. The dough was rested in stainless steel bowls at room temperature (22 ± 1°C) for 30 min, then divided and manually shaped into cylindrical breadsticks. Baking was conducted in a preheated oven at 180 ± 2°C for 20 min. After baking, the breadsticks were cooled at room temperature for approximately 2 h, and stored in airtight containers for subsequent analyses.

Table 1. Formulations of gluten-free breadsticks incorporated with chicken meat at 0% (BC00), 20% (BC20), 30% (BC30), 40% (BC40), 50% (BC50), and 60% (BC60).

Ingredient (g)	**BC00**	**BC20**	**BC30**	**BC40**	**BC50**	**BC60**
Tapioca flour	400	320	280	240	200	160
Minced chicken breast	-	80	120	160	200	240
Salt butter	50	50	50	50	50	50
Whole milk powder	15	15	15	15	15	15
Sugar	20	10	10	10	10	10
Salt	20	6	6	6	6	6
Xanthan gum	10	10	10	10	10	10
Guar gum	10	10	10	10	10	10
Fresh yeast	25	25	25	25	25	25
Water	355	355	355	355	355	355

Compositional analysis

The moisture content of the breadsticks was determined gravimetrically by drying samples at 105°C until a constant weight was achieved. Results were expressed as grams per 100 grams (g/100 g), and represented the mean of three replicates. The water activity (a_w) was measured at room temperature in triplicate using an Aqualab 4TE (Decagon Devices Inc., USA), calibrated with a standard solution of a_w = 0.250. The protein content was determined following the AOAC method No. 920.87 by measuring the total nitrogen *via* the Kjeldahl method, and multiplying it by a conversion factor of 6.25. The ash content was measured following the AOAC method No. 923.03.

Bulk density

The bulk density of the breadstick (D_b) was calculated by dividing the sample weight (W_b) by its equivalent solid volume (V_b). The volume (V_b) was determined by replacing the breadstick with rapeseed, measuring the rapeseed weight (W_r), and dividing it by the rapeseed density (D_r), as shown in Eq. 1. Five measurements were performed, and the mean volume was used in the calculation.

$$D_b = W_b \times \frac{D_r}{W_r} \quad \text{(Eq. 1)}$$

Texture analysis

Breadstick hardness was measured using a TA-XT2i Texture Analyser (Stable Micro Systems Ltd., Surrey, UK) equipped with a three-point bending rig (HDP/3PB) and a 30 kg load cell. Each sample was positioned on two adjustable supports spaced 20 mm apart on the base plate. Testing was conducted with pre-test and test speeds of 1 mm/s, and post-test speed of 10 mm/s. The maximum force (N) required to fracture each sample (defined as hardness) was recorded using the three-point bending test on a minimum of ten individual breadstick samples.

Colour evaluation

The colour of the breadsticks was measured using a Minolta Chromameter (Minolta CR-400, Osaka, Japan) following the CIE Lab* colour scale, where L* represents lightness (0 = black, 100 = white), +a* and -a* indicate redness and greenness, respectively, and +b* and -b* represent yellowness and blueness, respectively. For each sample, three measurements were taken and averaged. The total colour difference (ΔE) was calculated using Eq. 2.

$$\Delta E = \sqrt{[\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}]} \quad \text{(Eq. 2)}$$

X-ray computer tomography (CT) of breadsticks

Breadstick samples were prepared by sectioning 2 cm lengths using a scalpel. Each component was affixed to a revolving stage utilising double-sided adhesive tape. Micro-computed tomography (micro-CT) analysis was performed utilising a Skyscan 1173 system (Bruker-micro-CT, Kontich, Belgium) with data acquisition software version 1.6 (build 15). The X-ray source, featuring a tungsten anode, functioned at 40 kV and 100 µA without the application of an X-ray filter during the scanning process. Images were obtained in 1 MPixel mode, yielding transmission images with a resolution of 1,000 × 524 pixels. A total of 360 projection images were acquired during a complete 360° revolution, with a rotation increment of 0.1°. Each image was obtained with a 75 ms exposure duration, and averaged across 16 frames to improve image quality. The magnification settings produced a pixel size of 19.23 µm. Tomographic reconstruction and slice generation were executed utilising Vaa3D (version 3.100), an open-source visualisation platform. Image processing and quantitative analysis were conducted with ImageJ software (version 1.54).

Porosity (%) was determined from binarised 8-bit monochromatic two-dimensional pictures. In the binarised micro-CT scans, the white portions indicated the solid structure (skeleton) of the breadstick, whereas the black regions denoted the porous sections. After applying thresholding for image segmentation, area statistics were acquired through the "Set Measurements" feature in the "Analyse" menu of ImageJ. The backdrop of the image was consistently modified using the "Colour Picker" tool. Subsequently, the "Histogram" function was utilised to quantify the area of the black (porous) patches (B). The percentage porosity was subsequently computed using Eq. 3:

$$\%\text{Porosity} = \frac{\text{A}}{\text{B}} \times 100 \quad \text{(Eq. 3)}$$

X-ray diffraction (XRD) study of breadsticks

The XRD patterns of ground breadstick samples with differing quantities of chicken meat were examined utilising an X-ray diffractometer system (Siemens D5005, Bruker Analytical X-Ray Systems, Congleton, UK). Cu Kα radiation was utilised at an operating current of 40 mA, a voltage of 40 kV, and a wavelength (λ) of 1.54060 Å. About 500 mg of powdered sample was analysed at 0.05° 2θ increments within a range of 5° to 60° 2θ (Carvalho and Mitchell, 2001). Each sample was scanned twice to guarantee repeatability.

Sensory analysis

The organoleptic qualities of the breadsticks were subjected to sensory evaluation with a panel of 50 untrained, randomly selected participants from the Department of Food Science and Technology at the Faculty of Home Economics Technology, Rajamangala University of Technology Phra Nakhon. The sensory aspects evaluated comprised overall acceptability, flavour, colour, appearance, and texture, employing a nine-point hedonic scale. Panellists received breadstick samples, and were directed to evaluate each attribute based on their sensory experience. The hedonic scale spanned from 9 (liked very much) to 1 (extremely disliked), with intermediate values delineated as follows: 8 (liked very much), 7 (moderately liked), 6 (somewhat liked), 5 (neither liked nor disliked), 4 (slightly disliked), 3 (moderately disliked), and 2 (very disliked).

Statistical analysis

All data were analysed utilising SPSS software version 23.0 (IBM Corp., Chicago, IL, USA). Variations across samples were assessed using One-way analysis of variance (ANOVA), succeeded by Duncan's Multiple Range Test (DMRT) to identify statistically significant differences at a 95% confidence level ($p < 0.05$), with the results presented as mean ± standard deviation (SD). All measurements were performed in triplicate ($n = 3$).

Results and discussion

Composition of breadsticks

Table 2 presents the results of the proximate composition analysis of the breadstick samples. A consistent linear increase in moisture content was observed with increasing levels of chicken meat incorporation, reaching a maximum at 60%. The elevated moisture content was likely due to the protein in chicken meat, which provides additional water-binding sites through charged amino groups within the dough matrix (Umaraw *et al.,* 2021). Similarly, Umaraw and Chauhan (2015) reported an

Table 2. Principal component analysis and physical attributes of gluten-free breadsticks incorporated with chicken meat at 0% (BC00), 20% (BC20), 30% (BC30), 40% (BC40), 50% (BC50), and 60% (BC60).

Parameter	BC00	BC20	BC30	BC40	BC50	BC60
Moisture (g/100 g)	3.16 ± 0.01^{e}	3.18 ± 0.01^{e}	3.53 ± 0.01^{d}	3.94 ± 0.02^{c}	4.03 ± 0.01^{b}	4.26 ± 0.02^{a}
Ash (g/100 g)	1.61 ± 0.02^{f}	1.77 ± 0.02^{e}	1.92 ± 0.02^{d}	2.01 ± 0.01^{c}	2.22 ± 0.03^{b}	2.40 ± 0.01^{a}
Protein (g/100 g)	0.69 ± 0.14^{f}	3.97 ± 0.08^{e}	5.98 ± 0.19^{d}	6.49 ± 0.09^{c}	7.69 ± 0.10^{b}	8.91 ± 0.01^{a}
Bulk density (g/ml)	0.48 ± 0.01^{c}	0.50 ± 0.01^{c}	0.58 ± 0.01^{b}	0.61 ± 0.02^{a}	0.63 ± 0.02^{a}	0.63 ± 0.02^{a}
Hardness (N)	20.77 ± 2.02^{c}	20.22 ± 21.03^{c}	20.54 ± 2.67^{c}	20.72 ± 2.07^{c}	22.68 ± 2.35^{b}	24.28 ± 2.64^{a}
Fracturability (mm)	0.83 ± 0.07^{a}	0.75 ± 0.08^{b}	0.68 ± 0.07^{c}	0.66 ± 0.09^{c}	0.67 ± 0.08^{c}	0.68 ± 0.06^{c}
Colour unit						
L*	66.04 ± 1.62^{a}	65.20 ± 1.16^{a}	63.49 ± 0.81^{b}	63.26 ± 1.23^{b}	59.78 ± 1.84^{c}	58.43 ± 2.01^{c}
a*	11.36 ± 0.56^{a}	10.47 ± 1.23^{b}	9.54 ± 0.66^{c}	9.29 ± 0.38^{c}	6.25 ± 0.61^{d}	6.10 ± 0.53^{d}
b*	27.59 ± 0.58^{c}	28.27 ± 1.09^{c}	29.09 ± 1.88^{bc}	30.58 ± 1.08^{b}	33.59 ± 1.56^{a}	35.09 ± 1.45^{a}
ΔE	72.47 ± 1.18^{a}	71.83 ± 1.21^{b}	70.48 ± 0.97^{c}	70.87 ± 0.65^{c}	68.85 ± 1.13^{d}	68.43 ± 1.27^{d}

Mean values with different lowercase superscripts in similar column are significantly different ($p < 0.05$).

increase in moisture content in bread incorporated with chicken meat powder and boiled chicken meat that had been ground into small pieces using a blender. Additionally, Chakraborty *et al.* (2021) attributed the higher moisture content in breadsticks incorporated with extruded mustard seed meal concentrate to its high water-holding capacity (WHC). Protein content in the breadsticks increased proportionally with the amount of chicken meat incorporated, with the 60% chicken meat sample exhibiting the highest protein level (Table 2). A slight increase in ash content was also observed with increasing chicken meat incorporation, reflecting the mineral richness of meat (Shirley and Parsons, 2001). These findings agreed with previous studies which demonstrated that protein fortification through the incorporation of chicken powder or meat significantly enhanced the protein content of bread products (Farouk *et al.,* 2018). Berwal and Khanna (2013) reported that cookies prepared with 10% minced chicken meat and wheat flour showed an increase in protein content from 9.66% in the control cookies (without chicken meat) to 11.18%, and also provided essential amino acids such as lysine, tryptophan, and threonine. On the other hand, Sakhare *et al.* (2024) observed a decrease in protein and fat contents in chicken meat cookies formulated with increasing levels of rice flour, which may be attributed to the lower protein and fat contents of rice flour compared to wheat flour.

Bulk density of breadsticks

Table 2 presents the bulk density measurements of the breadstick samples, revealing a significant increase when incorporating chicken meat at levels ranging from 20 - 60%, compared to the control breadsticks. A strong correlation was observed between bulk density and protein content. Bulk density is a critical quality parameter for breadsticks, influencing texture and consumer perception. As shown in Table 2, the control breadsticks exhibited the lowest bulk density at 0.48 g/mL, while samples containing chicken meat showed substantially higher values, with the increase being more pronounced in breadsticks containing higher levels of chicken meat. The observed fluctuations in bulk density may be attributed to the potential alteration of the starch matrix structure upon the incorporation of chicken meat. Fan *et al.* (2017) demonstrated a synergistic reinforcement in myofibrillar protein/cassava starch composites during the heating process through dynamic rheological testing. The swelling of starch granules was responsible for this effect, as it compressed the protein matrix during heating, resulting in a firmer structure. According to Yang *et al.* (2019), the confocal laser scanning microscopy (CLSM) images of cooked corn starch-whey protein isolate systems indicated that proteins may interact with starch by becoming embedded within the internal starch matrix. This was partially attributable to the shattering and swelling of gelatinised starch, facilitating the formation of a continuous protein matrix interspersed with discontinuous starch inclusions. This effect can also be explained by the composite matrix formed during baking, consisting of sugars, lipids, and protein aggregates embedded within partially ungelatinised starch granules (Chevallier *et al.,* 2000). Although proteins from various sources are commonly used in gluten-free bakery products such as breads, pastas, and biscuits, gluten itself plays a pivotal role in forming the protein network during kneading and baking (Witczak *et al.,* 2017). Witczak *et al.* (2017) reported a decrease in volume and density trends in gluten-free bread partially supplemented with potato protein at concentrations of 2 - 10%. Similarly, da Rosa Machado and Thys (2019) observed reductions in bread volume when protein powders were incorporated into flour or starch at 10 - 20% by weight. In contrast, Korus *et al.* (2021) found that rapeseed protein supplementation increased both bread volume and density, highlighting that protein source and concentration can variably affect the structure of bakery products.

Hardness and fracturability of breadsticks

Breadsticks exhibited a rigid, slightly deformable structure that underwent a sudden brittle fracture, characterised by an abrupt drop in force immediately after the initial break. Compared to the control, the hardness of the breadsticks increased significantly with the incorporation of chicken meat (Table 2). This suggested that the microstructure of meat-incorporated breadsticks was less porous than that of the control samples. The observed increase in hardness correlated with the higher protein content from chicken meat, contributing to a firmer texture. Similar findings have been reported by Chakraborty *et al.* (2021) for breadsticks fortified with mustard seed meal concentrate, and by Khodaveisi *et al.* (2024) for bread containing carp meat paste. In the present work, fracturability was quantified by measuring the distance at the point of fracture, a parameter correlated with crispness. The results showed that increasing chicken meat content enhanced the crispness of the breadsticks, likely due to their larger volume, and more robust cellular structure compared to the control. Hosseini Shekarabi and Shahbazi (2021) reported that the addition of fish protein powder to bread formulations resulted in a more compact and stiffer dough, as fish protein does not form a network structure similar to gluten. Additionally, the presence of sulphur-containing amino acids in fish proteins may promote the formation of disulphide bonds, leading to alterations in the starch network and protein aggregation. Moreover, the higher protein content in fortified samples may partially account for decreased gas retention, causing gas cell instability, and resulting in a denser bread structure. Similar findings were reported by Khodaveisi *et al*. (2024) who observed comparable effects when incorporating carp fish mince into bread formulations.

Colour of breadsticks

Figure 1 shows representative images illustrating the appearance of breadsticks containing 0, 20, 30, 40, 50, and 60% chicken meat. Visually, as the chicken meat content increased, the breadsticks appeared slightly smaller and darker in colour. This change in physical appearance, particularly in size and coloration, reflected the influence of meat incorporation on product morphology. Given the subjective nature of visual colour assessment, which can vary significantly between observers, instrumental colour measurements were used to ensure objective evaluation. Table 2 shows significant differences in the L* (lightness), a* (red-green), and b* (yellow-blue) values among the samples, indicating that increasing chicken meat levels notably affected the colour profile of the breadsticks.

A homogeneous, rusty brown coloration developed during baking is indicative of high-quality bakery products. Alongside texture and aroma, colour is a critical attribute influencing consumer preference (Chakraborty *et al.,* 2021). Breadsticks containing chicken meat exhibited a noticeable increase in this desirable colour characteristic. As shown in Table 2, the L* values (lightness) of breadsticks with chicken meat were significantly lower ($p < 0.05$) than those of the control, with L* values decreasing slightly as the chicken meat content increased. Significant differences were also observed in the a* (red-green) and b* (yellow-blue) values across the samples. Specifically, the incorporation of chicken meat significantly increased the a* values (indicating increased redness) while decreasing the b* values (indicating reduced yellowness) compared to the control. The external colour of the chicken meat-incorporated breadsticks shifted toward a yellowish-brown hue, accompanied by a greater overall colour difference (ΔE) on the surface. This suggested that increasing the chicken meat content progressively darkened the breadsticks' crust. The intensified coloration was primarily attributed to Maillard and caramelisation reactions, resulting from the partial thermal degradation of polysaccharides during baking, thus contributing to the deepening of surface colour (Roncolini *et al.,* 2019).

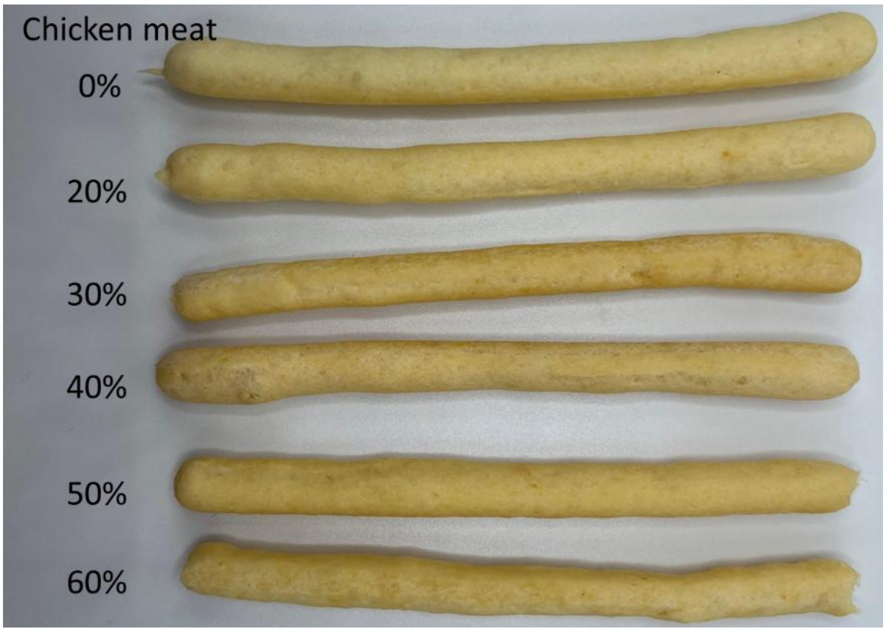


Figure 1. Photographs of gluten-free breadsticks incorporated with chicken meat at 0% (BC00), 20% (BC20), 30% (BC30), 40% (BC40), 50% (BC50), and 60% (BC60).

Microstructure

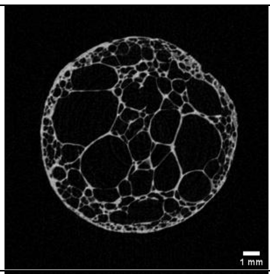
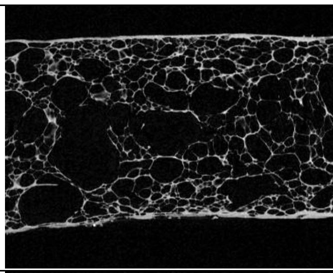
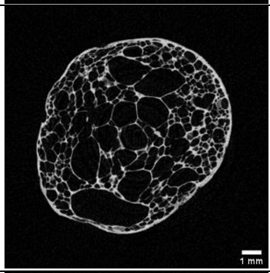
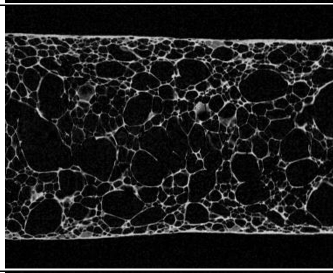
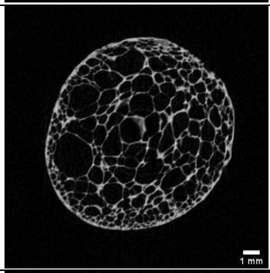
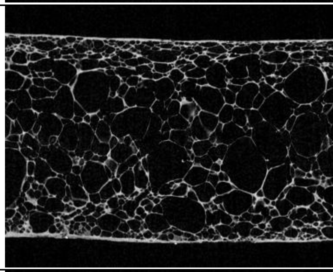
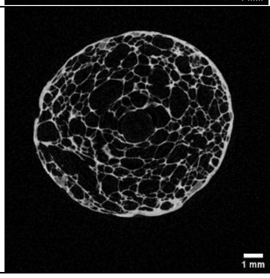
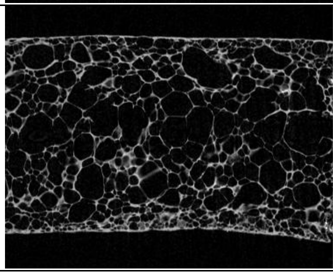
The effect of chicken meat incorporation on breadstick porosity was further investigated using micro-computed tomography (micro-CT). The results, illustrated through two-dimensional cross-sectional images, are presented alongside the quantitative porosity data in Table 3. Representative micro-CT images for both longitudinal and radial cross-sections revealed notable structural differences among the selected formulations. The control sample (BC00), which contained no chicken meat, exhibited the thinnest cell walls, and largest visible pore sizes compared to all other formulations. As the proportion of chicken meat increased, the cell walls became progressively thicker, and the pore sizes correspondingly smaller. However, no statistically significant differences in porosity were observed between the 40 and 60% chicken meat formulations. Among all samples, BC00 showed the highest porosity, characterised by large, irregular pores and a non-uniform internal structure. These results suggested that the high porosity of BC00 may stem from an open, interconnected gas cell network. This observation agreed with the findings of Wang *et al.* (2011), who reported that approximately 99% of bread porosity resulted from such interconnected pore structures. Therefore, the large average pore areas in BC00 were likely due to enhanced gas cell connectivity, which in turn influenced the textural and mechanical properties of the breadsticks.

These findings aligned well with those reported in related studies available in the literature. Pore size distribution in similar products has commonly been analysed through photographic or microscopic imaging techniques. For instance, Beck *et al.* (2018) demonstrated that up to 42% pea protein could be incorporated into fortified rice starch extrudates. In the present work, the observed decrease in bulk density and hardness of gluten-free breadsticks incorporated with chicken meat may be attributed to the increased rupture of developing air bubbles, resulting in greater surface porosity. Beck *et al.* (2018) suggested that protein-starch incompatibilities can compromise the structural integrity of bubble membranes during baking or extrusion. These incompatibilities increase the number of rupture points, potentially leading to a less uniform and more porous internal structure. Such interactions likely contribute to the observed textural changes in protein-incorporated breadsticks.

X-ray diffraction (XRD)

Various starch crystal types, shapes, the extent of starch melting and gelatinisation, and the extent of retrogradation have been studied using XRD. Each crystal type has its own unique diffractogram and peak intensities, as shown in a study by Dharmaraj *et al*. (2014). Crystallinity variations in the breadstick with different amounts of chicken meat (0, 20, 40, and 60%) were examined by analysing their diffraction

Table 3. 2D cross-sectional and longitudinal pore images of gluten-free breadsticks incorporated with different chicken meat at 0% (BC00), 20% (BC20), 30% (BC30), 40% (BC40), 50% (BC50), and 60% (BC60). Scale bar = 1 mm.

Breadstick sample	Radial direction	Longitudinal direction	% Porosity
BC00			57.21 ± 2.26[a]
BC20			56.01 ± 1.92[b]
BC40			54.94 ± 1.87[c]
BC60			54.18 ± 2.37[c]

Mean values with different lowercase superscripts in similar column are significantly different ($p < 0.05$).

patterns. Based on the diffraction principle, the intensity of peaks is determined by the quality of the organised semi-crystalline structures, and the differences in electron density between crystalline and amorphous lamellae (Adebiyi *et al*., 2016). As a result, peak intensity can be affected by both of these factors. In the present work, strong peaks were found to be associated with the crystalline region, and the diffused peaks shown to be associated with the amorphous portion of the breadstick samples investigated.

The XRD patterns of the breadsticks are presented in Figure 2. The diffraction pattern of the control sample without chicken meat (BC00) closely resembled that reported by Mihhalevski *et al.* (2012) for rye bread, exhibiting a characteristic double-peak pattern at 2θ angles of approximately 17° and 20° - 23°, indicative of B-type crystalline structures. In contrast, breadsticks containing chicken meat (BC20, BC40, and BC60) lacked a distinct peak at 17° 2θ. Instead, these samples displayed a broad, diffuse peak around 19° - 20° 2θ, corresponding to a V-type crystalline pattern, typically associated with amylose-lipid complexes in heat-processed cereal products.

This shift in crystallinity suggested that the incorporation of chicken meat altered the molecular organisation of starch, likely due to interactions between the added proteins and starch granules. The presence of V-type crystallinity in all chicken meat-containing samples indicated the transition from a more ordered B-type structure to a less ordered, heat-modified crystalline form. This transformation is characteristic of thermal processing, and may result from the disruption and partial reorganisation of starch crystallinity due to the gelatinisation and realignment of starch helices during baking (Adebiyi *et al.,* 2016). Moreover, all samples exhibited diffuse V-type peaks, supporting the hypothesis of increased thermal degradation, and a shift toward amorphous structure in the starch matrix. According to Sullivan *et al.* (2017), this is a predictable outcome of baking, leading to the loss of birefringence and crystallinity in starch granules. Similar reductions in crystallinity due to heat treatment have been observed in baked goods such as biscuits (Adebiyi *et al.,* 2016) and white bread (Sullivan *et al.,* 2017). Despite the limited number of XRD studies on bakery products, these findings indicated that starches in breadsticks without chicken meat retained a more crystalline and amorphous structure compared to those incorporated with chicken meat. Thus, XRD can serve as a valuable tool to assess the molecular organisation of starch in breadsticks, with the degree of crystallinity influenced by the protein content and thermal processing conditions.

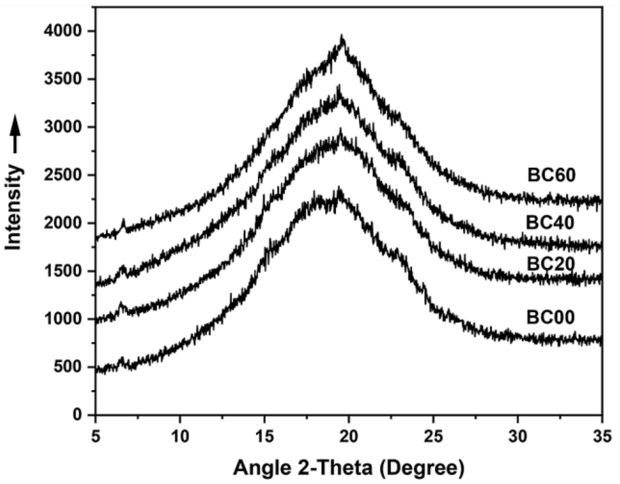


Figure 2. XRD patterns of gluten-free breadsticks incorporated with chicken meat at 0% (BC00), 20% (BC20), 30% (BC30), 40% (BC40), 50% (BC50), and 60% (BC60).

Descriptive sensory evaluation

A hedonic test was employed to evaluate consumer or panellist perceptions of the product, considering all key sensory attributes. The sensory panel assessed the following breadstick formulations: control (0% chicken meat) and samples containing 20, 30, 40, 50, and 60% chicken meat (Table 4). Significant differences were observed across the samples in terms of appearance, colour, taste, flavour, texture, and overall acceptability, indicating that varying levels of chicken meat incorporation had a pronounced impact on sensory characteristics.

Breadsticks incorporated with 40% chicken meat demonstrated significant improvements in appearance, colour, flavour, texture, and overall acceptability. However, these sensory attributes decreased when the chicken meat content was increased to 60%. The enhanced flavour scores observed with increasing chicken meat levels may be attributed to the intensified meat flavour derived from higher protein content and Maillard reaction products formed during baking. Notably, as the chicken meat content reached 50%, texture scores decreased markedly, likely due to the higher moisture content in meat-incorporated formulations compared to the control. The BC60 formulation exhibited a noticeably darker crumb and a less appealing overall appearance, a result of the high meat content. While moderate meat incorporation improved visual attributes, excessive incorporation had adverse effects. The increased presence of proteins and reducing sugars from chicken meat generally enhanced the breadsticks' susceptibility to aroma compound development *via* the Maillard reaction during baking (Roncolini *et al.,* 2019). These observations aligned with the findings of Umaraw *et al.* (2021), who reported a 30% linear increase in bread acceptability with chicken meat incorporation up to 30%, followed by a decrease at 35%. This suggested that while moderate incorporation enhanced product appeal, excessive incorporation may negatively affect key sensory characteristics.

The statistical analysis showed no significant differences among formulations BC40, BC50, and BC60 in terms of appearance, colour, taste, flavour, texture, and overall acceptability ($p > 0.05$), indicating that these samples could not be differentiated based solely on hedonic scores. The mean overall acceptability score for formulation BC40 was also not significantly different ($p > 0.05$) from those of the control sample and BC50. However, when considering the hardness and brittleness values presented in Table 2, breadsticks with higher chicken meat content exhibited a firmer and more brittle texture, along with a darker brown coloration. As a result, formulation BC40 was identified as the most appropriate candidate for further product development.

Table 4. Sensorial attributes for appearance, colour, taste, flavour, texture, and overall acceptance of gluten-free breadsticks incorporated with chicken meat at 0% (BC00), 20% (BC20), 30% (BC30), 40% (BC40), 50% (BC50), and 60% (BC60).

Parameters	Mean scores for acceptability				
	BC20	BC30	BC40	BC50	BC60
Appearance	6.60 ± 1.37^{b}	6.55 ± 1.32^{b}	7.53 ± 1.17^{a}	7.40 ± 1.12^{a}	7.08 ± 1.15^{a}
Colour	6.65 ± 1.29^{c}	6.73 ± 1.20^{bc}	7.60 ± 1.25^{a}	7.57 ± 1.11^{a}	7.15 ± 1.22^{ab}
Taste	6.95 ± 0.96^{a}	6.80 ± 1.02^{a}	7.22 ± 1.22^{a}	7.13 ± 1.16^{a}	6.90 ± 1.30^{a}
Flavour	6.98 ± 1.07^{b}	7.07 ± 0.97^{ab}	7.47 ± 1.17^{a}	7.22 ± 1.24^{ab}	7.28 ± 1.11^{ab}
Texture	7.25 ± 0.97^{ab}	6.95 ± 1.16^{b}	7.45 ± 1.17^{a}	7.28 ± 1.25^{ab}	7.05 ± 1.29^{ab}
Overall acceptance	7.17 ± 1.01^{ab}	7.05 ± 0.96^{b}	7.53 ± 1.03^{a}	7.22 ± 1.21^{ab}	7.07 ± 1.06^{b}

Mean values with different superscripts in the same low are significantly different ($p < 0.05$).

The control breadsticks received the lowest scores for both flavour and colour. Breadsticks incorporated with chicken meat achieved high overall acceptability scores, comparable to those of the control formulations, likely due to their elevated protein content. This increased protein level enhanced the formation of flavour-active compounds during baking. Specifically, the interaction between amino acids and reducing sugars through the Maillard reaction, combined with the presence of fat, contributed to the development of characteristic meat-like flavours that enhance sensory appeal. However, increasing the chicken meat content beyond 40% led to a slight decline in flavour scores, possibly due to the excessive formation of Maillard reaction products, which may introduce undesirable off flavours. Furthermore, the decrease in texture score may be attributed to the chicken protein forming a protective network around the partial gluten structure, leading to increased density and stickiness in the dough and the final baked products. A similar trend was observed by Liu *et al.* (2022), where the incorporation of more than 20% chicken protein powder into rye bread resulted in a significantly lighter brown crumb, and a slight but statistically significant increase in bitterness scores.

Therefore, the incorporation of chicken meat into breadstick formulations offered notable advantages in terms of enhancing protein content, and improving sensory attributes compared to formulations lacking meat. The development of functional bakery products requires not only physiological benefits, but also consumer acceptance in terms of appearance, flavour, and texture. To better understand the relationship between incorporation levels and sensory perception, further studies should be conducted across diverse consumer demographics.

Conclusion

The present work demonstrated that gluten-free breadsticks with high consumer acceptability could be produced using tapioca starch in combination with xanthan gum and guar gum. The present work focused on examining the interaction of chicken meat components at varying incorporation levels in the breadstick formulation. Incorporating tapioca flour-based gluten-free breadsticks with chicken meat could be a promising approach to enhance their nutritional profile, particularly in terms of protein content, while maintaining favourable sensory attributes. The incorporation of chicken meat led to significant increases in moisture content, ash content, protein content, hardness, bulk density, and yellowness compared to the control breadsticks. In contrast, lightness, redness (a* value), total colour difference (ΔE), and porosity decreased. The sensory characteristics of the breadsticks were markedly influenced by the incorporation of chicken meat, with the 40% chicken meat formulation yielding the most favourable results. This formulation not only exhibited a significantly higher protein content but also received the highest overall sensory acceptance. The XRD analysis revealed an increase in the intensity of V-type crystalline peaks with higher chicken meat incorporation, suggesting structural modifications in the starch matrix. These findings may inform the development of functional gluten-free bakery products that are both nutritious and appealing to consumers. Furthermore, optimising the formulation and processing parameters could further enhance the product's physicochemical and sensory qualities, thereby supporting public health, and driving interest in functional food innovations.

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References

Adebiyi, J. A., Obadina, A. O., Mulaba-Bafubiandi, A. F., Adebo, O. A. and Kayitesi, E. 2016. Effect of fermentation and malting on the microstructure and selected physicochemical properties of pearl millet (*Pennisetum glaucum*) flour and biscuit. Journal of Cereal Science 70: 132-139.

Beck, S. M., Knoerzer, K., Foerster, M., Mayo, S., Philipp, C. and Arcot, J. 2018. Low moisture extrusion of pea protein and pea fibre fortified rice starch blends. Journal of Food Engineering 231: 61-71.

Berwal, R. K. and Khanna, N. 2013. Production of value-added chicken meat mince incorporated cookies and their cost economics-benefit ratio. Pacific Business Review International 5(12): 61-70.

Bize, M., Smith, B. M., Aramouni, F. M. and Bean, S. R. 2017. The effects of egg and diacetyl tartaric acid esters of monoglycerides addition on storage stability, texture, and sensory properties of gluten-free sorghum bread. Journal of Food Science 82(1): 194-201.

Cakmak, H., Altinel, B., Kumcuoglu, S. and Tavman, S. 2013. Chicken meat added bread formulation for protein enrichment. Food and Feed Research 40: 33-41.

Cakmak, H., Altinel, B., Kumcuoglu, S., Kisla, D. and Tavman, S. 2016. Production of crispy bread snacks containing chicken meat and chicken meat powder. Anais da Academia Brasileira de Ciências 88(4): 2387-2399.

Carvalho, C. W. P. and Mitchell, J. R. 2001. Effect of sucrose on starch conversion and glass transition of nonexpanded maize and wheat extrudates. Cereal Chemistry 78(3): 342-348.

Chakraborty, P., Bhattacharyya, D. K. and Ghosh, M. 2021. Extrusion treated meal concentrates of *Brassica juncea* as functionally improved ingredient in protein and fiber rich breadstick preparation. LWT - Food Science and Technology 142: 111039.

Chevallier, S., Colonna, P., Della Valle, G. and Lourdin, D. 2000. Contribution of major ingredients during baking of biscuit dough systems. Journal of Cereal Science 31(3): 241-252.

Crockett, R., Ie, P. and Vodovotz, Y. 2011. How do xanthan and hydroxypropyl methylcellulose individually affect the physicochemical properties in a model gluten-free dough? Journal of Food Science 76(3): E274-E282.

da Rosa Machado, C. and Thys, R. C. S. 2019. Cricket powder (*Gryllus assimilis*) as a new alternative protein source for gluten-free breads. Innovative Food Science and Emerging Technologies 56: 102180.

Day, L., Cakebread, J. A. and Loveday, S. M. 2022. Food proteins from animals and plants: Differences in the nutritional and functional properties. Trends in Food Science and Technology 119: 428-442.

Dharmaraj, U., Parameswara, P., Somashekar, R. and Malleshi, N. G. 2014. Effect of processing on the microstructure of finger millet by X-ray diffraction and scanning electron microscopy. Journal of Food Science and Technology 51(3): 494-502.

Di Liberto, D., Carlisi, D., D'Anneo, A., Emanuele, S., Giuliano, M., De Blasio, A., ... and Lauricella, M. 2020. Gluten free diet for the management of non-celiac diseases: The two sides of the coin. Healthcare 8(4): 400.

El Khoury, D., Balfour-Ducharme, S. and Joye, I. J. 2018. A review on the gluten-free diet: Technological and nutritional challenges. Nutrients 10: 1410.

Fan, M., Hu, T., Zhao, S., Xiong, S., Xie, J. and Huang, Q. 2017. Gel characteristics and microstructure of fish myofibrillar protein/cassava starch composites. Food Chemistry 218: 221-230.

Farouk, M. M., Yoo, M. J. Y., Hamid, N. S. A., Staincliffe, M., Davies, B. and Knowles, S. O. 2018. Novel meat-enriched foods for older consumers. Food Research International 104: 134-142.

Hailemariam, A., Esatu, W., Abegaz, S., Urge, M., Assefa, G. and Dessie, T. 2022. Nutritional composition and sensory characteristics of breast meat from different chickens. Applied Food Research 2(2): 100233.

Hosseini Shekarabi, S. P. and Shahbazi, M. 2022. Partial substitution of wheat flour with fish protein powder influences physicochemical, rheological, and sensory properties of the flour, dough, and bread. Journal of Aquatic Food Product Technology 31(1): 2-18.

Kadam, S. U. and Prabhasankar, P. 2010. Marine foods as functional ingredients in bakery and pasta products. Food Research International 43(8): 1975-1980.

Khodaveisi, M., Bahramian, S. and Rokhzadi, A. 2024. Incorporation of common carp meat paste in bread formulation as a strategy to increase the usage of fish meat in the human diet and investigation of the physicochemical and organoleptic properties of bread. Human, Health and Halal Metrics 5(1): 1-8.

Knežević, N., Karlović, S., Takács, K., Szűcs, V., Knežević, S., Badanjak Sabolović, M. and Brnčić, S. R. 2024. Consumer satisfaction with the quality and availability of gluten-free products. Sustainability 16(18): 8215.

Korus, J., Chmielewska, A., Witczak, M., Ziobro, R. and Juszczak, L. 2021. Rapeseed protein as a novel ingredient of gluten-free bread. European Food Research and Technology 247(8): 2015-2025.

Liu, J., Tetens, I. and Bredie, W. L. 2022. Consumer perception and sensory properties of bakery products fortified with chicken protein for older adults. International Journal of Gastronomy and Food Science 27: 100484.

Marti, A. and Pagani, M. A. 2021. Nutritional challenges of gluten-free bakery products: A review. Trends in Food Science and Technology 110: 594-605.

Mihhalevski, A., Heinmaa, I., Traksmaa, R., Pehk, T., Mere, A. and Paalme, T. 2012. Structural changes of starch during baking and staling of rye bread. Journal of Agricultural and Food Chemistry 60(34): 8492-8500.

Rodríguez-Carrasco, Y., Font, G., Moltó, J. C. and Berrada, H. 2014. Quantitative determination of trichothecenes in breadsticks by gas chromatography-triple quadrupole tandem mass spectrometry. Food Additives and Contaminants Part A 31(8): 1422-1430.

Roman, L., Belorio, M. and Gomez, M. 2019. Gluten-free breads: The gap between research and commercial reality. Comprehensive Reviews in Food Science and Food Safety 18(3): 690-702.

Roncolini, A., Milanović, V., Cardinali, F., Osimani, A., Garofalo, C., Sabbatini, R., ... and Aquilanti, L. 2019. Protein fortification with mealworm (*Tenebrio molitor* L.) powder: Effect on textural, microbiological, nutritional and sensory features of bread. PLoS One 14(2): e0211747.

Sahagún, M. and Gómez, M. 2018. Assessing influence of protein source on characteristics of gluten-free breads optimising their hydration level. Food and Bioprocess Technology 11(9): 1686-1694.

Sakhare, S. B., Londhe, S. V., Chappalwar, A. M., Rindhe, S. N., Waghamare, R. N., Munde, V. K. and Patil, D. P. 2024. Development and quality assessment of chicken meat cookies enriched with various levels of rice flour. International Journal of Veterinary Sciences and Animal Husbandry 9(3): 507-510.

Shirley, R. B. and Parsons, C. M. 2001. Effect of ash content on protein quality of meat and bone meal. Poultry Science 80: 626-632.

Storck, C. R., da Rosa Zavareze, E., Gularte, M. A., Elias, M. C., Rosell, C. M. and Guerra Dias, A. R. 2013. Protein enrichment and its effects on gluten-free bread characteristics. LWT - Food Science and Technology 53(1): 346-354.

Sullivan, W., Hughes, J., Cockman, R. and Small, D. 2017. The effects of temperature on the crystalline properties and resistant starch during storage of white bread. Food Chemistry 228: 57-61.

Umaraw, P. and Chauhan, G. S. K. M. 2015. Protein enrichment of whole wheat bread with various forms of spent hen chicken meat. Indian Journal of Poultry Science 50(3): 276-281.

Umaraw, P., Chauhan, G., Mendiratta, S. K. and Verma, A. K. 2021. Optimization of processing conditions for development of chicken meat incorporated whole wheat bread. Journal of Food Science and Technology 58(7): 2792-2805.

Wang, S., Austin, P. and Bell, S. 2011. It's a maze: The pore structure of bread crumbs. Journal of Cereal Science 54(2): 203-210.

Witczak, T., Juszczak, L., Ziobro, R. and Korus, J. 2017. Rheology of gluten-free dough and physical characteristics of bread with potato protein. Journal of Food Process Engineering 40(3): e12491.

Yang, C., Zhong, F., Goff, H. D. and Li, Y. 2019. Study on starch-protein interactions and their effects on physicochemical and digestible properties of the blends. Food Chemistry 280: 51-58.