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DEVELOPMENT AND EVALUATION OF LOW-FAT CHICKEN BURGERS USING CHICKEN FEET MEAT AS A FUNCTIONAL FAT REPLACER

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Abstract
The increasing demand for healthier meat products has encouraged the development of innovative fat replacers in processed foods. This study evaluated the use of chicken feet meat, a collagen-rich poultry by-product, as a functional alternative to animal fat in chicken burger formulations. Two formulations were prepared: a control containing 20 % animal fat and a reformulated sample in which fat was replaced with 20 % chicken feet meat. Proximate composition, physicochemical characteristics, oxidative stability, microbial quality, and sensory attributes were assessed. Results demonstrated a significant reduction of fat (19.37 % → 4.81 %) and caloric value (249 → 131 kcal/100 g) in the reformulated burgers, accompanied by higher protein (15.18 % → 18.05 %), collagen (0.25 % → 1.12 %), and moisture contents (61.43 % → 71.84 %). Technologically, the reformulated product exhibited lower cooking loss, improved water-holding capacity, and a firmer texture. Microbiological analyses confirmed product safety during 90 days of frozen storage, with slightly lower bacterial counts and thiobarbituric acid (TBA) values indicating enhanced stability. Sensory evaluation demonstrated significantly higher scores for color, odor, taste, texture, and overall acceptability compared with the control. Furthermore, the reformulation offered a significant economic advantage by reducing raw material costs. These findings indicate that chicken feet meat is a cost-effective and sustainable fat replacer that enhances the nutritional profile, improves functional properties, and maintains consumer preference in chicken burgers. Beyond its health benefits, the valorization of chicken feet supports waste reduction and contributes to more sustainable poultry processing systems.

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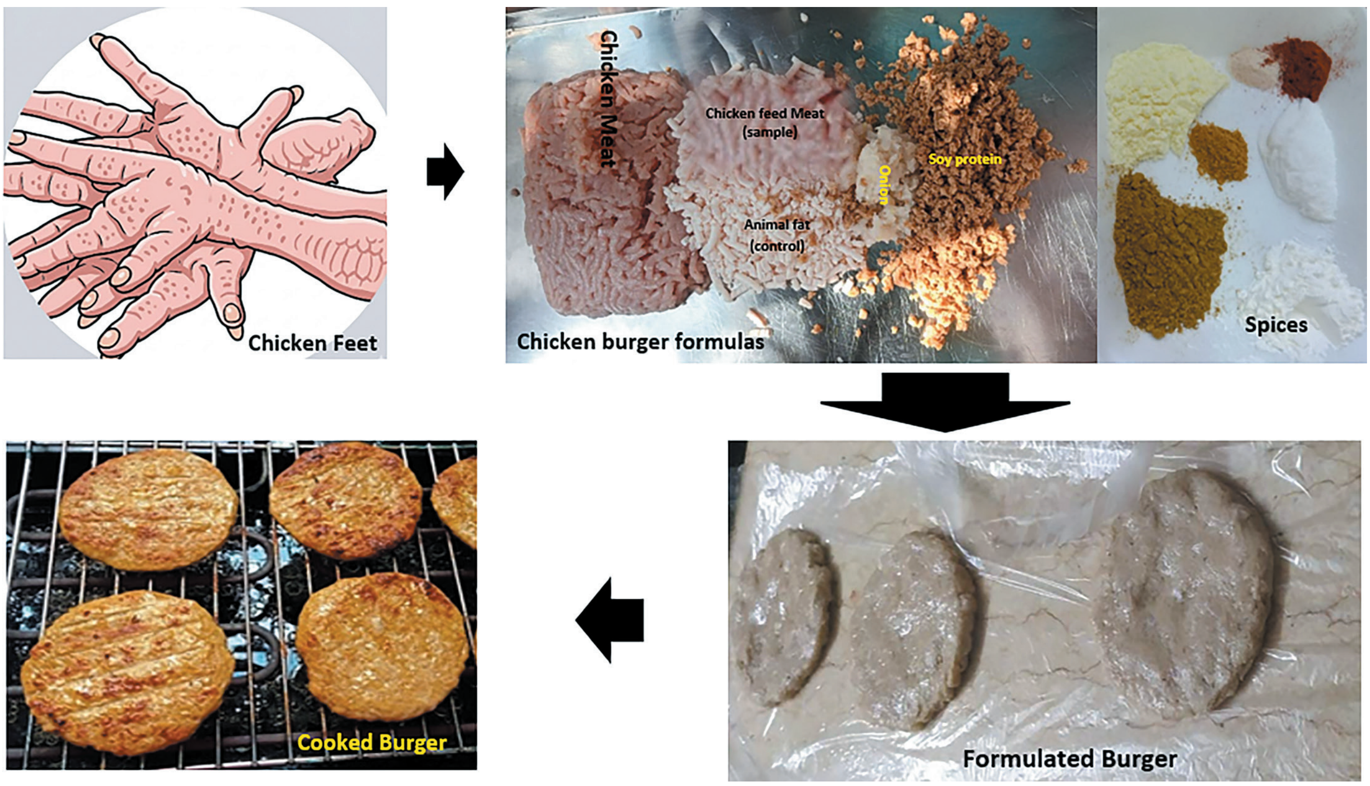
Graphical Abstract



Introduction

Chicken burgers have emerged as a globally popular food product, primarily due to their convenience, affordability, and high protein content, making them a staple in modern dietary habits. However, like many processed meat products, they are typically formulated with relatively high levels of animal fat — often exceeding 20 % of the formulation — to ensure desirable organoleptic properties. While fat contributes positively to juiciness, flavor, and texture, its excessive intake is strongly associated with obesity, cardiovascular disease, and other chronic health conditions, a link emphasized by recent global health guidelines [1]. Therefore, the development of low-fat chicken burgers that retain desirable sensory and technological properties is an important task for food scientists [2].

Numerous fat replacers have been explored to address the dual challenge of preserving sensory quality while improving nutritional profiles. Plant-based ingredients, such as olive oil, avocado, and flaxseed oil, are commonly employed to enhance the fatty acid composition by introducing beneficial unsaturated lipids, while animal-based substitutes like fish oil and poultry fat are utilized to boost flavor complexity. However, despite their nutritional and technological advantages, these alternatives often face significant limitations, including high formulation costs, susceptibility to oxidative rancidity during storage, and variable consumer acceptance due to potential textural deviations or off-flavors. Consequently, this has driven growing interest in utilizing sustainable, low-cost by-products — rich in bioactive compounds and dietary fibers — that can effectively improve product functionality while simultaneously addressing environmental concerns and promoting healthy meat formulations [3–5].

Chicken feet, a widely available poultry-processing by-product, are rich in collagen and proteins with unique gelling and water-binding properties. Collagen not only improves textural characteristics but also provides bioactive health benefits, including supporting joint health, bone density, and skin elasticity. Although collagen has been used in various food applications, limited research has investigated the direct use of chicken feet meat as a fat replacer in poultry-based products [6,7].

This knowledge gap highlights an opportunity to valorize chicken feet as a functional ingredient in meat processing. By incorporating chicken feet into chicken burger formulations, it may be possible to reduce fat content, improve nutritional value, and maintain consumer-preferred sensory qualities, while simultaneously contributing to waste minimization in the poultry industry. Accordingly, the objective of this study was to evaluate the effect of replacing 20 % of fat with chicken feet meat on the chemical composition, physicochemical characteristics, microbial stability, and sensory acceptability of chicken burgers. The findings aim to provide evidence for the development of healthier and more sustainable meat formulations.

Objects and methods

Objects

Fresh chicken breasts were procured from a local market and minced using a domestic meat mincer. A standardized spice mixture, salt, fresh onions, starch, powdered milk, and soybean were also sourced from the local market. Chicken feet were obtained from the same source and subjected to preliminary processing to ensure quality and safety. They were first soaked in water containing salt and vinegar to eliminate undesirable odors. Subsequently, they underwent a brief boiling treatment for 5 minutes to inactivate enzymatic activity and prepare them for further processing.

Chicken burger preparation

Chicken burger formulas (control and sample) were prepared by mixing well-minced chicken breast with different ingredients, which are presented in Table 1.

Table 1. Composition of formulated chicken feet burger

Ingredients	Control, %	Sample, %
Chicken breasts	60	60
Beef suet (kidney fat)	20	0
Chicken feet meat	0	20
Soybean flour	10	10
Minced onion	5	5
Salt	1.7	1.7
Spices	1.3	1.3
Milk powder	1	1
Starch	1	1

Chemical composition

Chemical composition (fat, protein, moisture, and collagen) of boiled chicken feet meat and samples of chicken burgers was determined using Food Scan™ Pro meat analyzer [8]. Ash content, representing the total mineral residue remaining after complete combustion of organic matter, was determined using the international standards [9]. Samples were subjected to dry ashing in a muffle furnace at 500–600 °C. The organic matter was incinerated in the presence of oxygen, resulting in the release of CO_2 and N_2, along with volatilization of water and organics. The residual ash was weighed and expressed as a percentage of the original sample mass.

Cooking loss

Cooking loss (%) was determined according to [10]. After grilling each sample, cooking loss (%) was calculated as follows:

$$\text{Cooking loss }\% = \frac{F - G}{F} \times 100\,, \qquad (1)$$

where: F — fresh burger sample weight (g); G — grilled burger sample weight (g).

Water holding capacity

The water holding capacity (WHC) of the samples was assessed using the filter paper press method, as described by [11]. A 0.3 g chicken burger sample was placed on ashless filter paper (Whatman No. 41) and subjected to a 1 kg weight for 10 minutes. The pressure created two distinct zones on the paper; their surface areas were quantified using a planimeter. The outer zone, representing exuded water, indicated WHC, while the inner zone reflected tissue plasticity. The WHC was calculated by deducting the area of the inner zone from the outer zone and reported in square centimeters (cm^2).

Thiobarbituric acid (TBA)

The quantification of thiobarbituric acid (TBA) was performed according to the protocol established by [12], with minor modifications. Briefly, 1 mL of the sample homogenate was combined with 2 mL of a stock reagent. This stock solution, containing 0.37% TBA, 15% TCA, and 0.25 N HCl, was gently warmed to 75 °C in a water bath SW22, (Julabo, Germany) to ensure the complete solubility of TBA. The reaction mixture was subsequently incubated in a boiling water bath for 15 minutes to allow for the development of a pink pigment. After cooling under running tap water and centrifuging at 2000 rpm for 15 minutes, the absorbance was recorded at 532 nm using a Unico UV-2000 spectrophotometer (Dayton, NJ, USA). TBA values were reported as mg of malonaldehyde per kg of chicken burger samples.

Tenderness and color

Tenderness was evaluated by measuring the shear force (N) using an Instron Universal Testing Machine (Model 2519–105, USA). Six replicates were analyzed for each sample, with the crosshead speed set to 200 mm/min [10]. Color measurements were obtained using a Chroma meter (Konica Minolta, Model CR 410, Japan), which was calibrated with a white tile and light trap according to the manufacturer's instructions. Color values were expressed using the CIE L*, a*, b*, C, and H color system [13], with five spectral readings recorded for each sample. Lightness (L*) ranged from 0 (dark) to 100 (light), while redness (a*) values ranged from positive (reddish) to negative (greenish). Yellowness (b*) values were also estimated, ranging from positive (yellowish) to negative (bluish). Furthermore, Chroma and Hue angle were calculated.

Microbial load

Microbial load was quantified using the Total Plate Count (TPC) method to assess product safety and hygienic quality. Enumeration was conducted via the pour plate technique using Plate Count Agar (PCA). The inoculated plates were incubated in an inverted position at 30 °C for 24–48 hours, and colony-forming units (CFUs) were subsequently enumerated. The microbiological analyses were performed under controlled ambient conditions (22.5 °C; 42.1% relative humidity), following the methodology described by [14].

Sensory evaluation

A structured sensory evaluation was conducted to assess the organoleptic properties and hedonic preference comparing a conventional chicken burger (control) with a reformulated low-fat prototype. A panel of twenty trained assessors evaluated the freshly grilled samples immediately after thermal processing. The evaluation focused on five key attributes: color, aroma, taste, texture, and overall acceptability. Quantification was performed using a 9-point hedonic scale (1 = 'dislike extremely'; 9 = 'like extremely'). To ensure standardized testing conditions and mitigate carryover effects, panelists were provided with individual utensils and scorecards, with water supplied for palate cleansing between successive samples [10,15,16].

Statistical analysis

All quantitative data were statistically analyzed using one-way analysis of variance (ANOVA) to determine significant differences among treatment groups. This method allowed for the comparison of mean values across the control and low-fat chicken burger samples. Differences were considered statistically significant at ($p < 0.05$). The ANOVA analysis provided a robust statistical basis for evaluating consumer acceptance scores, chemical composition, and microbiological data across multiple replicates [17].

Results and discussion

Chemical composition of boiled chicken feet

The proximate analysis of boiled chicken feet (Table 2) elucidates a nutritional profile highly conducive to application in meat product formulation, particularly for fat replacement and texture modification. The data highlights a significant presence of structural proteins and moisture that collectively suggest this by-product can serve as a functional ingredient capable of mimicking the technological roles of fat [18]. The most notable finding is the substantial collagen content (5.54%), a fibrous protein that plays a pivotal role in forming thermally irreversible gels upon heating, which is critical in low-fat formulations where fat reduction often leads to undesirable hardness and dryness; indeed, this high collagen content supports the ability to maintain structural integrity and juiciness. This corroborates observations by Araújo et al. [7], who demonstrated that collagen gel from chicken feet significantly improved water-holding capacity (WHC) in chicken sausages, and Sousa et al. [19], who noted that up to 50% of fat could be replaced using collagen without compromising sensory quality. Furthermore, the protein content (15.62%) and high moisture level (66.14%) observed in this study reinforce this potential. The high moisture is indicative of the tissue's ability to bind water, an essential function for yield and succulence, while the protein fraction acts as a natural binder to enhance matrix cohesion, aligning with Huff-Lonergan and Lonergan [20] on protein-water interactions. Additionally, Kim et al. [21] reported that chicken feet gelatin increased processing yield and succulence in semi-dried jerky, further supporting these findings. Regarding the moderate natural fat content (12.52%) and calculated caloric value (176 Kcal/100g), these figures suggest a promising profile for "light" meat products where the intrinsic fat contributes to mouthfeel and palatability without necessitating exogenous fat addition. This is consistent with Araújo et al. [22], who highlighted the nutritional and textural benefits of poultry connective tissue, and Mohammed et al. [23], who emphasized the value of chicken secondary products in enhancing nutritional quality. Ultimately, the chemical composition of boiled chicken feet, characterized by its unique balance of collagen, moisture, and protein, provides a robust scientific basis for its utilization as a fat replacer and functional additive in chicken burgers [24].

Table 2. Chemical composition of boiled chicken feet

Parameters	Boiled chicken feet
Collagen, %	5.54 ± 0.42
Fat, %	12.52 ± 0.06
Moisture, %	66.14 ± 0.16
Protein, %	15.62 ± 0.25
*Carbohydrates, %	0.18
Calories (Kcal /100 g)	176

* Calculated by difference; the experimental values (means and SD for $n = 3$).

Chemical composition and some physical properties of chicken burger formulas

Proximate composition and nutritional implications

The proximate analysis in Table 3 demonstrates a significant compositional shift in the reformulated chicken burger, primarily driven by the substitution of conventional animal fat with chicken feet collagen. The most pronounced change was the substantial reduction in fat content, decreasing from 19.37 % in the control to 4.81 % in the sample. This reduction aligns with the global recommendations of the World Health Organization (WHO) regarding limiting saturated fat intake to prevent cardiovascular diseases (CVDs) and supports the concept of producing healthier meat products with fat replacers [25]. Consequently, the caloric value of the product was reduced by nearly half (from 249 to 131 kcal/100 g), categorizing the reformulated product as a functional, low-calorie meat alternative.

The significant increase in collagen content (0.25 % to 1.12 %) is a direct result of the chicken feet incorporation, a by-product rich in connective tissue. Similar findings were reported by Araújo et al. [7], who noted that adding collagen gel extracted from chicken feet significantly increased the protein content and reduced fat in chicken sausages. Furthermore, the increase in moisture content from 61.43 % to 71.84 % can be attributed to the enhanced water-binding capacity of the collagen gel. This hydrophilic nature of collagen allows it to trap water molecules within the protein matrix, preventing exudation and improving juiciness, a phenomenon also observed by Pavanello et al. [26] in chicken burgers produced with hydrolyzed collagen as a partial fat substitute.

The protein content also increased significantly (15.18 % to 18.05 %), enhancing the nutritional density of the burger. The slight increase in ash content (0.31 % to 0.40 %) may be attributed to the mineral content present in the chicken feet, such as calcium and phosphorus, which are naturally higher in bone and cartilage tissues compared to pure muscle meat.

Functional properties, cooking loss and water holding capacity (WHC)

The functional properties of the reformulated burger showed marked improvements. Cooking loss was significantly lower in the sample (18.85 %) compared to the control (26.29 %). This improvement in cooking yield is a critical economic factor for the meat industry. The reduction in cooking loss is likely due to the formation of a stable gel network by the collagen and the increased protein matrix, which immobilizes water and fat, preventing their expulsion during thermal processing. These results corroborate the findings of Araújo et al. [7], where sausages formulated with chicken feet collagen gel exhibited superior water holding capacity and reduced cooking loss compared to standard formulations.

Water holding capacity (WHC), assessed via the filter paper press method, also indicated better performance in the sample (0.61 cm^2) compared to the control (0.92 cm^2). In this method, a smaller area of fluid release indicates superior water retention. This enhancement suggests that the collagen gel effectively replaces the lubricating and water-binding role of the removed animal fat, preventing the texture from becoming dry or gritty, which is a common defect in low-fat meat products. This observation aligns with Schmidt et al. [27], who developed reduced-fat chicken sausages with improved functional properties.

Textural profile (shear force)

The shear force analysis revealed that the reformulated burger was slightly firmer than the control (2.99 N vs. 2.42 N). This increase in hardness is a common outcome of fat reduction, as fat acts as a lubricant that softens the meat matrix. However, the increase in shear force in this study is likely also associated with the cohesive properties of the added collagen gel, which forms a rigid protein network upon heating. Kim et al. [21] reported that shear force in chicken jerky decreased with the addition of gelatin due to its plasticizing effect at high concentrations; however, in the current formulation, the gel content appears to reinforce the structure, providing a "bite" or firmness that is desirable in burgers. Similarly, Choe et al. [28] noted that the quality characteristics of reduced-fat sausages depend heavily on the type of fat replacer used. The pH values remained stable and within the optimal range for meat product stability (pH ~6.0), indicating that the reformulation did not adversely affect the acid-base balance required for protein functionality.

Color profile

Instrumental color evaluation (Table 4) showed a significant decrease in lightness (L*) in the reformulated sample (56.16) compared to the control (59.04). This darkening effect is typically expected in low-fat meat products because fat globules reflect light, contributing to a lighter appearance. Replacing beef suet with darker chicken feet and collagen-rich connective tissue results in a darker surface. However, the non-significant differences in redness (a*) and yellowness (b*) suggest that the core color pigment (myoglobin) was not significantly affected, preserving the visual appeal of the cooked meat product.

Lipid oxidation stability

TBA values showed a slight, non-significant reduction in the reformulated sample (0.22 mg MDA/kg) compared to the control (0.28 mg MDA/kg). While not statistically significant, this downward trend suggests that the collagen inclusion might possess mild antioxidant properties or that the reduction in total fat content provided fewer substrates for lipid oxidation. This is consistent with Araújo et al. [7], who reported that chicken feet collagen gel treatments had lower TBARS values and higher antioxidant activity compared to standard sausages during storage.

Finally, the reformulation of chicken burgers using chicken feet meat was successful in producing a low-fat, high-protein, and low-calorie product with superior functional properties. The improvements in cooking yield and water retention, coupled with acceptable textural and color profiles, suggest that chicken feet collagen is a viable and sustainable fat substitute in meat processing, offering a solution to valorize poultry by-products while meeting consumer demand for healthier meat options.

Table 3. Chemical composition and some physical properties of control and low fat chicken burger

Parameters	Control	Sample
Collagen, %	**0.25 ± 0.07^b**	**1.12 ± 0.14^a**
Fat, %	**19.37 ± 0.07^a**	**4.81 ± 0.02^b**
Moisture, %	**61.43 ± 0.10^b**	**71.84 ± 0.07^a**
Protein, %	**15.18 ± 0.04^b**	**18.05 ± 0.11^a**
Ash, %	**0.31 ± 0.11^a**	**0.40 ± 0.12^a**
*** Carbohydrates, %**	**3.46**	**3.78**
Calories (Kcal /100 g)	**249**	**131**
Cooking loss, %	**26.29 ± 0.23^a**	**18.85 ± 0.35^b**
WHC, cm²	**0.92 ± 0.20^a**	**0.61 ± 0.10^b**
pH	**6.03 ± 0.09^a**	**6.12 ± 0.08^a**
Shearing force, N	**2.42 ± 0.24^a**	**2.99 ± 0.44^a**
TBA, mg MDA/kg	**0.28 ± 0.05^a**	**0.22 ± 0.07^a**

*** Calculated by difference; WHC: Water Holding Capacity (cm²); TBA: Thiobarbituric Acid; The experimental values (means and SD for *n* = 3) with small letter are significantly different ($P \leq 0.05$).**

Table 4. Color values of control and low fat chicken burger

Parameters	Control	Sample
L*	**59.04 ± 0.38^a**	**56.16 ± 0.30^b**
a*	**2.76 ± 0.21^a**	**2.94 ± 0.10^a**
b*	**23.74 ± 0.85^a**	**22.35 ± 0.79^a**
C	**23.90 ± 0.82^a**	**23.13 ± 0.56^a**
H	**83.36 ± 0.68^a**	**82.48 ± 0.31^a**

The experimental values (means and SD for *n* = 3) with small letter are significantly different ($P \leq 0.05$).

Microbiological evaluation

Hygienic quality and safety assessment

The microbiological profile presented in Table 5 serves as a critical indicator of the hygienic conditions maintained during processing and the stability of the product during frozen storage. A primary safety criterion in meat products is the absence of coliform bacteria, which act as hygienic markers and potential indicators of fecal contamination. The non-detection of coliforms (ND) in both the control and the reformulated sample throughout the 3-month storage period underscores the high standard of hygiene employed during the manufacturing process. Also, Sheng et al. [29] emphasized the importance of monitoring microbial contamination in cooked chicken feet products, reinforcing the need for strict hygienic protocols when utilizing these by-products.

The total bacterial count (TBC)

The total bacterial count (TBC) was monitored to evaluate the shelf-life potential and microbial stability of the burgers under frozen storage conditions (–18 °C). Freezing acts as a hurdle technology that typically arrests or strongly retards microbial growth below about –10 °C, as *psychrotrophic* and *psychrotolerant* bacteria predominately remain metabolically inactive at such temperatures. However, certain *psychrotolerant* and psychrophilic bacteria can survive for extended periods and may undergo limited multiplication during handling or thawing episodes at mild refrigeration temperatures (around 4–7 °C), where growth of *psychrotrophic* microorganisms is still possible. In the current study, a gradual increase in TBC was observed in both groups over the 3-month storage period. This trend is likely attributable to the survival of cold-tolerant microorganisms and limited growth during thawing at 4 °C and subsequent handling, rather than continuous proliferation within the freezer. Despite this increase, TBC at the end of 90 days (6.7×10^5 CFU/g for the control and 5.6×10^5 CFU/g for the reformulated sample) remained below the typical spoilage threshold of 10^7 CFU/g, indicating that the products maintained an acceptable microbiological quality throughout storage, in line with reported data for frozen chicken meat products where TBC often ranges from 10^5 to 10^7 CFU/g depending on initial contamination and processing conditions [30,31].

An inhibitory or stabilizing effect of the reformulation is evident from the consistently lower TBC observed in the reformulated sample compared to the control at all sampling intervals (zero, one, two, and three months). At the initial stage, the reformulated sample recorded 2.7×10^2 CFU/g, compared to 3.4×10^2 CFU/g in the control. This difference persisted, culminating in the treated sample showing a lower load (5.6×10^5 CFU/g) than the control (6.7×10^5 CFU/g) by the third month. This suggests that the lower fat content (~5 % vs ~19 %) and the specific protein matrix of the chicken feet collagen may have reduced the availability of nutrients for *lipolytic* *psychrotolerant* bacteria and slightly limited their survival during repeated thawing–handling cycles. The reduction in total fat also limits the protective effect of lipid droplets against ice crystal damage, yet the overall microbial load remained within safe limits [30–34].

The microbiological data confirm that the reformulated chicken burger with chicken feet meat is safe for consumption and complies with hygienic standards. The absence of coliforms and the lower TBC compared to the control indicate that the processing conditions were hygienic and that the reformulation may contribute to a marginal improvement in microbial stability during frozen storage, in agreement with previous studies showing that formulation adjustments in reduced-fat poultry products are important for maintaining microbiological stability. These results support the practical application of this formulation as a safe, shelf-stable meat product, although the observed increase in counts emphasizes the importance of controlled thawing and handling practices to minimize microbial growth.

Table 5. Microbiological analysis of control and chicken feet burger

Targeted microbial group	Coliform CFU/g		Total bacterial count CFU/g	
	Control	Sample	Control	Sample
Zero time	N.D.	N.D.	3.4×10^2	2.7×10^2
After 1 month	N.D.	N.D.	4.5×10^3	3.8×10^3
After 2 months	N.D.	N.D.	5.3×10^4	5.1×10^4
After 3 months	N.D.	N.D.	6.7×10^5	5.6×10^5

* N.D.: not detected

Sensory evaluation

Overcoming the "low-fat" sensory barrier

Sensory evaluation is the ultimate determinant of a product's market viability, particularly when formulating low-fat meat products, as the removal of fat often leads to undesirable changes in texture, juiciness, and flavor. In this study, the reformulated sample, where 20 % of the animal fat was replaced with chicken feet meat, achieved significantly higher mean scores ($p \leq 0.05$) than the control in all evaluated attributes. This finding is of particular importance because it demonstrates that the functional fat replacer not only maintained but actively enhanced the organoleptic profile compared to the conventional high-fat formulation. These results contradict the common industry challenge where fat reduction typically correlates with lower consumer acceptance, confirming the success of the formulation strategy.

Texture and mouthfeel enhancement

One of the most critical challenges in producing low-fat meat products is maintaining a tender and juicy texture. The reformulated sample received a significantly higher texture score (8.8) compared to the control (8.4). This sensory improvement aligns with the proximate composition data, which showed a substantial increase in moisture content (71.84 %) and collagen content (1.12 %) in the reformulated burger. The high water-holding capacity (WHC) and the gel-forming ability of collagen derived from chicken feet likely prevented the product from becoming dry or rubbery during cooking. Instead, the collagen-protein matrix acted as a lubricant and moisture binder, mimicking the mouthfeel typically provided by animal fat. This supports the findings of Kim et al. [21] who reported that the addition of chicken feet gelatin to chicken jerky resulted in a significant decrease in shear force (increased tenderness), and Pavanello et al. [26] reinforced that hydrolyzed collagen improves the texture of reduced-fat chicken burgers.

Color, odor, and taste profiles

The superior color score of the reformulated sample (8.8 vs. 8.2) suggests that the browning reaction and visual appearance were optimized by the replacement. While instrumental color analysis (Section 3.2) indicated a slight reduction in lightness (L*), panelists evidently perceived the reformulated sample as more aesthetically appealing, possibly due to a richer, more "cooked" appearance resulting from the Maillard reaction facilitated by the protein-rich chicken feet.

Regarding odor and taste, the reformulated sample outperformed the control (8.6 and 8.8, respectively). This suggests that the inclusion of chicken feet meat did not introduce any off-flavors or "gamey" odors, which are often concerns when utilizing meat by-products. On the contrary, the enhancement in taste scores may be attributed to the retention of volatile flavor compounds within the improved gel network or the inherent flavor profile of the cartilaginous tissue. Kim et al. [21] found no significant differences in flavor scores when adding chicken feet gelatin to jerky, while Abedelmaksoud et al. [32] noted that additives in nuggets could maintain sensory acceptability up to certain limits. Choe et al. [28] also found that using skin and fiber mixtures as fat replacers maintained acceptable sensory profiles. In the present study, the chicken feet replacement appears to have synergistically enhanced the flavor profile, potentially compensating for the loss of fatty acids, which usually contribute to flavor richness in meat.

Overall acceptability

The ultimate measure of success, overall acceptability, was significantly higher in the reformulated sample (8.7) than in the control (8.4). This confirms that the health benefits (lower fat, higher protein) did not come at the expense of sensory pleasure. The data validates the hypothesis that chicken feet meat is not merely a low-cost filler but a value-adding ingredient that improves product quality. As concluded by Araújo et al. [7], the technological and bioactive properties of chicken feet collagen allow for the production of healthier meat products without compromising, and indeed potentially improving, the sensory characteristics desired by consumers. The sensory evaluation confirms that the reformulated chicken burger is superior to the conventional counterpart in terms of color, odor, taste, texture, and overall acceptability. The successful integration of chicken feet meat as a fat replacer overcame the textural defects typical of low-fat products, resulting in a juicier, more palatable, and healthier meat option with high consumer potential.

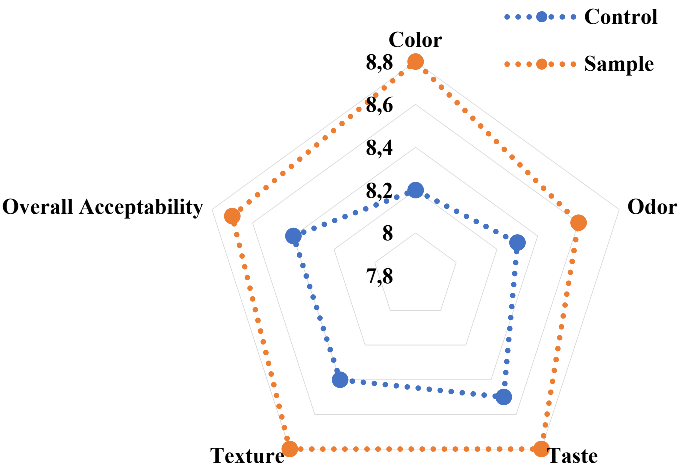


Figure 1. Organoleptic evaluation of control and chicken feet burger

TBA of control and samples during frozen storage (–18 °C) for 90 days

Progression of lipid oxidation during frozen storage

Lipid oxidation is a primary determinant of meat product quality, leading to rancidity, discoloration, and nutritional degradation. The thiobarbituric acid (TBA) values presented in Figure 2 and Table 8 reveal a progressive accumulation of malondialdehyde (MDA) in both formulations over the 90-day frozen storage period. This gradual increase, despite the low-temperature storage (–18 °C), confirms that oxidative reactions continue at a slowed pace over time. The mechanism is driven by the propagation of free radical chains within the lipid fraction and the interaction of these radicals with oxygen and proteins.

Superiority of the reformulated formulation can be seen from the fact that the reformulated chicken burger sample consistently exhibited significantly lower TBA values compared to the control ($p < 0.05$) throughout the entire storage duration. By the end of the storage period (Day 90), the control sample reached 0.84 mg MDA/kg, whereas the reformulated sample showed significantly lower values of 0.64 mg MDA/kg. This reduction in TBA values suggests that the reformulation strategy significantly enhanced the oxidative stability of the product. The superior resistance to oxidation in the reformulated sample can be attributed to two synergistic factors. First, the substantial reduction in total fat content (from ~19 % to ~5 %) reduced the substrate available for lipid peroxidation, thereby limiting the generation of secondary oxidation products. Second, the inclusion of chicken feet meat introduces functional bioactive compounds, specifically collagen and gelatin, which possess inherent antioxidant properties. Previous literature supports this mechanism. Nuñez et al. [33] and Araújo et al. [7] demonstrated that collagen and gelatin from animal sources can retard lipid oxidation in meat matrices. This antioxidant activity is often attributed to the ability of collagen-derived peptides to scavenge free radicals and chelate pro-oxidant metal ions [34,35], thereby interrupting the oxidative chain reaction. Pavanello et al. [26] and Rather et al. [24] further corroborated that such protein-based formulations effectively stabilize meat products against oxidative deterioration during storage.

Safety and rancidity thresholds

Notably, despite the increase in TBA values over time, all samples remained well below the critical threshold of 2 mg MDA/kg, which is generally considered the limit for the onset of perceivable rancidity in meat products [7]. This confirms that both the control and the reformulated burger maintained acceptable flavor profiles throughout the 90-day frozen storage period. However, the consistently lower TBA values in the reformulated sample suggest a longer window of sensory stability and a lower risk of off-flavor development compared to the high-fat control.

Economic and sustainability implications, cost-effectiveness and commercial viability

Beyond the chemical and sensory improvements, the economic analysis highlights the industrial relevance of this formulation strategy. The reformulated chicken burger demonstrated a distinct economic advantage, with raw material costs reduced from 180 L.E/kg in the control to 150 L.E/kg in the reformulated sample. This reduction of 30 L.E per kilogram (approximately 16.7 % cost savings) is significant in the highly competitive meat processing sector, where profit margins are often dictated by raw material costs. By substituting expensive animal backfat with lower-cost chicken feet, a by-product typically undervalued in the primary meat industry, the formulation offers a commercially viable solution for producing premium "healthier" meat products without the associated premium cost structure.

Valorization of poultry by-products

The economic advantage is intrinsically linked to environmental sustainability. Chicken feet constitute a significant volume of poultry slaughterhouse waste. The current study demonstrates a successful "waste-to-value" application, transforming chicken feet into a functional ingredient that enhances nutritional profile and oxidative stability. This valorization supports circular economy principles by reducing the environmental burden of waste disposal while creating a high-quality, sustainable food ingredient [23,24,36]. Finally, the reformulation of chicken burgers with chicken feet meat not only yields a product with superior nutritional quality, functional properties, and oxidative stability but also presents a compelling economic case for industrial adoption. The significant reduction in production costs, coupled with the valorization of a poultry by-product, positions this formulation as a sustainable, healthy, and economically advantageous alternative to conventional high-fat chicken burgers.

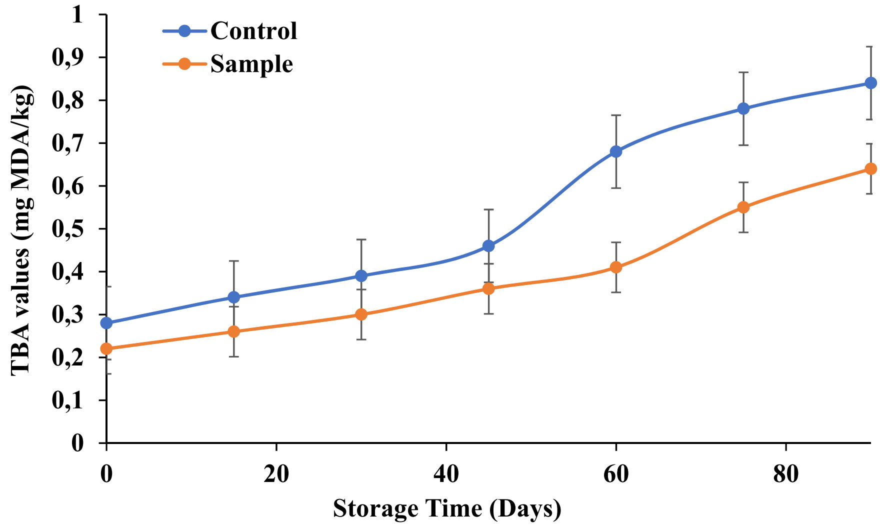


Figure 2. TBA values (mg MDA/kg) of control and low-fat chicken burgers during frozen storage (–18 °C)

Conclusion

This study successfully demonstrated the viable application of chicken feet meat as an innovative and functional fat replacer in chicken burger formulations. The substitution of animal fat with chicken feet resulted in a significant improvement in the nutritional profile, characterized by a marked reduction in total fat and caloric content alongside a substantial increase in protein and collagen levels. From a technological standpoint, the reformulated product exhibited superior functional properties, including enhanced water holding capacity, reduced cooking loss, and favorable textural firmness, which translated into improved juiciness and mouthfeel. Critically, sensory evaluation confirmed that the reformulated burger outperformed the control in all organoleptic attributes — color, odor, taste, texture, and overall acceptability — indicating that the health benefits were achieved without compromising, and in fact enhancing, sensory quality. Furthermore, the product demonstrated good microbiological safety with lower bacterial counts and enhanced oxidative stability, as evidenced by lower TBA values throughout frozen storage. The economic analysis further highlighted the cost-effectiveness of the formulation, reducing raw material costs by valorizing poultry by-products. Collectively, these findings validate chicken feet meat as a sustainable, functional, and economical alternative to animal fat, offering a significant contribution to the development of healthier, high-quality processed meat products.

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