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SUSTAINABLE STRATEGIES FOR THE USE OF ANIMAL BY-PRODUCTS IN MEAT PRODUCTS WITH HETEROGENEOUS STRUCTURE: APPROACHES TO COMBAT FOOD WASTE

Paul-Corneliu BOIȘTEANU, Elena-Iuliana FLOCEA, Mihai-Cătălin CIOBOTARU, Marius-Mihai CIOBANU

"Ion Ionescu de la Brad" Iasi University of Life Sciences, 3 Mihail Sadoveanu Alley, 700490, Iasi, Romania

Corresponding author email: marius.ciobanu@iuls.ro

Abstract

Food waste is a major problem that has negative effects on the environment and the global economy. In recent years, research has focused on promoting food circularity and sustainability. Animal by-products, with a valuable nutritional profile, offer significant potential to replace synthetic additives. This study examines the integration of beef fat from the meat industry bone by-products into heterogeneous meat products. Various fat proportions (2%, 4% and 6%) were investigated to assess the impact on the overall quality. Although some segments of the population reject fat-added meat products due to health concerns, the research aims to identify sustainable solutions that are both environmentally and health beneficial, thus contributing to a significant reduction in food waste.

Key words*: by-products, food waste, meat products.*

INTRODUCTION

Meat by-products are rich in bioactive peptides and functional ingredients, which can be valorized to improve meat product formulations (Boişteanu et al., 2025). Addressing regulatory and safety barriers is important for the effective utilization of these by-products, promoting sustainability in the meat industry, and in light of recent research on the impact of feed management technologies on mineral oil hydrocarbons (MOH) contamination, which highlights the importance of on-farm control measures to reduce risks and ensure food safety throughout the production chain (Gagaoua et al., 2024; Matei et al., 2024). The meat supply chain experiences substantial losses, with 20% of meat intended for consumption wasted (Pinto et al., 2022). By-products often end up in landfills or incineration, contributing to environmental pollution (Mohan & Long, 2021). Valorization of these by-products can lead to sustainable practices, reducing overall food waste and enhancing resource efficiency (Pinto et al., 2022; Mohan & Long, 2021; Gucianu et al., 2024). While the valorization of animal by-products presents numerous benefits, challenges remain in implementing these processes effectively across the meat supply chain (Gucianu et al., 2024). The potential for innovation in this area is significant, yet it requires careful management to ensure safety and sustainability (Boişteanu et al., 2024). Animal by-products, due to their rich nutritional profile, hold substantial potential as natural alternatives to synthetic additives (Zugravu et al., 2017). The sustainable strategies for utilizing animal by-products in meat products focus on valorization, regulatory frameworks, and innovative processing techniques. These strategies aim to transform waste into valuable resources, thereby enhancing the sustainability of the meat industry while addressing environmental concerns (Anchidin et al., 2024). Meat by-products can be processed to extract bioactive peptides, which have health benefits and can be incorporated into functional foods (Gagaoua et al., 2024). The meat industry is increasingly turning by-products into marketable items, including high-value ingredients for food and non-food applications (Baldi et al., 2021; Mohan & Long, 2021). The evolution of the rendering industry has led to the production of safe, high-quality products from animal by-products, contributing to a sustainable food chain (Woodgate, 2023). Innovations in processing techniques allow for the efficient conversion of by-products into valuable resources, such as biofuels and animal feeds, thus reducing waste (Mohan & Long, 2021; Jiang et al., 2020). Utilizing by-products can significantly lower greenhouse gas emissions associated with meat production, contributing to climate change mitigation (Jiang et al., 2020). While these strategies present significant opportunities for sustainability, challenges remain in consumer acceptance and the implementation of innovative technologies (Anchidin et al., 2024; Ciobanu et al., 2024; Ciobanu et al., 2025). Balancing economic viability with environmental responsibility is essential for the future of the meat industry.

MATERIALS AND METHODS

To achieve the objectives of the study, three samples with different percentages of fat (2%, 4%, 6%) resulting from the boiling heat treatment of bone by-products from the meat industry were realized. The fat obtained may represent a viable alternative to various synthetic components used to improve the final quality of food products. The raw material used was purchased on the local market and certified in accordance with European Union regulations on food safety and traceability of products of animal origin, including Regulations (EC) No 854/2004 and (EU) No 1169/2011. The experimental batches, together with the ingredients used and the heat treatments applied, are presented in Table 1. They were carried out in food processing and research workshops in compliance with the applicable regulations, including Regulations (EC) No 853/2004 on the hygiene of products of animal origin and (EC) No 854/2004 on official controls of products intended for human consumption, as well as other relevant food safety and hygienic processing regulations. The experimental samples involved the incorporation of fat obtained by boiling beef bone by-products to replace synthetic binding agents. The experimental samples include SF_1 - 2% fat introduced into the product; SF_2 - 4% fat introduced into the product; SF_3 - 6% fat introduced into the product, and the control sample, where no fat was introduced. The control sample and the experimental batches were subjected to the same heat treatment as shown in Table 1 and Table 2.

Table 1. Experimental batch formulation

Sample	Sample components			
	Raw material	Fat	Salt	Other ingredients
	%			
SM	96	-	2	2
SF_1	94	2	2	2
SF_2	92	4	2	2
SF_3	90	6	2	2

SM - sample control; SF1 - 2% fat; SF2 - 4% fat; SF3 - 6%

Table 2. The applied head tratament

Heat treatment stage	Time	Temperature inside the cell	Temperature in the thermal centre	Humidity
	minutes	°C	°C	%
Drying I	30	45	30	10
Smoking	40	55	40	10
Boiling	-	74	72	99
Drying II	10	80	72	10

The experimental samples were refrigerated for 24 hours and then subjected to laboratory analysis to evaluate the physicochemical profile. Gross chemical determinations included quantitative analysis of moisture, protein, collagen and salt content using near-infrared spectroscopy (NIR), a versatile and non-destructive method described by Gucianu et al. (2024). These determinations were performed using the Food Check meat analyser (Bruins Instruments, Germany). NIR spectroscopy refers to a region of the electromagnetic spectrum between 700 and 2500 nanometers, corresponding mostly to the colors red, orange, and yellow in the visible spectrum. In this range, various substances absorb and emit light, allowing significant interactions with biological materials and systems (Ciobanu et al., 2023).

The evaluation of the color characteristics of the samples was carried out using the MINOLTA Chroma Meter, model CR-410

(Konica Minolta, Osaka, Japan), according to the CIE Lab chromatic system. Parameters analyzed included L* (brightness: 0 - black, 100 - white), a* (positive values for red, negative for green) and b* (positive values for yellow, negative for blue). After calibrating the equipment with a white standard plate, CIELAB values were recorded for three samples. Color intensity (chroma) was determined by the formula: Chroma = $\sqrt{(a^2 + b^2)}$. The pH value was determined with a Hanna Instruments portable pH meter, model HI99163, by taking five measurements for each batch at different points of each sample, following the pH dynamics as a function of temperature. Texture parameters were analyzed using a Lloyd Instruments TA1Plus texturometer (AMETEK, UK), equipped with a force cell with a measuring capacity of up to 500 N. Testing was carried out at a constant speed of 100 mm/min with an initial extension of 90 mm. The equipment was operated using software version 4.1.5.999 and Embedded version 2.0.300. Data distribution was evaluated using SPSS Statistics software version 26.0 (IBM Corp., 2019). Statistical comparisons were performed using one-way analysis of variance (ANOVA) followed by the Tukey post-hoc test in IBM SPSS Statistics version 21. Differences were considered significant for p values < 05.

RESULTS AND DISCUSSIONS

According to the data presented in Table 3, the analyzed batches showed statistically significant differences. As expected, the fat content showed significant variations ($p < 0.05$) between the SM sample and SF_1, SF_2, and SF_3.

Table 3. Arithmetic mean ± standard deviation of the physicochemical parameters determined for the analysed batches

Physicochemical parameters					
%					
	Fat	Moisture	Protein	Collagen	Salt
SM	6.3±0.158^a	71.76±0.563^d	20.52±0.363^c	19.22±0.083^d	2.84±0.054^c
SF_1	8.62±0.311^b	70.42±0.311^c	20.36±0.054^c	18.64±0.054^c	2.64±0.134^b
SF_2	10.88±0.148^c	68.51±0.158^b	19.76±0.260^b	18.14±0.089^b	2.62±0.148^a
SF_3	14.02±0.083^d	65.74±0.421^a	19.14±0.089^a	17.36±0.054^a	2.62±0.044^a

Superscript letters that differ within the same column denote statistically significant differences, as assessed by one-way ANOVA followed by Tukey's multiple comparison test ($p \leq 0.05$). SM - sample control; SF_1 - 2% fat; SF_2 - 4% fat; SF_3 - 6% fat.

Fat incorporation was significant, influencing at the same time the other physico-chemical parameters of the product. This increase was accompanied by a statistically significant decrease in moisture content, indicating an inverse relationship between fat and water retention in the matrix. The dilution effect of the fat addition also contributed to a gradual decrease in protein and collagen concentrations, with the lowest values recorded in sample SF_3 (19.22% protein and 17.36% collagen, respectively). Salt content showed minimal variation, but significant differences were observed between samples, probably due to changes in water binding capacity and salt distribution in the modified matrix. These results suggest that the incorporation of rendered beef fat from bone by-products alters the overall composition of the product, with potential implications for both texture and nutritional profile. Despite the moderate protein reduction, the valorization of animal by-products contributes to a more sustainable production model and may offer functional benefits in terms of juiciness and palatability, provided consumer acceptance barriers are addressed (Manoliu et al., 2023).

The color parameters showed significantly influenced by the incorporation of beef fat obtained from bone by-products, as shown in Table 4. These changes highlight the impact of fat addition on the optical properties of the product, influencing consumer perception and overall appearance. Increased fat levels contributed to a brighter and more saturated color profile, which may enhance product appeal despite potential pigment dilution.

The brightness values L*(D65) were significantly increased in all reformulated samples (SF_1-SF_3) compared to the control (SM), with the highest value recorded in SF_1 (56.906), indicating a brighter appearance. This can be attributed to the presence of the added fat, which typically scatters light more efficiently in the matrix, increasing the perceived brightness. The parameter a*(D65) showed a slight but significant decrease, especially in the SF_3 sample (13.69) compared to the control SM (14.11). This reduction suggests a myoglobin pigment dilution effect due to the inclusion of fat. However, the differences were marginal, and the overall red appearance of the product remained visually acceptable.

b*(D65) values increased significantly with fat level, especially in SF2 and SF3 (13.37 and 13.53, respectively), indicating a shift towards a warmer color hue. Similarly, Chroma (C*), which expresses color saturation, was significantly higher in all samples with added fat compared to the control. The highest chroma value was observed in SF_1 (19.36), suggesting a more vivid and intense color perception in the reformulated product.

Table 4. The color results obtained from the analyzed batches of the reformulated product

	L*(D65)	a*(D65)	b*(D65)	Chroma (C*)
SM	55.65±0.755^{a}	14.11±0.105^{b}	12.17±0.181^{a}	18.64±0.020^{b}
SF_1	56.90±0.365^{b}	14.02±0.060^{b}	13.34±0.149^{b}	19.36±0.027^{a}
SF_2	56.74±0.241^{b}	13.84±0.396^{ab}	13.37±0.551^{b}	19.25±0.025^{a}
SF_3	56.72±0.330^{b}	13.69±0.104^{a}	13.53±0.157^{b}	19.25±0.013^{a}

Superscript letters that differ within the same column denote statistically significant differences, as assessed by one-way ANOVA followed by Tukey's multiple comparison test ($p \leq 0.05$). SM - sample control; SF_1 - 2% fat; SF_2 - 4% fat; SF_3 - 6% fat

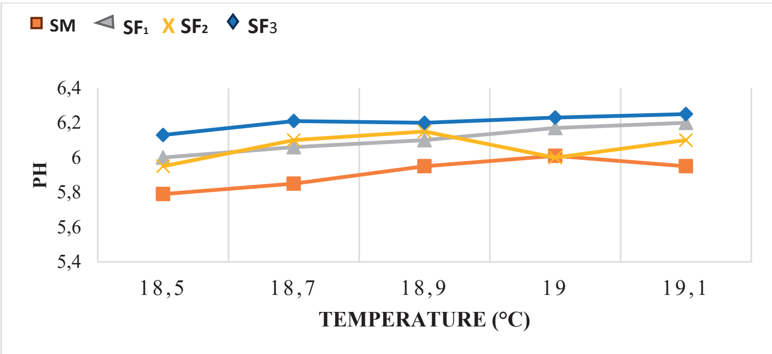

Figure 1. The pH variation at different temperatures (18.5-19.1 °C) for both the control samples (SM) and the experimental variants (SF_1, SF_2, SF_3)

Figure 1 illustrates the variation in pH at different temperatures (18.5-19.1°C) for the control samples (SM) and the reformulated ones (SF_1, SF_2, SF_3). All samples showed a general trend of increasing pH values with rising temperature. Notably, the sample with the highest fat content (SF_3) exhibited the most stable and highest pH values across the entire temperature range analyzed, suggesting a potential buffering effect provided by the added beef fat. In contrast, the control sample showed more pronounced pH fluctuations, which may indicate lower thermal resistance.

The incorporation of beef fat derived from bone by-products had a noticeable impact on the texture profile of the reformulated meat products in the absence of the edible membrane (Table 5). Among the analyzed parameters, hardness have results significantly from the control (SM: 10.61 N) to SF_1 (9.96 N). However, a slight decrease was observed at higher fat levels (SF_2 and SF_3), indicating a potential softening effect due to matrix restructuring at elevated fat concentrations.

Adhesiveness decreased progressively from the control to the SF3 sample, with statistically significant differences ($p \leq 0.05$), suggesting improved product handling and lower stickiness at higher fat levels.

This may be beneficial in terms of machinability and consumer acceptability. Springiness and cohesiveness were also affected. Springiness dropped from 0.36 (SM) to 0.17 (SF_3), while cohesiveness remained relatively stable, except for a slight decrease in SF_2. These changes indicate a tendency toward a less elastic and more deformable texture as fat content increased, possibly due to the weakening of the protein network.

Table 5. Evaluation of the textural profile of analyzed batches without edible membrane

Sample	TPA (Texture Profile Analysis)					
	Hardness (N)	Adhesiveness (N x mm)	Springiness	Cohesiveness	Gumminess (N)	Chewiness (J)
Without membrane*						
SM	10.61 ± 0.564^{a}	50.77 ± 0.602^{c}	0.36 ± 0.018^{d}	0.19 ± 0.029^{b}	1.67 ± 0.355^{a}	0.60 ± 0.122^{b}
SF_1	9.96 ± 0.356^{b}	46.99 ± 1.313^{b}	0.30 ± 0.019^{c}	0.22 ± 0.030^{b}	2.39 ± 0.262^{ab}	0.72 ± 0.090^{b}
SF_2	8.76 ± 1.662^{b}	44.74 ± 2.508^{b}	0.22 ± 0.013^{b}	0.17 ± 0.031^{ab}	1.68 ± 0.517^{b}	0.37 ± 0.101^{a}
SF_3	8.47 ± 0.871^{b}	41.55 ± 0.992^{a}	0.17 ± 0.158^{a}	0.23 ± 0.025^{b}	2.17 ± 0.186^{a}	0.37 ± 0.060^{a}

Superscript letters that differ within the same column denote statistically significant differences, as assessed by one-way ANOVA followed by Tukey's multiple comparison test ($p \leq 0.05$). SM - sample control; SF_1 - 2% fat; SF_2 - 4% fat; SF_3 - 6% fat; *edible membrane (natural) with a diameter of 28-30 mm.

Gumminess and chewiness, which are derived parameters combining hardness, cohesiveness, and springiness, showed variable responses. While gumminess values remained in a narrow range with no consistent trend, chewiness decreased significantly in the SF2 and SF3 samples compared to the control, which might indicate a softer, less resistant structure during mastication. Overall, the textural modifications observed in fat-enriched samples reflect a balance between structural reinforcement (at low fat levels) and softening effects (at higher fat inclusion). These outcomes suggest that the inclusion of beef fat from bone by-products can be optimized to improve or tailor textural properties, depending on the target sensory profile and processing characteristics. Covering the samples with an edible membrane significantly altered the textural profile of the reformulated products, particularly in combination with the fat level introduced (Table 6). Hardness values were considerably higher in all membrane-coated samples compared to their counterparts without membrane (Table 5), indicating that the edible casing contributed to a firmer structure. However, a progressive decrease in hardness was observed with increasing fat content, from 22.11 N in the control (SM) to 14.22 N in SF_3 ($p \leq 0.05$), suggesting that higher fat inclusion softens the internal matrix despite the structural contribution of the membrane.

Table 6. Evaluation of the textural profile of analyzed batches covered with edible membrane

Sample	TPA (Texture Profile Analysis)					
	Hardness (N)	Adhesiveness (N x mm)	Springiness	Cohesiveness	Gumminess (N)	Chewiness (J)
With membrane*						
SM	22.11 ± 1.044^{b}	48.39 ± 0.880^{c}	0.41 ± 0.031^{d}	0.24 ± 0.110^{a}	5.52 ± 2.564^{b}	2.31 ± 1.208^{b}
SF_1	20.53 ± 2.150^{b}	$44.50\pm0.\ 927^{b}$	0.33 ± 0.015^{c}	0.25 ± 0.036^{a}	5.26 ± 1.073^{b}	1.72 ± 0.304^{a}
SF_2	15.43 ± 0.307^{a}	41.89 ± 0.709^{a}	0.27 ± 0.013^{b}	0.28 ± 0.011^{a}	4.40 ± 0.212^{a}	1.27 ± 1.103^{a}
SF_3	14.22 ± 1.888^{a}	40.76 ± 0.379^{a}	0.20 ± 0.023^{a}	0.28 ± 0.052^{a}	4.03 ± 0.994^{a}	0.89 ± 0.164^{a}

Superscript letters that differ within the same column denote statistically significant differences, as assessed by one-way ANOVA followed by Tukey's multiple comparison test ($p \leq 0.05$). SM - sample control; SF_1 - 2% fat; SF_2 - 4% fat; SF_3 - 6% fat; *edible membrane (natural) with a diameter of 28-30 mm.

Adhesiveness followed a similar decreasing trend, with significantly lower values in SF_2 and SF_3. This behavior may be attributed to the higher lipid content reducing friction and stickiness, while the membrane itself could have contributed to a more cohesive and smoother surface texture. Springiness and cohesiveness were moderately affected by the treatments. Springiness values decreased significantly from 0.41 in SM to 0.20 in SF_3, indicating a reduction in the elastic behavior of the samples as fat content increased. Cohesiveness, on the other hand, remained statistically unchanged across batches, implying that the structural integrity of the internal matrix was preserved regardless of fat level or membrane presence. Gumminess and chewiness showed the same decreasing trend observed in membrane-free samples, with values significantly lower in SF_2 and SF_3 compared to the control. Chewiness dropped from 2.31 J (SM) to 0.89 J (SF_3), reflecting a more tender and less resistant texture, likely desirable in terms of sensory attributes. These results confirm that while the edible membrane enhances structural parameters such as hardness, its effect is modulated by the internal composition of the product, particularly fat content. Therefore, optimizing both membrane use and fat level offers a promising strategy to fine-tune the textural properties of heterogeneous meat products while sustainably valorizing by-products.

CONCLUSIONS

The inclusion of beef fat derived from bone by-products, combined with the use of an edible membrane, significantly influences the physicochemical and textural characteristics of reformulated meat products. At moderate inclusion levels (2-4%), fat contributes to a firmer structure and quality improvement by enhancing color intensity and brightness, while higher concentrations (6%) lead to texture softening and reduced elasticity. The edible membrane improves hardness and overall cohesiveness; however, its impact diminishes as fat content increases. Overall, optimizing fat proportion and membrane application can serve as a sustainable and functional strategy for valorizing animal by-products, reducing food waste, and developing products that replace synthetic additives. Upcoming research will aim to conduct an in-depth sensory evaluation of the product and determine its suitability for market introduction.

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