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DEVELOPMENT AND NUTRITIONAL CHARACTERIZATION OF BEEF BONE MARROW-BASED PRODUCTS: PLAIN AND SOY-ENRICHED FORMULATIONS

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Abstract

The valorisation of animal by-products into nutrient-dense foods has received increasing attention in food science due to its potential to enhance resource use efficiency and reduce food waste within sustainable food systems. This study aimed to develop a beef marrow-based spread and to evaluate its nutritional value in both a plain formulation and a soy-enriched variant (soy at a 1:2 ratio with bone marrow on a w/w basis). Beef marrow is rich in lipids, proteins, and bioactive compounds; however, its application in paste-based food products remains limited. Both formulations were analysed for total fat content, fatty acid profile and protein content, oxidative stability, and shelf life. Results indicated a predominance of unsaturated fatty acids (UFA) in both products. The plain formulation exhibited higher levels of polyunsaturated fatty acids (PUFA) and more favourable lipid quality indices, whereas soy enrichment increased protein content and the proportion of monounsaturated fatty acids (MUFA), thereby improving oxidative stability, likely due to increased oleic acid content. Compared with conventional animal fat sources, beef bone marrow exhibited a favourable UFA profile, supporting its nutritional value and potential application in food formulations. Overall, bone marrow represents a valuable animal by-product with strong potential for incorporation into circular food systems.

Key words*: alternative protein sources, food valorisation, lipid quality, nutritional enhancement.*

INTRODUCTION

In the context of the circular economy and sustainable food production, increasing attention has been directed toward the valorisation of slaughterhouse by-products as value-added food ingredients (de Oliveira, Lago, & Dal'Magro, 2021; Mohan & Long, 2021). Beef bone marrow is a lipid-rich by-product containing essential fatty acids and bioactive compounds, representing a concentrated source of energy and nutrients (Adeyeye, 2014; Hoa et al., 2026). Compared with other animal fats, bone marrow has been reported to possess a distinct lipid composition and nutritional profile, which may provide functional and technological advantages in food applications. Although beef bone marrow has been consumed since ancient times (Blasco et al., 2019) in various cuisines worldwide (Adeyeye, 2014; Zahra & Cacciafoco, 2026), scientific literature remains limited regarding its use as a processed food ingredient and the development of marrow-based products. In particular, little information is available on the physicochemical properties of bone marrow pastes and on formulation strategies designed to modify lipid content and improve nutritional balance.

In this context, the present study aims to develop a beef bone marrow paste in both a simple formulation and an enriched version containing soy to adjust the lipid content. Furthermore, the study evaluates its properties through physicochemical composition analysis and other relevant characteristics to highlight its potential as a value-added food ingredient.

MATERIALS AND METHODS

Raw Materials, Auxiliary Ingredients, and Processing Flow

For the preparation of a beef bone marrow paste product and its soy-enriched formulation, the ingredients and quantities used are presented in Table 1.

Table 1. Ingredients used for Beef Bone Marrow Paste Products

Specification	Unit	Simple beef bone marrow	Soy-enriched beef bone marrow
Bone marrow	g	419	419
Lemon juice	ml	105	105
Soybean	g	-	210
Salt	g	4.5	4.5
Pepper	g	2	2

For the preparation of one batch of bone marrow paste, 7.236 kg of veal bones containing marrow were used. For each formulation (plain or soy-enriched), one independent production batch was prepared. From each batch, three subsamples were collected, and from each subsample, three analytical replicates were performed for each determination. The bones were roasted in an oven at 180°C for approximately 30 minutes, after which the marrow was extracted and homogenised using a blender. The resulting mass was subsequently passed through a fine sieve to remove any residual bone fragments that may have remained after cutting. The amount of unfiltered marrow obtained was 1081 g, corresponding to a yield of 14.9%, while 838 g remained after filtration, corresponding to a usable (filtered) yield of 11.6%. These yields may vary depending on the type of bones used for marrow extraction (Adeyeye, 2014).

In the soy-enriched bone marrow spread, 100 g of soybeans were combined with 200 g of beef bone marrow. The soybeans were first soaked for 8 hours, then boiled for 2 hours, after which they were blended and mixed with the bone marrow. Immediately after preparation, the beef bone marrow spread was stored under refrigerated conditions at 4°C. All analyses, except those related to freshness determination, were performed on day 1.

Physicochemical Analysis of Beef Marrow Paste

Moisture, protein, and fat contents were determined using standard analytical methods: moisture by oven drying, protein by the Kjeldahl method, and fat by Soxhlet extraction. Freshness of the marrow paste was evaluated through acidity determination, the Kreiss test, and the Nessler reaction (Răducu et al., 2025).

Determination of peroxide value

The peroxide value (PV) was determined in the lipid fraction extracted from marrow paste samples using an iodometric titration method adapted from ISO 3960 for fat-rich food matrices. Lipids were extracted from homogenized samples using a chloroform solvent system, followed by solvent evaporation under reduced pressure. Approximately 2.0-5.0 g of extracted fat were dissolved in a mixture of glacial acetic acid and chloroform (3:2, v/v). Subsequently, 0.5 mL of saturated potassium iodide solution was added, and the mixture was maintained in darkness for 1 min with continuous agitation. After the addition of 30 mL of distilled water, the liberated iodine was titrated with 0.01 N sodium thiosulfate solution using starch as an indicator near the endpoint. A blank sample was prepared and analyzed under identical conditions.

Analysis of fatty acids compositions

Extraction of lipids from samples

The lipid extraction procedure followed the method described by Senila, Kovacs & Senila (2025) with minor modifications. Briefly, 3 g of sample were extracted with 50 mL of a chloroform: methanol mixture (2:1, v/v) and subjected to ultrasonic treatment (ISOLAB, Germany) for 15 minutes. After extraction, the mixtures were filtered, and the resulting liquid phase was further treated with 20 mL of 0.74% KCl solution. The extracts were then centrifuged at 5000 rpm for 10 minutes to separate the organic layer, which was subsequently filtered through anhydrous Na_2SO_4 to remove residual water. The solvent was evaporated using a rotary evaporator (Laborota 4010, Heidolph), and the recovered oil was dried in an oven at 60 °C.

Fatty acid methyl esters (FAMEs)

The fatty acid composition of the samples was analyzed by gas chromatography coupled with a flame ionization detector (GC-FID), following transesterification of fatty acids into their corresponding fatty acid methyl esters (FAMEs) using potassium methoxide. For this purpose, 0.06 g of each sample was dissolved in

isooctane, after which 0.2 mL of a 2 mol L^{-1} methanolic potassium hydroxide solution (CH_5KO_2) was added, and the mixture was vigorously shaken for 30 seconds. The reaction mixture was then treated with 1 g of sodium hydrogen sulfate monohydrate ($NaHSO_4 \cdot H_2O$) to prevent saponification of the methyl esters and to neutralize the excess alkali. Each oil sample was subjected to trimethylation and analyzed in triplicate. A standard reference mixture - Supelco 37 Component FAME Mix (CRM47885, Sigma-Aldrich) was used for chromatographic identification and calibration. The fatty acid contents are expressed as the relative percentage of each component, calculated by internal normalization of the chromatographic peak areas.

Determination of fatty acid methyl esters (FAMEs) content using GC-FID

The fatty acid methyl esters (FAMEs) content in samples were determined using a gas chromatograph with flame ionization detector (GC-FID) (Agilent Technologies, 6890N), equipped with a ZB-WAX capillary column (30 m x 0.25 mm x 0.25 µm). The carrier gas was helium at a constant flow rate of 1 mL min-1. The split ratio was 1:20, and the injected volume was 1 µl. The GC oven temperature program consisted of three stages: 60°C for 1 min, from 60 to 200°C (rate 10°C min^{-1}, 2 min), and from 200 to 220°C (5°C min^{-1}, 20 min). Both injector and detector temperatures were at 250°C to ensure complete vaporization of the sample and detection sensitivity. The retention times of the sample FAMEs were compared with those of the Supelco FAME standard mixture.

Nutritional Lipid Indices Derived from Fatty Acid Composition

To calculate the nutritional indices of the fatty acid profile, the Atherogenic Index (AI) was determined according to the formula presented below (Dal Bosco et al., 2024; Ulbricht & Southgate, 1991). This index is widely used worldwide for the evaluation of food products, including meat, seeds, fish, dairy products, and related foods.

$$AI = [C12:0 + (4 \times C14:0) + C16:0]/(UFA)$$

UFA – unsaturated fatty acids.

The Thrombogenicity Index (TI), proposed by Ulbricht and Southgate (1991), is used to evaluate the potential of a food to contribute to blood clot formation and associated cardiovascular risk.

$$TI = (C14:0 + C16:0 + C18:0)/[(0.5 \times MUFA) + (0.5 \times n\text{-}6)\ n\text{-}3) + (n\text{-}3/n\text{-}6)]$$

MUFA – monounsaturated fatty acids.

The Healthy Fatty Index (HFI) is used to analyze which types of fats are predominant in food products. Beneficial fats are assigned higher values, while a score below 1 is associated with saturated fatty acids (SFA), which indicate an increased risk of cardiovascular diseases.

$$HFI = (MUFA \times 2) + (n-6 \times 4) + (n-3 \times 8) + \frac{n-3}{n-6} / (SFA \times 1) + (MUFA \times 0.5) + (n-6 \times 0.25) + (n-3 \times 0.125) + \frac{n-6}{n-3}$$

Microbiological analyses

Materials

Selective and non-selective culture media used in this study included Plate Count Agar, chromogenic coliform agar, chromogenic *Staphylococcus aureus* medium, *Salmonella–Shigella* Agar, chromogenic *Listeria* medium, Bile Esculin Azide agar, chromogenic ESBL agar and Columbia agar. All media were obtained from BioMaxima (Poland).

Total Aerobic Plate Count (TAPC) was determined using the standard plate count method (Datta et al., 2012), briefly, 10 g of sample were aseptically weighed and homogenised in 90 mL sterile saline solution to obtain the initial 10^{-1} dilution. Subsequent decimal serial dilutions were prepared up to 10^{-6}. For enumeration, 1.0 mL aliquots from appropriate dilutions were inoculated into sterile Petri dishes, followed by the addition of molten Plate Count Agar using the pour plate technique (Jay, 2002). After solidification, plates were incubated aerobically at 37°C for 48 h. Plates presenting countable colonies were selected, and results were expressed as colony forming units per gram (CFU/g). In addition, the presence of specific foodborne and indicator bacteria was investigated using selective culture media. Serial decimal dilutions of homogenised samples were inoculated onto chromogenic coliform agar for detection of *Escherichia coli*, chromogenic *Staphylococcus aureus* medium

for presumptive *Staphylococcus aureus*, *Salmonella-Shigella* Agar (SSA) for *Salmonella* spp. and *Shigella* spp., selective chromogenic *Listeria* medium for *Listeria monocytogenes,* Bile Esculin Azide agar for *Enterococcus* spp., and chromogenic ESBL agar for screening of ESBL producing *Enterobacteriaceae*. In parallel, dilutions were also inoculated onto Columbia agar, used as a non-selective nutritive medium to allow recovery of stressed or injured bacterial cells and to screen for overall microbial growth. Plates were incubated aerobically at 37 °C for 24–48 h, and results were recorded as the presence or absence of characteristic growth. Microbiological determinations were performed at days 1, 3, 7, and 14 during refrigerated storage of the product.

Statistical analyses

All data were statistically analysed using the GraphPad Prism version 8.0.1 (GraphPad Software, San Diego, California, USA), the results are presented as mean values ± standard deviation (mean ± SD).

RESULTS AND DISCUSSIONS

Physico-chemical composition

The physico-chemical composition of bone marrow varies depending on the species (Adeyeye, 2014; West & Shaw, 1975), the type of bone from which it is extracted (Abd-El-Aal & Mohamed, 1989), the maintenance system (Steiner-Bogdaszewska et al., 2022), the age (Field et al., 1974), and the physiological state of the animal (Murden et al., 2017). Following physico-chemical analyses of the two varieties of beef bone marrow paste, we obtained, as expected, a higher dry matter (DM) content in the plain beef bone marrow paste and a higher water content in the soy-enriched formulation (Figure 1). The moisture content of beef bone marrow is not constant and may vary depending on the anatomical origin of the bone (Calhoun, Schnell & Mandigo 1998). Literature reports that flat bones (e.g., pelvis, ribs, vertebrae) contain a higher proportion of red marrow and thus exhibit higher moisture levels, whereas long bones (e.g., femur, tibia, humerus) predominantly contain fatty marrow characterized by lower water content. The water content of raw beef bone marrow is approximately 11.51 ± 0.31 % as reported for unprocessed material (Fuerniss et al., 2024) In contrast, in the present study the sample consisted of roasted beef bone marrow that was subsequently blended, sieved, and filtered, leading to a reduction in moisture content due to the removal of liquid fractions. Lemon juice was then incorporated during formulation. The resulting final processed product of the plain beef bone marrow paste had a mean moisture content of 12.83%.

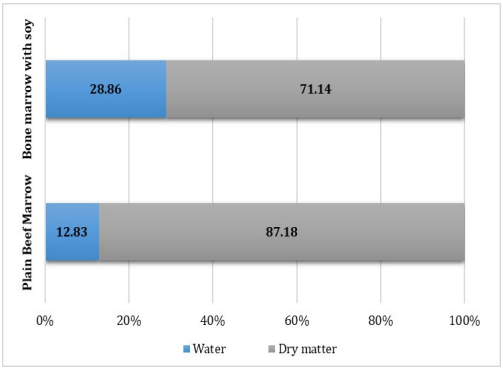


Figure 1. Water and dry matter content in plain and soy-enriched beef marrow pastes

In Figure 2, the chemical analyses of the two preparations are shown. Beef marrow is naturally highly lipid-rich, with the plain beef marrow paste exhibiting an average lipid content of 83.13 ± 1.78% (range 81.23-86.21%) on a wet basis. When expressed on a dry matter basis, this corresponds to approximately 95.4% (moisture 12.83%), confirming the strongly lipid-dominant nature of the product. Lipid content may vary depending on species, gender, and age of the animals. These findings are consistent with literature data reported by Adeyeye (2014), who described similarly high lipid levels in bovine marrow fat, with values of 98.7% in rams and 98.2% in bulls on a dry matter basis, highlighting natural biological variability between animal sources.

In the beef marrow paste formulated with soy, the average lipid content was lower, measuring 61.81 ± 4.49%. This was due to the addition of soy protein, with a minimum value of 54.30% and a maximum of 69.17%. In terms of protein content, it is generally quite low, given that marrow is primarily composed of lipids. For the plain beef marrow paste, the average protein content was 0.96 ± 0.05%, while in the

formulation containing soy, the average protein content increased to 6.06 ± 1.07%.

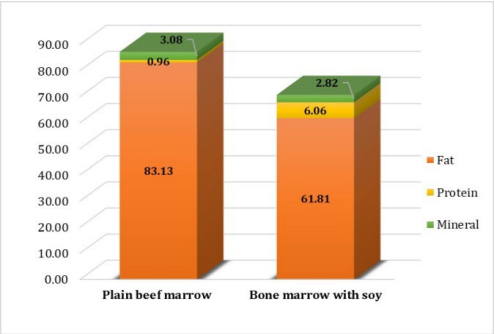


Figure 2. Chemical composition of plain and soy-enriched beef marrow pastes

The mineral content showed only small differences between the two beef marrow pastes, with values ranging from 2.36% to 3.87%. The plain beef marrow paste had an average mineral content of 3.08 ± 0.41%, whereas the beef marrow paste with soy showed a slightly lower average value of 2.82 ± 0.30%. The average salt content of the plain beef bone marrow paste was 2.26 ± 0.33 %, while the soy-enriched formulation exhibited a lower mean value of 1.62 ± 0.09%.

Fatty Acid Composition

Following the analysis of the two varieties of beef bone marrow paste (plain and soy-enriched), several differences can be observed regarding their nutritional value as well as the oxidative stability of the products (Table 2).

In both samples, oleic acid (C18:1 n-9) was identified as the predominant fatty acid. However, its concentration was considerably higher in the soy-enriched bone marrow paste (47.06%) compared with the plain beef bone marrow paste (31.47%). Scientific literature indicates that bovine bone marrow is naturally rich in oleic acid, with reported values ranging between 34.8% and 46.14% of the total fatty acid content, depending on factors such as the age of the animal, diet or bone type (Adeyeye, 2014; Küçük et al., 2018).

Oleic acid has been associated with reduced LDL cholesterol oxidation and moderate cardioprotective effects, being important from both nutritional (Xu, Xu, & Sohouli, 2026) and technological perspectives (Olmo-Cunillera et al., 2023).

Table 2. Fatty acid composition of beef bone marrow paste

Fatty acid	Soy-enriched	Simple
C8:0	-	-
C10:0	-	-
C11:0	-	-
C12:0	-	-
C13:0	-	-
C14:0	1.867	1.2799
C14:1 (n9)	-	-
C15:0	0.5533	0.4786
C15:1	-	-
C16:0	17.0526	19.1677
C16:1 (n7)	2.156	0.8487
C17:0	1.0707	2.4879
C17:1	0.1973	0.2353
C18:0	12.2186	7.3422
C18:1 (c+t) (n9)	47.062	31.4737
C18:2 (c+t) (n6)	13.0156	29.7971
C18:3 (n6)	0.3793	2.9385
C18:3 (n3)	1.3793	3.2013
C20:0	0.2781	-
C20:1 (n9)	0.5673	-
C20:2(n-6)	-	0.2156
C21:0	-	-
C20:4 (n6)	0.6726	0.5335
C20:3 (n3)	0.46253	-
C20:5 (n3)	0.40256	-
C22:0	0.66564	-
C22:1 (n9)	-	-
C22:2 (n6)	-	-
C23:0	-	-
C24:0	-	-
C22:6 (n3)+C24:1 (n9)	-	-
SFA	33.7	30.8
MUFA	50.0	32.6
PUFA	16.3	36.7
omega 6	14.1	33.5
omega 3	2.2	3.2
omega 9	47.6	31.5

SFA – saturated fatty acids; MUFA – monounsaturated fatty acids; PUFA –polyunsaturated fatty acids.

Palmitic acid (C16:0), the principal SFA in animal lipids, was identified at levels of 17.05% in the soy-enriched bone marrow paste and 19.17% in the plain beef bone marrow paste. These values are lower than those commonly reported for bovine adipose tissue and are closer to the values described for human and bovine bone marrow, where palmitic acid accounts for approximately 23-31% of the total fatty acids (Adeyeye, 2014; Griffith et al., 2009). Lower levels of Palmitic acid (C16:0) are considered favorable.

Linoleic acid (C18:2 n-6) showed considerably higher levels in the plain bone marrow paste

(29.80%) compared with the soy-enriched bone marrow paste (13.02%). The elevated omega-6 content largely accounts for the increased PUFA value and the higher HFI score of the plain bone marrow sample. Thermal processing may additionally contribute to modifications in fatty acid composition, as PUFA are particularly susceptible to oxidative reactions and thermal degradation (Fogerty et al.,1990).

Alpha-linolenic acid (C18:3 n-3) was also higher in plain bone marrow sample (3.20%) compared with soy-enriched bone marrow paste (1.38%). Although the levels are moderate, the presence of omega-3 fatty acids is important due to their anti-inflammatory and cardioprotective effects. It should be noted that C18:3n-3 (α-linolenic acid ALA) was the only omega-3 fatty acid detected in the plain formulation, with no longer-chain omega-3 fatty acids identified. Furthermore, C18:3 n-6 (γ-linolenic acid, GLA) was included in the total omega-6 fraction in both formulations, and its contribution was explicitly accounted for in the omega-6 calculation (0.3793% in the soy-enriched sample and 2.9385% in the plain sample). The omega-6/omega-3 ratio was 6.41 in the soy-enriched sample and 10.47 in the plain beef bone marrow paste. From a nutritional perspective, lower ratios are considered more favourable, as an excess of omega-6 fatty acids may promote the synthesis of pro-inflammatory mediators. Dietary recommendations generally suggest ratios below 4:1. Thus, although the plain bone marrow paste exhibited a higher HFI, the soy-enriched sample showed a more balanced fatty acid profile in terms of inflammatory potential. This imbalance may also be attributed to the applied thermal processing.

The MUFA/SFA ratio was significantly higher in the soy-enriched beef bone marrow sample (1.48) compared with the plain bone marrow paste (1.06), confirming the predominance of MUFA in the soy-containing product. Higher MUFA/SFA ratios are associated with improved oxidative stability and beneficial metabolic effects (Mensink & WHO, 2016).

The PUFA/SFA ratio was higher in the plain bone marrow paste (1.19) compared with 0.48 in the soy-enriched paste. According to nutritional guidelines, PUFA/SFA ratios above 0.45 are considered beneficial for cardiovascular health. Thus, both products may be regarded as nutritionally adequate; however, the plain bone marrow paste exhibited a greater enrichment in PUFA (WHO, 2003).

Nutritional Lipid Quality Indices

The calculated lipid quality indices indicated a relatively low atherogenic potential for both formulations. Both samples were characterized by a reduced content of atherogenic fatty acids and a higher proportion of unsaturated fatty acids. The plain beef marrow paste exhibited an AI value of 0.35, while the beef marrow paste with soy showed a slightly higher AI value of 0.37. It should be noted that the contribution of C12:0 was zero in both samples, as this fatty acid was not detected, and therefore did not influence the calculated index. Regarding the Thrombogenicity Index (TI), it is lower in plain beef bone marrow paste (0.65 vs. 0.80) compared to the beef bone marrow with soy variant, indicating a reduced tendency for thrombus formation and a more cardioprotective lipid profile. Their values are below 1, which suggests that beef marrow paste has a lower thrombogenic potential than most processed meat products, much lower than high-fat dairy products, and similar to the values reported for certain marine foods considered cardioprotective (Rashidimehr et al., 2025).

The Healthy Fatty Index (HFI) exhibited a higher value in the plain beef bone marrow paste sample (3.39), indicating a superior lipid profile. The beef bone marrow paste supplemented with soy showed a slightly lower HFI value (2.53); however, it demonstrated improved oxidative stability and a predominantly MUFA profile.

Overall, the results indicate that the plain beef bone marrow paste exhibits a more PUFA-rich lipid profile and higher nutritional index values, whereas the soy-enriched formulation provides enhanced oxidative stability and a more balanced fatty acid composition, characterized by the predominance of oleic acid and other monounsaturated fatty acids.

Freshness and Storage Stability

To determine the freshness level and storage period under refrigeration conditions, acidity, Kreiss, and Nessler reactions were assessed. As shown in Table 3, due to the high fat content of the marrow, the plain marrow paste exhibited weakly positive changes in both Kreiss and Nessler reactions starting from day 3, while the

acidity was considerably higher compared to pork fat or beef tallow.

The peroxide value of the plain beef bone marrow paste showed an initial increase from day 3, exceeding 10 meq O_2/kg by day 7, in agreement with the other freshness indicators. In contrast, the soy-enriched paste remained relatively stable until day 7, with peroxide values exceeding 10 meq O_2/kg only from day 14 onwards.

Table 3. Assessment of freshness changes in beef bone marrow paste (plain vs. soy-enriched) during storage

Day	Peroxide value meq O_2/kg		Acidity g oleic acid %		Kreiss		Nessler	
	A	B	A	B	A	B	A	B
1	5.28 ± 0.05	4.74 ±0.04	1.53	1.12	-	-	-	-
3	7.60 ±0.05	5.45 ±0.07	1.86	1.25	±	-	±	-
7	> 10	7.75 ± 0.05	2.56	1.47	+	±	+	±
14		> 10	2.78	1.64	++	+	++	+

A – Plain beef marrow; B – Soy-enriched beef bone marrow paste; (–) negative (fresh); (±) weakly positive (incipient deterioration); (+) positive (spoiled); (++) strongly positive (advanced spoilage stage).

This increased susceptibility can be attributed to the high lipid content, as foods rich in fats, particularly unsaturated fatty acids, are prone to oxidation, which leads to the formation of free fatty acids and other degradation products that contribute to rancidity and reduced shelf life (Geng, Liu & Zhang, 2023). Throughout the storage period, Total Aerobic Plate Count remained below the detection limit, and no detectable growth of specific foodborne or indicator bacteria was observed on any of the selective culture media used. *Escherichia coli*, *Staphylococcus aureus*, *Salmonella* spp., *Shigella* spp., *Listeria monocytogenes*, *Enterococcus* spp., and ESBL-producing *Enterobacteriaceae* were not detected at any sampling point. Similarly, no microbial growth was observed on the non-selective Columbia agar, indicating the absence of recoverable viable bacteria, including potentially stressed or injured cells.

CONCLUSIONS

This study demonstrates that beef bone marrow-based pastes, in both plain and soy-enriched formulations, possess distinct and tunable lipid profiles with potential relevance for the development of functional lipid-based foods. The plain formulation was characterised by a higher proportion of PUFA and more favourable nutritional lipid indices, whereas soy incorporation improved the MUFA's fraction and enhanced oxidative stability, likely associated with increased oleic acid content. From a valorisation perspective, beef bone marrow represents a high value animal by-product with strong potential for integration into circular food systems, contributing to resource efficiency through the transformation of a lipid-rich fraction into a functional food ingredient.

Compared with conventional animal fat sources, bone marrow exhibited a favourable fatty acid composition enriched in unsaturated lipids, supporting its nutritional relevance and potential application in reformulated fat-based products.

The study was conducted using a single production batch per formulation and a single thermal processing condition, which provides an initial controlled assessment of lipid composition. As such, the observed variability primarily reflects within-batch and analytical variation, while also indicating the need for future studies including multiple batches and a broader range of processing conditions further to strengthen the robustness and generalisability of the findings. In addition, sensory acceptability was not evaluated, representing an important direction for future work to better contextualise consumer relevance and application potential.

Furthermore, the omega-6/omega-3 ratio observed in the best-performing formulation (6.41) remains above the commonly recommended threshold of 4:1; however, this still reflects an improvement in fatty acid balance compared with conventional animal fat sources, highlighting the potential of formulation optimisation strategies to enhance the nutritional profile in future developments further.

Future research, including multiple independent production batches and optimised thermal treatments particularly milder and more controlled processing conditions may improve the robustness of the findings and allow a more comprehensive assessment of lipid stability and process-dependent changes, as well as sensory performance and consumer acceptability.

Overall, the findings highlight beef bone marrow as a promising sustainable raw material for the development of nutritionally enhanced lipid based products, with formulation dependent modulation of both nutritional quality and functional properties.

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