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RECEIVED 25 October 2025

REVISED 18 December 2025

ACCEPTED 04 February 2026

PUBLISHED 25 February 2026

CITATION

Koczka V, Marosvölgyi T, Szabó Z,
Dergez T and Szabó É (2026) Fatty acid
composition of ground-beef products
and their plant-based meat substitutes
available in Hungary.
Front. Nutr. 13:1732327.
doi: 10.3389/fnut.2026.1732327

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Fatty acid composition of ground-beef products and their plant-based meat substitutes available in Hungary

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Background: In recent years, plant-based diets have gained popularity. The food industry has responded by introducing a range of alternative products that significantly differ from whole-food, plant-based diets in terms of their composition and processing levels. This study aimed to compare the fatty acid composition and fatty acid-based nutritional quality indices of ground beef-based foods with those of their plant-based counterparts available in the Hungarian market.

Methods: This study examined six plant-based and four beef hamburger patties, along with one plant-based and one beef minced meat product, each with three distinct expiration dates. Following homogenization and lipid extraction, the fatty acid composition was analyzed by gas chromatography. Based on the fatty acid values, several nutritional indices were calculated, including the unsaturation index (UI), atherogenicity index, thrombogenicity index, and hypocholesterolemic/hypercholesterolemic index (hHI).

Results: Significant differences ($p < 0.01$) in fat content were observed between plant-based and animal-based products, based on both label information and gravimetric measurements (plant-based: 10.25% [8.60%; 14.87%], animal-based: 19.67% [16.16%; 26.68%], median [Q1; Q3]). Distinct fatty acid composition profiles were identified between and within the product groups for both animal- and plant-based products. Except for one product, plant-based alternatives exhibited higher UI and hHI (UI: 129.62 [96.84; 146.10]; hHI: 50.13 [45.69; 54.14]) than beef-based products (UI: 8.18 [3.13; 11.59]; hHI: 1.35 [1.23; 1.43]).

Conclusion: The findings indicate that plant-based meat alternatives (except those containing coconut oil) have lower saturated and higher polyunsaturated fatty acid compositions than beef-based products, leading to more beneficial nutritional value. Further analytical and clinical studies are necessary to provide a more comprehensive understanding of the long-term health effects of these foods.

KEYWORDS

fatty acid, lipid content, nutritional index, plant-based diet, plant-based meat alternatives, polyunsaturated fatty acid, vegan products

1 Introduction

Meat consumption has been essential to human evolution, serving as a vital source of macro- and micronutrients (1). The essential nutrients found in meat, including high-quality protein, heme iron, essential fatty acids, vitamin B12, other B vitamins, retinol, zinc, and bioactive compounds such as creatine and carnosine, may have contributed to the development of the large human brain and supported cognitive functioning and physical growth (2). Over the past two decades, the global population has grown, and rapid economic development has driven meat demand up by nearly 60%, surpassing 360 million tons, with further growth anticipated. Large quantities of beef, pork, and poultry are consumed worldwide. Industrial meat production significantly contributes to greenhouse gas emissions, deforestation, and biodiversity loss, making it a critical factor in sustainability (3–5).

Excessive meat consumption poses risks to both the environment and human health. The World Health Organization's International Agency for Research on Cancer (IARC) has classified processed meat as carcinogenic and red meat as probably carcinogenic, primarily because of the evidence linking them to colorectal cancer (6). Furthermore, the consumption of red and processed meat may adversely affect the incidence of cardiovascular diseases (7), type 2 diabetes (8), and various other cancers, including esophageal, gastric, lung, and breast cancer (9–12).

Recent studies have highlighted the protective effects of substituting animal protein sources with plant-based sources against certain diseases and mortalities (13–16). The demand for plant-based meat substitutes (PBMS) is increasing as consumers seek healthier, more sustainable, and ethical alternatives (17, 18). These products offer solutions to the challenges associated with meat production and the adverse health effects of excessive meat consumption (19).

The fatty acid (FA) composition of foods varies and plays a crucial role in nutrition. A high intake of certain saturated fatty acids (SFA) is associated with elevated low-density lipoprotein (LDL) cholesterol levels and an increased risk of cardiovascular disease (20–22). Conversely, the consumption of monounsaturated and polyunsaturated fatty acids (MUFA and PUFA, respectively) is associated with improved blood lipid profiles and a reduced risk of cardiovascular disease and metabolic disorders (23, 24). Consequently, dietary guidelines recommend limiting SFA (and eliminating *trans* fats) while emphasizing the importance of adequate PUFA consumption for cardiovascular health (25, 26). Among PUFAs, essential fatty acids (EFAs) cannot be synthesized by the human body and must be obtained from the diet. Both omega-6 (n-6) essential linoleic acid (C18:2n-6, LA) and omega-3 (n-3) essential alpha-linolenic acid (C18:3n-3, ALA), along with their most important longer-chain derivatives, arachidonic acid (C20:4n-6, AA), eicosapentaenoic acid (C20:5n-3, EPA), and docosahexaenoic acid (C22:6n-3, DHA), have demonstrated beneficial health effects that can influence various aspects of human physiology (27–30).

PBMSs contain various vegetable oils and fats that replicate the juiciness and flavor of meat products. Common fat ingredients include coconut, rapeseed, sunflower, soybean, and palm oil. The choice of fat source determines the FA profile of the final product, which can vary significantly. When coconut or palm oil is used, the composition contains a higher proportion of SFAs, whereas in other cases, MUFAs and PUFAs predominate in different proportions (31–33). According to the NOVA classification (34), most PBMS, although not all, are

considered ultra-processed foods, similar to meat-based burger patties, raising questions about their health impacts (35, 36).

To date, few studies have examined the composition of plant-based meat substitutes using analytical techniques. While some authors have focused on mineral (31, 37–39), protein (31, 37), or fatty acid content (40, 41), others have determined the major macro- and micronutrients (38).

Given the increasing prevalence of PBMSs in Hungary and the limited availability of analytical studies on this topic, this study aimed to investigate the differences in fat content and FA composition between minced beef-based products (BBPs) and PBMSs. Understanding the nutritional differences between these substitutes and traditional meat products is crucial. Therefore, we also aimed to compare the fatty acid-derived nutritional indices of these products.

2 Materials and methods

2.1 Sample collection

The selection criteria targeted chilled (non-frozen), semi-finished products of both plant and animal origins, including all locally available products in the selected stores. Between August and October 2023, seven plant-based and five animal-based products were purchased from leading food retail chains in Pécs, Hungary. The included products were hamburger patties, but there was also one minced product from each origin. Three separate samples of each product with different expiration dates were collected to account for the potential batch variability. All products were purchased in vacuum-packed form, transported to the laboratory in a cooler bag, and stored at 5 °C until further processing before their expiration date. Homogenization was performed using an electric meat grinder by running each sample through the machine twice. The grinder was thoroughly cleaned between samples to prevent cross-contamination. The homogenized samples were stored at –80 °C until chemical analysis.

2.2 Reagents and standards

The reagents used in this study have been previously described (33). Fatty acid methyl esters (FAMES) were analyzed by calculating the area under the curve (AUC). Fatty acids were identified based on the retention times of external standards, including the 37 Component FAME Mix (Supelco Merck KGaA, Darmstadt, Germany), The Bacterial Acid Methyl Esters CP Mixture (Matreya LLC., State College, PA, USA), and GLC-463, –473, and –674 (Nu-Check-Prep, Elysian, MN, USA). Peaks were identified by comparing them with authentic mixtures of the weighed FAME methyl ester, and the individual FA response factors, determined from these weighed standards, along with the percentage AUC (relative concentration; w/w%), were used to calculate the weight percentage of each determined FA (42).

2.3 Lipid extraction and fatty acid analysis

We measured 100 mg of pre-homogenized material using a precision analytical balance (OHAUS Explorer EX225D/AD) and placed it in a specialized tissue grinder (KIMBLE Dounce). The material was further crushed and transferred into a pre-weighed

screw-cap test tube, with 2.5 mL of chloroform added in several portions. Subsequently, 2.5 mL of methanol was introduced into the test tube and incubated at 37 °C for 20 min. Subsequently, 1.25 mL of water was added, and the mixture was incubated in a refrigerator for 20 min. The test tubes were then centrifuged at 3000 RPM for 15 min at 4 °C (Sanyo-Harrier 18/80, refrigerated). The lower chloroform phase, which contained the lipids, was extracted using a Pasteur pipette and transferred to a pre-weighed tube for further analysis. Chloroform was removed using nitrogen in an automatic evaporator (Biotage TurboVAP). The tube containing the dry, evaporated lipids was weighed to a constant weight on an analytical balance, and the lipid content of the sample was calculated.

We added 5 mL of chloroform to the tubes containing a known amount of lipids that had been evaporated to dryness. After homogenization, we measured a solution with 1 mg of lipids in a screw-top test tube and evaporated the chloroform. The steps for converting lipids to methyl esters have been described previously (33). The fatty acid composition was determined using a Thermo Trace 1,300 gas chromatograph (GC) equipped with an autosampler AI1310, flame ionization detector (FID), and programmed temperature vaporization (PTV) injector. Separation was achieved using a capillary column (Agilent J&W VF-23 ms, 60 m × 0.25 mm × 0.25 μm; Agilent J&W Scientific, Folsom, CA, USA). The column oven temperature was initially set at 120 °C for 2 min, then increased to 250 °C at a rate of 3 °C·min⁻¹, and held at 250 °C for 3 min. The carrier gas was H₂ at 1.8 mL/min. Fatty acids were determined in the range of C6:0 to C26:0. The fatty acid composition of each sample was determined based on 12 chromatograms (two parallel runs of the samples after two independent analytical procedures from samples collected on three different dates). Chromatograms were evaluated using Chromeleon 7.1 software (version 7.1, Thermo Fisher Scientific, Sunnyvale, CA, USA).

2.4 Nutritional index calculation

The nutritional indices of fatty acids were calculated based on the formulas published by Chen et al. (43) and the Healthy Fatty Index (HFI) by Dal Bosco et al. (44), as follows:

Essential fatty acids (EFA):

$$EFA = C18 : 2n - 6 + C18 : 3n - 3$$

n-3/n-6 polyunsaturated fatty acid (PUFA) ratio:

$$\frac{\Sigma n - 3 \text{ PUFA}}{\Sigma n - 6 \text{ PUFA}}$$

Σn-3 PUFA denotes the sum of n-3 polyunsaturated fatty acids (C18:3n-3 + C20:5n-3 + C22:5n-3 + C22:6n-3).

Σn-6 PUFA denotes the sum of n-6 polyunsaturated fatty acids (C18:2n-6 + C18:3n-6 + C20:2n-6 + C20:3n-6 + C20:4n-6 + C22:2n-6 + C22:4n-6).

Unsaturation index (UI):

$$UI = 1 \times (\% \text{ monoenoics}) + 2 \times (\% \text{ dienoics}) + 3 \times (\% \text{ trienoics}) + 4 \times (\% \text{ tetraenoics}) + 5 \times (\% \text{ pentaenoics}) + 6 \times (\% \text{ hexaenoics}).$$

monoenoics:

$$C14:1n-5 + C15:1n-5 + C16:1n-7 + C17:1n-7 + C18:1n-$$

$$12 + C18:1n-9 + C18:1n-7 + C20:1n-12 + C20:1n-9 + C22:1n-9;$$

$$\text{dienoics: } C18:2n-6 + C20:2n-6 + C22:2n-6; \text{ trienoics: } C18:3n-3 +$$

$$C18:3n-6 + C20:3n-6; \text{ tetraenoics: } C20:4n-6 + C22:4n-6; \text{ pentaenoics: } C20:5n-3 +$$

$$C22:5n-3; \text{ hexaenoics: } C22:6n-3.$$

Atherogenicity index (AI):

$$AI = \frac{C12 : 0 + 4 \times C14 : 0 + C16 : 0}{\Sigma \text{UFA}}$$

ΣUFA denotes the sum of unsaturated fatty acids (C14:1n-5 + C15:1n-5 + C16:1n-7 + C17:1n-7 + C18:1n-12 + C18:1n-9 + C18:1n-7 + C18:2n-6 + C18:3n-3 + C18:3n-6 + C20:1n-12 + C20:1n-9 + C20:2n-6 + C20:3n-6 + C20:4n-6 + C20:5n-3 + C22:1n-9 + C22:2n-6 + C22:4n-6 + C22:5n-3 + C22:6n-3).

Thrombogenicity index (TI)

$$TI = \frac{C14 : 0 + C16 : 0 + C18 : 0}{0.5 \times \Sigma \text{MUFA} + 0.5 \times \Sigma n - 6 \text{ PUFA} + 3 \times \Sigma n - 3 \text{ PUFA} + \frac{\Sigma n - 3 \text{ PUFA}}{\Sigma n - 6 \text{ PUFA}}}$$

ΣMUFA denotes the sum of monounsaturated fatty acids (C14:1n-5 + C15:1n-5 + C16:1n-7 + C17:1n-7 + C18:1n-12 + C18:1n-9 + C18:1n-7 + C20:1n-12 + C20:1n-9 + C22:1n-9).

Σn-6 PUFA denotes the sum of n-6 polyunsaturated fatty acids (C18:2n-6 + C18:3n-6 + C20:2n-6 + C20:3n-6 + C20:4n-6 + C22:2n-6 + C22:4n-6).

Σn-3 PUFA denotes the sum of n-3 polyunsaturated fatty acids (C18:3n-3 + C20:5n-3 + C22:5n-3 + C22:6n-3).

Hypocholesterolemic/hypercholesterolemic index (hHI)

$$hHI = \frac{cis \text{ C18 : } 1n - 9 + \Sigma \text{PUFA}}{C12 : 0 + C14 : 0 + C16 : 0}$$

ΣPUFA denotes the sum of polyunsaturated fatty acids (C18:2n-6 + C18:3n-6 + C18:3n-3 + C20:2n-6 + C20:3n-6 + C20:4n-6 + C20:5n-3 + C22:2n-6 + C22:4n-6 + C22:5n-3 + C22:6n-3).

Healthy fatty index (HFI)

$$HFI = \frac{(2 \times \Sigma \text{MUFA}) + (4 \times \Sigma n - 6 \text{ PUFA}) + (8 \times \Sigma n - 3 \text{ PUFA}) + \frac{\Sigma n - 3 \text{ PUFA}}{\Sigma n - 6 \text{ PUFA}}}{(1 \times \Sigma \text{SAT}) + (0.5 \times \Sigma \text{MUFA}) + (0.25 \times \Sigma n - 6 \text{ PUFA}) + (0.125 \times \Sigma n - 3 \text{ PUFA}) + \frac{\Sigma n - 6 \text{ PUFA}}{\Sigma n - 3 \text{ PUFA}}}$$

Σ MUFA denotes the sum of monounsaturated fatty acids (C14:1n-5 + C15:1n-5 + C16:1n-7 + C17:1n-7 + C18:1n-12 + C18:1n-9 + C18:1n-7 + C20:1n-12 + C20:1n-9 + C22:1n-9).

Σ n-6 PUFA denotes the sum of n-6 polyunsaturated fatty acids (C18:2n-6 + C18:3n-6 + C20:2n-6 + C20:3n-6 + C20:4n-6 + C22:2n-6 + C22:4n-6).

Σ n-3 PUFA denotes the sum of n-3 polyunsaturated fatty acids (C18:3n-3 + C20:5n-3 + C22:5n-3 + C22:6n-3).

Σ SAT denotes the sum of all determined saturated fatty acids (C6:0 - C26:0, excluding C7:0 and C22:0).

2.5 Statistical analysis

Statistical significance was set at $p < 0.05$. Data were analyzed using the Kruskal-Wallis and Mann-Whitney tests, with Bonferroni correction applied for multiple comparisons. All statistical analyses were performed using IBM SPSS Statistics for Windows, version 29.0 (SPSS Inc., Chicago, IL, USA). Fatty acid composition is expressed as the weight percentage (w/w%) of total fatty acids. Data are presented as medians with interquartile ranges (IQR) in the tables and figures.

3 Results

3.1 Label information

We analyzed the nutritional information presented on product labels, with a particular focus on total fat and saturated fatty acids, which are mandated for inclusion on labels in the European Union. The PBMS category demonstrated considerable diversity in formulation, particularly in terms of protein composition and fat sources (Table 1). Peas were identified as the primary protein source in most PBMS products (five products). According to the labels, three PBMS utilized a single type of oil as a fat source, whereas another three employed a combination of two oils. These products incorporated rapeseed, sunflower, and coconut oils. Such variations result in a broad spectrum of nutritional profiles compared to beef products. According to the detailed information on the label (Supplementary Table 1), PBMSs exhibited a highly diverse composition of ingredients, whereas BBPs constituted a much more uniform group. Consequently, PBMSs are diverse not only in their lipid composition but also in their energy content and macronutrients.

We also assessed the concordance between the declared values and those obtained through chemical analysis. For each product, the total fat content indicated on the label was compared with laboratory measurements (Figure 1). SFA values were also examined when data were available (Table 2).

The declared total fat values in the products examined ranged from as low as 1.8 g/100 g in Product D (PBMS with no added oils) to 30 g/100 g in Product I (beef patty). Generally, PBMS products had a significantly lower median fat content (10.25% [8.60%; 14.87%], median [Q1; Q3]), with a maximum of 18 g/100 g, whereas BBPs had a higher median fat content (19.67% [16.16%; 26.68%]), reaching up to 30 g/100 g. The total fat content of PBMS varies widely, highlighting the diversity within this category. Although BBPs were more consistent in composition, with both protein and fat derived solely from beef and tallow, this apparent uniformity did not translate into similar total fat and SFA contents (Figure 1).

PBMS products containing coconut oil (Products B, C, and G) had higher SFA values than those formulated with only unsaturated oils (Products A, E, and F). In general, PBMSs had lower SFA content than BBPs; however, product K (a BBP) had a similar SFA content to PBMS products using unsaturated oils (Table 2).

In most samples, discrepancies were identified between the labeled values and analytical measurements (Figure 1). These inconsistencies varied in both magnitude and direction; approximately half of the products understated their actual fat content, whereas the other half overstated it. The deviations ranged from minor differences to substantial variations, exceeding 15 g/100 g. In a PBMS sample (Product A), the measured fat content was nearly double the labeled value. An even greater discrepancy was observed in a beef product (Product K), where the measured fat content was more than four times the declared amount, raising concerns regarding the reliability of the label claim. Conversely, overstatements were observed in some samples. A BBP (Product H) contained approximately 40% less measured total fat than that stated on the label.

Discrepancies were also observed between the declared and measured SFA contents (Table 2). As with the total fat content, products that underestimated the total fat content also tended to underestimate the SFA content. For most products, the measured values were 1.5 times higher than those indicated on the label. However, for one BBP (product K), the measured saturated fat content was five times higher than that indicated on its label. Conversely, another BBP (product H) contained only approximately 40% of the SFAs indicated on its label. The underestimated PBMSs contained 30–45% lower SFA than that stated on the label. One beef product (product L) did not contain quantitative fat content data, as this is not mandatory for minced meat products. The label only stated that the fat content was “not more than 20%.” According to laboratory analysis, the fat content was approximately 16 g/100 g, of which 8.5 g/100 g was saturated fat.

3.2 Fatty acid composition of the products

Table 3 presents the primary FA compositions for each PBMS (designated A–G) and BBP (designated H–L). The PBMS group exhibited considerable heterogeneity in FA profiles, reflecting their diverse lipid sources, whereas the BBP group demonstrated greater uniformity in FA profiles. Within the PBMSs, the predominant FAs were unsaturated oleic acid (C18:1n-9, OA) and LA, whereas in the BBPs, they were saturated palmitic acid (C16:0, PA) and monounsaturated OA. Lauric acid (C12:0) was nearly absent in most PBMSs (0–0.3 w/w% of total FAs), except in coconut oil-based products (Products B, C, and G). The product containing only coconut oil as the fat source exhibited the highest concentration of C12:0, exceeding half of the total FA content. In contrast, BBPs consistently displayed low C12:0 values.

The predominant SFA in beef, PA, was significantly more abundant in BBPs than in PBMSs (Table 3). In BBPs, the PA content remained within a narrow range, constituting approximately one-quarter of the total FAs. Conversely, in PBMSs, the PA content exhibited greater variability, ranging from 5 to 12.5%. The principal MUFA in BBPs was OA, which comprised approximately 40% of the total FAs. In contrast, PBMSs demonstrated substantial variability in OA content: one PBMS, formulated with high-OA oils (Product A), achieved nearly 60% of the total FAs, surpassing the BBP range, whereas the coconut-based PBMS (Product B) contained only approximately 6.5%, the lowest among all products.

TABLE 1 Characteristics of the products included in the study based on the main protein and fat source.

Sample ID	Product code	Main protein source	Main fat source
1	A	soy, wheat	rapeseed oil, sunflower oil
2	B	pea	coconut oil
3	C	pea	rapeseed oil, coconut oil
4	D	wheat	n.d.
5	E	pea	sunflower oil
6	F	soy, pea, wheat, mushroom	sunflower oil
7	G	pea	rapeseed oil, coconut oil
8	H	beef	beef
9	I	beef	beef
10	J	beef	beef
11	K	beef	beef
12	L	beef	beef

n.d.: no data; product codes A-G denote plant-based meat substitutes, H-L denote meat products.

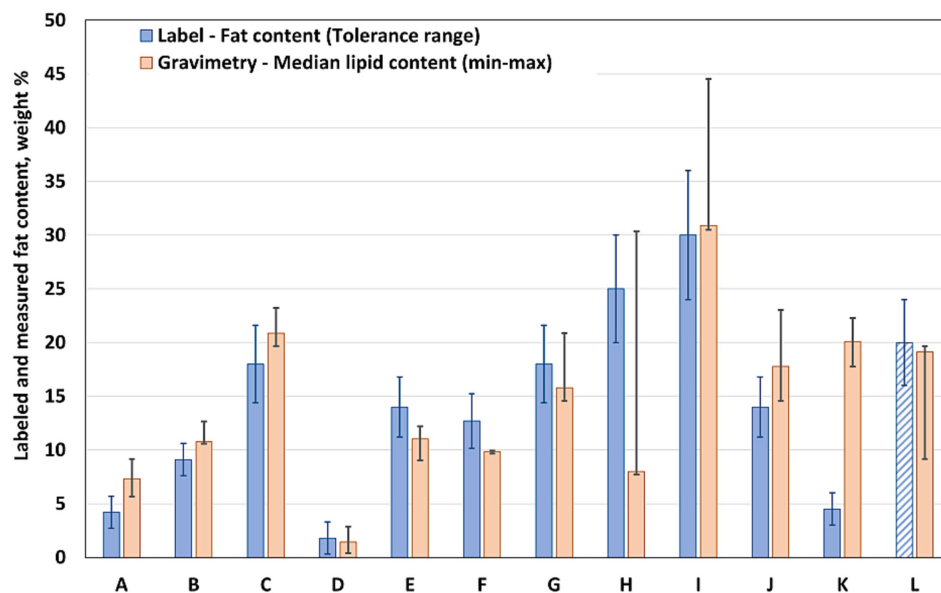


FIGURE 1

Comparison of total fat content on product labels (blue) with measured values (orange). Product codes A–G denote plant-based meat substitutes, and H–L denote beef-based products; the tolerance range for total fat is based on EU regulation (54).

The concentrations of the two EFAs (LA and ALA) were significantly lower in BBPs than in PBMSs (Table 3). The essential n-6 LA was found at low levels in BBPs, with a maximum of 3.7 w/w%, but was abundant in nearly all PBMSs. PBMS products enriched with sunflower oil (Products E and F) showed notably high LA levels of approximately 60%, whereas the product using only coconut oil (Product D) showed much lower values. The essential n-3 ALA levels were exceedingly low in BBPs (≤ 0.5 w/w%), whereas several PBMSs contained relatively high ALA levels. Formulations based on rapeseed oil (Products A, C, and G) contained approximately 5 w/w% ALA, which was approximately ten times higher than that in BBPs.

Table 4 summarizes the fatty acid compositions of each product, highlighting the general compositional patterns. BBPs demonstrated significantly elevated levels of total SFA, MUFA, and *trans* isomeric fatty acids (TFA), while exhibiting reduced levels of n-6 and n-3 PUFAs

compared to PBMSs. Consistent with the aforementioned individual fatty acids, the total SFA content in PBMSs exhibited considerable variability, ranging from approximately 10–85 w/w% of the total fatty acids. Notably, Product B, which exclusively utilized coconut oil as its fat source, was an outlier with an exceptionally high SFA content. In contrast, all BBPs consistently exhibited high SFA levels of approximately 50 w/w%. There were several significant differences in the SFA values, not only between the two groups but also among the products within each group. One group of SFAs, medium-chain fatty acids, was present in negligible amounts in BBP, whereas in the PBMS products containing coconut oil, this group constituted the majority of the total SFA (Figure 2). The highest value was observed in the product containing only coconut oil (Product B); however, in the other two products containing coconut oil along with other vegetable oils (Products C and G), values exceeding 20 w/w% were recorded, which is substantially higher

TABLE 2 Comparison of saturated fat content on product labels with measured values.

Product code	Saturated fat content from label	Tolerance around the declared value of the saturated fat content		Saturated fat content from measurement	Deviation between declared and measured values
	(g/100 g)	Limits (*: g/100 g)	Range (g/100 g)	Median (Range) (g/100 g)	(%)
A	0.5	±0.8*	0.0–1.3	0.80 (0.55–0.88)	+ 60
B	6.5	±20%	5.2–7.8	9.41 (9.16–11.01)	+ 45
C	5.4	±20%	4.3–6.5	7.15 (6.76–8.85)	+ 32
D	0.6	±0.8*	0.0–1.4	0.24 (0.07–0.50)	– 60
E	1.9	±0.8*	1.1–2.7	1.23 (0.94–1.34)	– 35
F	1.3	±0.8*	0.5–2.1	0.91 (0.85–0.93)	– 30
G	5.4	±20%	4.3–6.5	5.52 (4.79–8.02)	+ 2
H	10	±20%	8.0–12.0	3.70 (3.53–13.43)	– 63
I	16	±20%	12.8–19.2	17.41 (17.29–23.73)	+ 9
J	5.7	±20%	4.6–6.8	8.58 (7.07–11.17)	+ 50
K	1.9	±0.8*	1.1–2.7	9.56 (7.76–10.46)	+ 403
L	n.d.	n.d.	n.d.	8.50 (4.68–9.90)	-

n.d.: no data; *: total fat < 20 g / 100 g; product codes A-G denote plant-based meat substitutes, H-L denote beef-based products.

Data are expressed as median (min, max) for measured total fat content (n = 3) and as median (min-max) for calculated saturated fat content (n = 12).

The deviation between the declared and measured values was calculated based on the declared and median values of the measured saturated fat content.

than those found in the other products. In contrast, total branched-chain fatty acids, including both iso and anteiso branched-chain fatty acids, were present in BBPs at approximately 2 w/w%, whereas they were only found in very small amounts in PBMSs (Figure 3). Similarly, the concentrations of total odd-chain SFAs and the sum of the two major odd-chain SFAs, C15:0 and C17:0, were significantly higher in BBPs (above 1 w/w%) than in PBMS (Figure 4).

Similar to the SFA values, the BBPs had a relatively uniform MUFA content (approximately 45%). In contrast, PBMSs ranged from very low MUFA (<10% in Product B) to very high MUFA (>60% in Product A) contents. PBMSs were essentially devoid of TFAs (<0.1%), whereas all BBPs contained significantly higher TFA levels (~1–3.5%). The differences in PUFA content were even more pronounced. Both n-6 and n-3 PUFAs were significantly higher in PBMSs than in BBPs. The n-6 PUFA values varied from approximately 3–4 w/w% to nearly 60% (Product E) in PBMS products formulated with seed oils. The total n-3 PUFA content was considerably higher in the PBMS group than in the BBPs, reflecting the inclusion of ALA-containing oils as a fat source. Several PBMS products contained approximately 5% n-3 PUFA (those with rapeseed oil), whereas all beef products contained very low levels of n-3 PUFAs. PBMSs presented a much broader and more heterogeneous FA profile than that of BBPs. In some PBMSs, depending on the oil used, SFAs were predominantly C12:0, with smaller amounts of C14:0 and C8:0 (Product B, C, and G). In contrast, other products primarily featured SFAs, such as C18:0 and C16:0 (Supplementary Table S2). We also observed several differences in the n-3 and n-6 PUFA compositions. Notably, Product B contained PUFAs with 22 carbon atoms, and we detected 0.47 w/w% C20:4n-6 in Product G, whereas other PBMSs mainly included only the two EFAs, LA and ALA. Conversely, the FA composition of BBP was considerably more uniform, with fewer significant differences among individual products (Supplementary Table S2).

3.3 Nutritional indices

3.3.1 Essential fatty acid index

The EFA index values (Table 5), which reflect the relative abundance of EFAs, were substantially higher (approximately 10–20 times) in PBMS than in BBPs. The highest EFA scores were observed for products D, E, and F, which exceeded 55. Products A, C, and G also demonstrated significant EFA content, whereas product B was an outlier in the PBMS group, owing to its low EFA content. In contrast, the BBP group exhibited a narrow range of values, underscoring the markedly lower presence of EFAs in BBP.

3.3.2 The n-3/n-6 polyunsaturated fatty acids

There was considerable variation in n-3/n-6 PUFA values (Table 5) among the PBMSs, with levels ranging from very low to 0.35. In contrast, almost all BBPs exhibited similar values of approximately 0.15, except for product J, which had a value approximately four times greater. The PBMSs could be categorized into two subgroups: one with a relatively high n-3/n-6 PUFA ratio (products A, B, C, and G) and another with a very low ratio (products D, E, and F). Furthermore, no significant differences were observed between the PBMSs and BBPs.

3.3.3 Unsaturation index

The UI (Table 5), which reflects the degree of unsaturation in the lipid profile, was significantly elevated in PBMSs compared to that in BBPs, with a notable group difference. This finding indicates a higher prevalence of unsaturated FAs in the plant-based groups. The PBMSs exhibited a broad range of UI values (18.49–149.54), with the majority of samples, including products A, D, E, and F, demonstrating values

TABLE 3 Main fatty acid composition of the plant-based and beef-based products.

w/w%	Plant-based meat substitutes (PBMS)						Beef-based products (BBP)						PBMS vs. BBP p
	A	B	C	D	E	F	G	H	I	J	K	L	
C12:0	ABCD 0.05 [0.02]	AEFGHIJKLM 55.23 [1.84]	BENOPQRST 18.08 [3.63]	FNUVab 0.06 [0.02]	CGOUWXYZ12 0.27 [0.23]	0.02 [0.01]	DHVW34567 18.92 [5.38]	IPaX3 0.09 [0.01]	JQY4 0.07 [0.01]	KRbZ5 0.08 [0.02]	LS16 0.07 [0.02]	MT27 0.08 [0.02]	<0.05
C16:0	^a ABCDEFGHIJ 7.30 [0.93]	^a KLbMNOPQ 6.39 [0.59]	AKRSctUVVWX 5.27 [0.21]	BLR 12.45 [0.44]	CS 6.43 [0.23]	Dc 5.87 [0.40]	Eb 5.25 [0.48]	FMT 25.87 [2.30]	GNU 28.29 [1.49]	HOV 25.17 [2.76]	IPW 28.34 [2.77]	JQX 28.57 [1.05]	<0.001
C18:1n-9	ABCDE ^a 59.18 [1.23]	AFGHbJ 6.71 [0.61]	FKLab 43.77 [3.21]	BKMNO ^c 24.55 [1.36]	CLPqQ 28.49 [1.73]	Daef 31.26 [0.15]	GMPe 42.36 [3.47]	HNd 41.12 [2.16]	Eb 36.14 [3.00]	ab 38.69 [1.62]	IOQf 41.33 [3.22]	Jc 38.43 [4.13]	<0.05
C18:2n-6	ABab 22.23 [0.75]	Cc 3.80 [0.53]	dD 13.77 [1.26]	EFGH 55.10 [0.89]	CIJKLM 59.18 [1.64]	ceNOPQ 58.41 [0.12]	fR 14.94 [1.45]	le 3.72 [1.67]	AdEjNf 1.15 [0.12]	BDFKOR 0.73 [0.24]	aGLP 1.51 [0.54]	bHMq 1.70 [0.15]	<0.001
C18:3n-3	AaBbCD 4.89 [0.28]	cEd 0.75 [0.07]	FeGHI 4.98 [0.34]	Jkghi 1.51 [0.17]	jk 0.50 [0.10]	AcFjL 0.19 [0.02]	jLmMnNO 5.15 [0.43]	am 0.50 [0.40]	BEeGkkm 0.15 [0.03]	Bfn 0.42 [0.13]	CdHghN 0.22 [0.08]	DBo 0.26 [0.13]	<0.001

Each data point represents the median value of 12 measurements (three different expiration dates, two parallel chemical analyses, and two runs on a gas chromatograph for each sample).

Data are expressed as median [interquartile range].

Common superscript letters and numbers in the same row denote a significant difference between the given products: ^{a,b,c}: 0.001 ≤ p < 0.05; ^{A,B,C,1,2,3}: p < 0.001.

TABLE 4. Summarized fatty acid values of the plant-based and beef-based products.

W/W%	Plant-based meat substitutes (PBMS)												Beef-based products (BBP)												PBMS vs. BBP		
	A	B	C	D	E	F	G	H	I	J	K	L	P	A	B	C	D	E	F	G	H	I	J	K	L	P	
SAT	10.07 [0.98]	86.91 [1.33]	34.75 [5.21]	17.28 [0.45]	11.01 [0.13]	9.20 [0.49]	34.96 [5.51]	45.75 [1.47]	56.14 [3.16]	48.31 [0.48]	47.11 [3.82]	50.36 [6.24]	10.07 [0.98]	86.91 [1.33]	34.75 [5.21]	17.28 [0.45]	11.01 [0.13]	9.20 [0.49]	34.96 [5.51]	45.75 [1.47]	56.14 [3.16]	48.31 [0.48]	47.11 [3.82]	50.36 [6.24]	<0.001		
MUFA	62.39 [1.47]	8.49 [0.81]	46.35 [3.44]	26.26 [1.44]	29.28 [1.78]	32.01 [0.17]	44.83 [3.63]	46.27 [4.98]	39.38 [3.71]	43.62 [2.61]	47.99 [2.94]	43.79 [7.66]	62.39 [1.47]	8.49 [0.81]	46.35 [3.44]	26.26 [1.44]	29.28 [1.78]	32.01 [0.17]	44.83 [3.63]	46.27 [4.98]	39.38 [3.71]	43.62 [2.61]	47.99 [2.94]	43.79 [7.66]	<0.001		
TFA	0.10 [0.05]	0.01 [0.02]	0.03 [0.01]	0.04 [0.01]	0.04 [0.01]	0.04 [0.01]	0.04 [0.04]	1.05 [0.91]	0.90 [0.39]	3.62 [1.48]	0.96 [0.49]	0.96 [0.46]	0.10 [0.05]	0.01 [0.02]	0.03 [0.01]	0.04 [0.01]	0.04 [0.01]	0.04 [0.01]	0.04 [0.04]	1.05 [0.91]	0.90 [0.39]	3.62 [1.48]	0.96 [0.49]	0.96 [0.46]	<0.001		
n-6 PUEFA	22.28 [0.76]	3.83 [0.53]	13.81 [1.31]	55.14 [0.89]	59.19 [1.64]	58.44 [0.56]	14.98 [1.44]	4.10 [1.80]	1.28 [0.15]	0.86 [0.27]	1.66 [0.54]	2.05 [0.28]	22.28 [0.76]	3.83 [0.53]	13.81 [1.31]	55.14 [0.89]	59.19 [1.64]	58.44 [0.56]	14.98 [1.44]	4.10 [1.80]	1.28 [0.15]	0.86 [0.27]	1.66 [0.54]	2.05 [0.28]	<0.001		
n-3 PUEFA	4.89 [0.28]	0.75 [0.07]	5.02 [0.39]	1.51 [0.17]	0.50 [0.10]	0.19 [0.02]	5.15 [0.43]	0.64 [0.46]	0.18 [0.05]	0.54 [0.17]	0.26 [0.14]	0.34 [0.24]	4.89 [0.28]	0.75 [0.07]	5.02 [0.39]	1.51 [0.17]	0.50 [0.10]	0.19 [0.02]	5.15 [0.43]	0.64 [0.46]	0.18 [0.05]	0.54 [0.17]	0.26 [0.14]	0.34 [0.24]	<0.001		

Each data point represents the median value of 12 measurements (three different expiry dates, two parallel chemical analyses, and two runs on a gas chromatograph for each sample). Data are expressed as median [interquartile range]; Common superscript letters in the same row denote a significant difference between the given products: a,b,c: 0.001 ≤ p < 0.05; A, B, C: p < 0.001. Abbreviations: SAT: sum of all saturated fatty acids, MUFA: sum of all monounsaturated fatty acids, TFA: sum of all trans isomeric fatty acids, n-6 PUEFA: sum of all n-6 polyunsaturated fatty acids, n-3 PUEFA: sum of all n-3 polyunsaturated fatty acids.

exceeding 120, indicating elevated levels of PUFAs. Conversely, the BBPs consistently presented lower UI values, averaging approximately 50, with product H exhibiting the highest value within this group.

3.3.4 Atherogenicity index

In the PBMS group, the AI values (Table 5) were significantly lower than those in the BBP group. Most PBMSs (products A, D, E, and F) demonstrated a markedly reduced atherogenic potential relative to BBPs, with only two products (C and G) exhibiting AI levels comparable to those of BBPs. The sole exception was product B, which had an AI exceeding 8, surpassing the average observed in BBPs and indicating a lipid profile characterized by atherogenic SFAs. BBPs consistently exhibited higher IA values, ranging from 0.70 to 0.96.

3.3.5 Thrombogenicity index

TI followed a pattern similar to that of AI (Table 5), with significantly lower values observed in the PBMS group than in the BBP group. In the PBMS group, the values mainly ranged from 0.16 to 0.32, except for product B, which exhibited the highest TI values, reaching nearly 2.5. In contrast, the BBP group showed TI values ranging from 1.63 (product H) to 2.62 (product I), with most values exceeding 1.7.

3.3.6 Hypocholesterolaemic to hypercholesterolaemic index

The hHI (Table 5), which reflects the equilibrium between cholesterol-lowering and cholesterol-raising FAs, was markedly elevated in the PBMS group, indicating a more advantageous lipid profile. Products A, E, and F attained the highest values, each exceeding 11. Conversely, product B demonstrated a significantly low ratio of 0.15, diverging from the group's mean. The BBP values were confined to a narrow range of 1.22–2.20, underscoring the consistently low hHI profile characteristic of beef fat.

3.3.7 Healthy fatty index

The HFI was significantly higher in the PBMS group than that in the BBPs group. Again, HFI values showed a wide range in PBMSs, reaching the highest values (above 2.9) in products A, C, D, and G, while two products (products B and F) had even lower values than BBPs. In contrast, the HFI of all the BBPs was approximately 1.3.

4 Discussion

In the present study, the lipid content of PBMSs was significantly lower than that of BBPs, with several differences noted in FA composition and nutritional indices. The median lipid content in PBMSs was approximately half that of BBPs, with values of 10.25 and 19.67%, respectively, consistent with the existing literature. Previous studies have similarly reported significantly lower fat and saturated fat contents in plant-based burgers than in beef-based burgers across various regions, including Australia (7.2 ± 4.8 vs. 13.7 ± 7.8; p = 0.001 and 1.5 ± 1.6 vs. 6.2 ± 4.1; p = 0.005) (45), the UK (10.3 ± 5.0 vs. 15.0 ± 6.8; p < 0.001 and 1.7 ± 1.5 vs. 6.6 ± 2.7; p < 0.001) (46), Brazil (8.91 ± 6.63 vs. 16.88 ± 4.38; p = 0.048 and

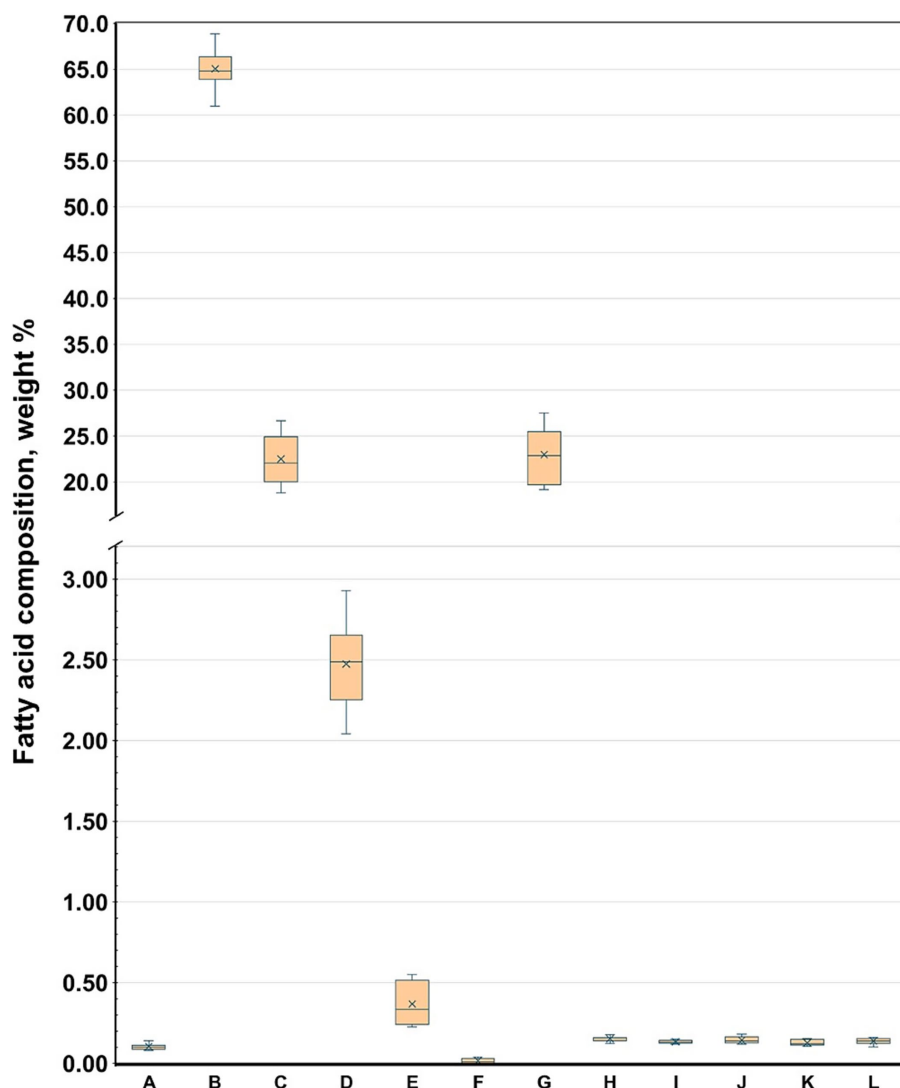


FIGURE 2

Sum of all medium-chain saturated fatty acids in the investigated products. Product codes A–G denote plant-based meat substitutes, and H–L denote beef-based products; sum of medium-chain saturated fatty acids denote: C6:0 + C8:0 + C9:0 + C10:0 + C11:0 + C12:0. Alt text: Box plot comparing the weight percentages of medium-chain saturated fatty acids across plant-based meat substitutes and beef products, showing that coconut-oil-based items, especially product B, have markedly higher levels, while all beef samples contain minimal amounts.

3.20 ± 4.19 vs. 6.21 ± 1.38 ; $p = 0.056$) (47), South Africa (7.3 ± 5.9 vs. 13.7 ± 4.2 and 2.2 ± 3.2 vs. 6.0 ± 2.8) (48), Sweden (15 vs. 20 and 6 vs. 26) (49), Europe (9.13 ± 4.56 vs. 14.87 ± 5.18 and 1.54 ± 1.68 vs. 6.45 ± 2.42) (50), Spain (8.4 vs. 12.6 and 1.9 vs. 5.1) (51), Hong Kong (10.125 vs. 16.85 ; $p < 0.001$ and 2.3 vs. 5.83 ; $p < 0.001$) (52), and the USA (53). A review comparing different meat products and their plant-based substitutes also found that plant-based alternatives generally have lower total fat and saturated fat contents (9.17 vs. 20 and 1.6 vs. 12 , respectively) (32).

Our research identified significant discrepancies between the reported and actual lipid content of the products. According to European Union regulations (54), the permissible tolerance for fat content on labels is ± 1.5 g if the fat content is below 10 g per 100 g of food, and $\pm 20\%$ if it ranges from 10 to 40 g per 100 g. In the Hungarian PBMSs, we observed both lower and higher lipid contents than declared; however, these values remained within the acceptable tolerance range. In contrast, within the BBPs, one product (K) exhibited a measured fat content approximately four times higher than declared,

while another product (H) contained 40% less fat than indicated on the label, both of which are unacceptable. These discrepancies may be attributed to the inadequate homogenization of the products, as suggested by the significant distance between quartiles. Additionally, they may have resulted from variations in production time, as we collected three different samples with three distinct expiration dates. A study conducted in Spain indicated that both the fat content and FA composition of meat products exhibit seasonal variability; however, this variability does not exceed 6% (55). Furthermore, fat content may vary depending on the methods used for its determination (56). It is essential to acknowledge that such inaccuracies may affect the calculation of energy and fat intakes in patients. Previous studies have also reported that the measured fat content is significantly higher than that indicated on the labels (57, 58). In Colombian whey products designed for sports nutrition, the labels indicated lower macronutrient content, including fat content, than the values measured (59). Conversely, another study identified that protein bars and protein puffs contained approximately 50% more fat than indicated, whereas other products,

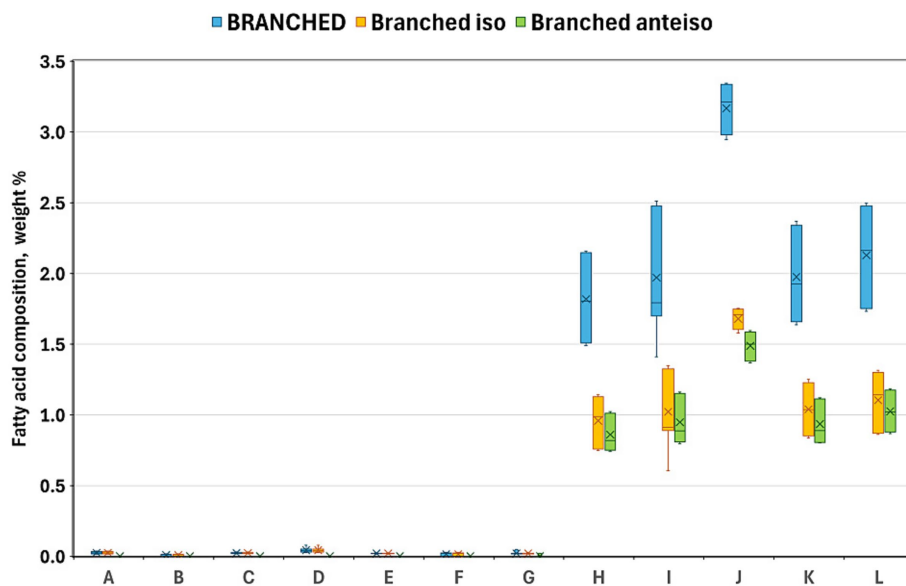


FIGURE 3

Sum of all branched-chain fatty acids (blue), iso (orange), and anteiso (green) branched-chain fatty acids in the investigated products. Product codes A–G denote plant-based meat substitutes, and H–L denote beef-based products; iso branched-chain fatty acids denote: C14:0i + C15:0i + C16:0i + C17:0i + C18:0i; anteiso branched-chain fatty acids denote: C15:0ai + C17:0ai; all branched-chain fatty acids denote: sum of iso and anteiso branched-chain fatty acids. Alt text: Clustered box plot comparing total, iso-, and anteiso-branched chain fatty acid percentages in plant-based and beef products, showing that beef samples contain substantially higher levels (about 1–3% of total fatty acids), while plant-based alternatives contain almost none.

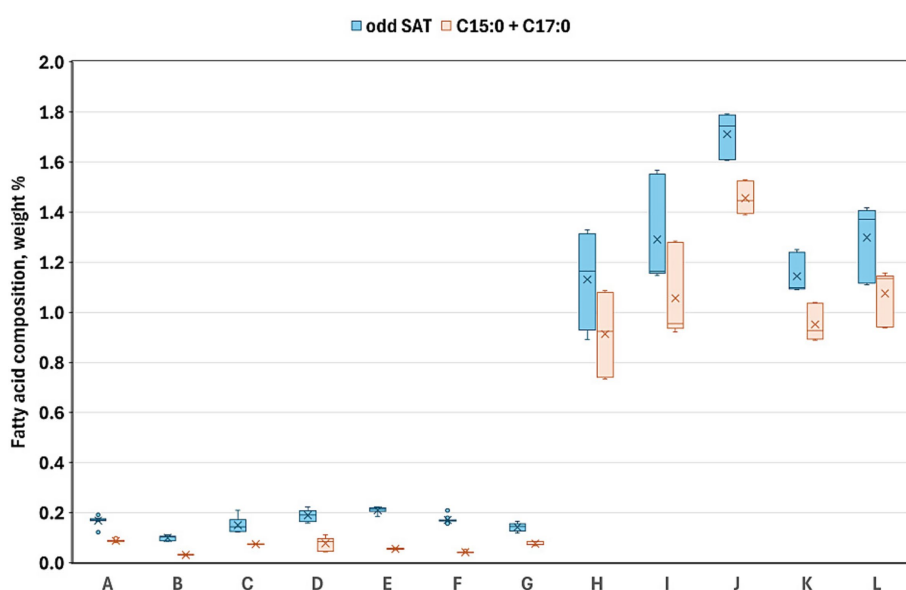


FIGURE 4

Sum of all odd-chain saturated fatty acids (blue) and sum of C15:0 + C17:0 (red) in the investigated products. Product codes A–G denote plant-based meat substitutes, and H–L denote beef-based products; sum of odd-chain saturated fatty acids denote: C9:0 + C11:0 + C13:0 + C15:0 + C17:0 + C19:0 + C21:0 + C23:0 + C25:0. Alt text: Clustered box plot comparing odd-chain saturated fatty acids, and sum of C15:0 and C17:0, between plant-based and beef products, showing markedly higher levels in beef samples (around 0.8–1.8%) and negligible amounts in plant-based ones.

such as peanut butter and Greek yogurt, exhibited a fat content that was 15–25% lower than labeled (60).

In recent decades, the food industry has actively engaged in the development of meat alternatives, with researchers exploring various meat analogs. Although other options are available, plant-based substitutes are the most extensively studied and widely marketed (61, 62).

These alternatives aim to replicate the taste, texture, and overall sensory experience of meat products while minimizing the environmental impact of livestock farming. They are made from various proteins, including soy, pea, and wheat, and different types of fats (63, 64).

In Hungarian PBMSs, the primary fat sources were coconut, rapeseed, and sunflower oils, similar to those found in Italian (37) and

TABLE 5 Nutritional indices of fatty acids in the plant-based and beef-based products.

Median [IQR]	Plant-based meat substitutes (PBMS)						Beef-based products (BBP)						PBMS vs. BBP
	A	B	C	D	E	F	G	H	I	J	K	L	p
EFA	^{ABab} 26.95 [0.52]	Cc 4.56 [0.60]	de 18.78 [1.61]	fDEFG 56.61 [1.07]	CHIJKL 59.75 [1.59]	cgMNOP 58.60 [0.13]	hQ 20.09 [1.88]	fHg 4.25 [2.05]	AddIMh 1.32 [0.12]	BeEJNQ 1.15 [0.37]	aFKO 1.66 [0.52]	bGLP 2.00 [0.24]	<0.001
n-3/n-6 PUFA	aAB 0.22 [0.02]	bC 0.19 [0.01]	DEFcde 0.37 [0.01]	aDGH 0.03 [0.00]	AbEIJ 0.01 [0.00]	BCFKLfg 0.00 [0.00]	GIK 0.35 [0.01]	cM 0.15 [0.07]	dN 0.14 [0.05]	HJLMNhi 0.63 [0.02]	efh 0.13 [0.11]	gi 0.16 [0.10]	0.147
UI	ABa 121.74 [0.91]	ACDEFGb 18.49 [1.99]	Cc 89.34 [8.07]	DHIde 140.63 [1.07]	EfjKLM 149.37 [1.26]	FgNOPQ 149.54 [2.00]	Gh 90.23 [7.78]	bfj 56.87 [0.52]	BcHJNh 42.55 [3.76]	aIKO 47.55 [1.11]	dLP 53.01 [2.84]	eMQ 49.51 [5.93]	<0.001
AI	ABab 0.09 [0.01]	AcCDEde 8.65 [1.05]	cf 0.67 [0.16]	CFgh 0.16 [0.01]	DGHij 0.08 [0.00]	EfjkLMN 0.07 [0.01]	dj 0.66 [0.17]	ek 0.70 [0.06]	BFGK 0.96 [0.13]	agHL 0.81 [0.07]	iM 0.77 [0.14]	bhjN 0.84 [0.10]	<0.001
TI	AaBCDEF 0.16 [0.02]	AGbHIQ 2.43 [0.21]	Gjd 0.26 [0.04]	abe 0.32 [0.01]	KLfMQ 0.22 [0.00]	HgNOhP 0.19 [0.01]	IRi 0.26 [0.03]	Bg 1.62 [0.05]	CJeKNQR 2.60 [0.33]	DdLOi 1.88 [0.06]	Efh 1.77 [0.26]	FMP 2.02 [0.44]	<0.001
hHI	ABabC 11.55 [1.46]	ADEFGH 0.15 [0.02]	Dc 2.20 [0.50]	EIde 6.42 [0.23]	FfjKLM 12.79 [0.11]	GNOPQR 15.13 [1.23]	Hg 2.17 [0.57]	fN 1.59 [0.17]	BcIJOg 1.22 [0.14]	adKP 1.40 [0.14]	bLQ 1.41 [0.27]	CeMR 1.31 [0.14]	<0.001
HFI	ABaCDEF 4.87 [0.13]	AGHIJb 0.40 [0.05]	GKLc 2.91 [0.37]	HMNdeQ 3.53 [0.20]	IhR 1.90 [0.31]	BKMOiR 0.86 [0.06]	JOPj 2.95 [0.40]	abi 1.48 [0.10]	CLNhP 1.04 [0.09]	Dd 1.33 [0.02]	Ee 1.33 [0.20]	FcjQ 1.26 [0.14]	<0.001

Abbreviations denote: EFA: essential fatty acids, n-3/n-6 PUFA: n-3/ n-6 polyunsaturated fatty acids, UI: unsaturation index, AI: atherogenicity index, TI: thrombogenicity index, hHI: hypocholesterolemic/hypercholesterolemic index, HFI: healthy fatty index.

Belgian plant-based burgers (65). These three vegetable oils are the most commonly used for PBMSs worldwide. However, in some countries, other oils are also common, such as olive oil in Brazil (31, 47) and canola oil in Hong Kong (52), South Africa (48), Canada (40), and the USA (38). Soybean oil is used in certain products in Hong Kong (52) and South Africa (48), whereas cocoa butter is used in PBMSs in South Africa (48) and the USA (38).

The FA composition of PBMSs exhibited considerable variation, not only compared to BBPs but also among different PBMS products. In these plant-based products, the primary fat source determines the FA profile of the product. Coconut oil predominantly comprises medium-chain fatty acids, with lauric acid being the most abundant (46.64–48.03 w/w%) (66, 67). Consequently, lauric acid had the highest value in the product where coconut oil served as the sole fat source (product B). In the two products where coconut oil was combined with other vegetable oils, the lauric acid levels were significantly lower than those in product B but were still markedly higher than those in products without coconut oil. Conversely, the principal FA in rapeseed oil is OA (56.8–66.6 w/w%), a MUFA (33, 68, 69). Therefore, OA is the predominant FA in PBMSs utilizing rapeseed oil. However, this oil is also a substantial source of n-3 EFA, ALA (7.8–10.0 w/w%), resulting in high ALA values in the three products containing rapeseed oil. The primary FA in sunflower oil is n-6 EFA, LA (20.36–69.56 w/w%) (33, 70, 71); thus, in the three PBMS products employing this oil as the main fat source, LA was found in the highest concentration. Our findings concur with previous studies that reported high lauric acid levels in plant-based burgers made with coconut oil in Brazilian (171.35–326.28 mg/g total fat; mean±SD) (31), Italian (median: 23.83 w/w%) (37), Canadian (13.15 ± 0.01 w/w%; mean±SD) (40) and US PBMSs (26.91 mg/g) (38). In contrast, the addition of sunflower oil or rapeseed/canola oil resulted in elevated LA values (15.14–17.82 w/w%) (38) and ALA levels (4.39–7.17 w/w%) (40).

The FA composition of the BBPs was more consistent and aligned with the existing literature. The two primary FAs in beef are PA and OA, comprising approximately 25% and 35–40% of the total FAs, respectively (37, 40, 41, 72). Beef-based hamburger patties and minced meat are high in saturated fats (45–55% of total fat) and MUFAs (40–48% of total fats), but they contain low levels of PUFAs, as previously described (37, 38, 40).

Compared to PBMSs, all BBPs exhibited measurable TFA values, primarily ruminant *trans* isomers, along with branched-chain and odd-chain fatty acids, mainly C15:0 and C17:0. These FAs are produced by bacteria residing in the rumen of ruminants, such as beef (73–76), although the human microbiome can also generate branched-chain fatty acids (77), and fermented products are rich sources of these FAs (78). Some evidence indicates that TFAs derived from ruminants may offer health benefits, such as lowering the risk of type 2 diabetes (79) and eczema (80), although the findings remain inconsistent.

Various indices can be used to assess the health impacts of different foods based on their FA composition (43). The EFA index, which summarizes the LA and ALA content of food, indicated that PBMSs using sunflower oil as the primary fat source had the highest values. Vegetable oils, rich in essential LA and ALA, resulted in a significantly higher EFA index in nearly all PBMSs compared to beef, except for the product that used only coconut oil as the main fat source. The n-3/n-6 PUFA ratio was highest in the three products that used rapeseed oil as the primary fat source. In contrast, the main FA in sunflower oil is LA, an n-6 FA, resulting in an extremely low ratio in PBMSs made with sunflower oil. This indicates a high level of n-6 PUFAs compared with n-3 PUFAs. The AI represents the ratio of the sum of the main saturated (primarily proatherogenic) fatty acids to the main unsaturated (primarily antiatherogenic)

fatty acids (81). The TI reflects the thrombogenic potential of foods containing pro-thrombogenic (mainly saturated) and anti-thrombogenic (MUFAs, n-3, and n-6 PUFAs) fatty acids in varying proportions (81). Nutritional indices of plant-based alternatives often suggest potential health benefits, with lower AI (0.11 vs. 0.64) and TI (0.26 vs. 1.87) than that of beef (31). However, PBMSs made with coconut oil can exhibit higher AI and TI values than those made with beef due to their high saturated fat content [AI: 5.43 ± 0.51 vs. 0.64; TI: 4.23 ± 0.32 vs. 1.87 (31) and AI: 1.47 vs. 0.77 (37)]. Similarly, vegetable oils, except coconut oil, are rich in unsaturated fatty acids, resulting in a significantly higher UI in most PBMSs than in BBPs. Generally, the wide variation in formulations means that nutritional profiles can differ substantially between products. According to the current nutritional recommendations of the World Health Organization (WHO) and European Food Safety Authority (EFSA), SFA intake should be as low as possible, preferably no more than 10% of the total energy intake, and it is recommended to replace SFAs in the diet with PUFAs or plant-based MUFAs. The total fat intake should be 20–35% of the total energy intake, while there are no current recommendations for cis MUFA and PUFA intake (26, 82). Based on the calculated nutritional indices, the FA composition of the PBMSs included in this study, except those containing coconut oil, was much closer to the recommended FA intake than that of BBPs. Therefore, certain PBMSs may be more beneficial than traditional BBPs in terms of FA intake. In the early 2000s, two additional indices were introduced to evaluate the health effects of foods: the hHI, which describes the relationship between hypocholesterolemic fatty acids (mainly OA and PUFAs) and hypercholesterolemic fatty acids (mainly SFAs) (83) and the health-promoting index (HPI), which is the inverse of the AI (43).

In the present study, products rich in SFAs (BBP and PBMSs made with coconut oil) exhibited significantly lower hHI values than those using vegetable oils. Consequently, the nutritional indices of PBMSs (except those made solely with coconut oil) suggest a cardioprotective potential with reduced atherogenic and thrombogenic potential compared to traditional BBPs. A relatively new index, the HFI, considers the complexity of the FA composition of food in a more detailed manner than previous indices (44). This index aims to better differentiate between products with varying FA compositions by applying higher coefficients to the numerator for FAs with more beneficial effects and lower coefficients for the same FAs in the denominator than in the numerator. In the present study, PBMSs made with sunflower oil or rapeseed oil had the highest HFI values, indicating the potentially most beneficial effects of these products, whereas the product made solely with coconut oil (product B) had an even lower HFI value than BBPs in general.

In recent years, there has been a growing interest in consuming PBMSs instead of meat, as PBMSs can contribute to a sustainable diet with a lower environmental impact, especially when compared to the production of beef and other ruminant meats (84). Traditional plant-based diets, such as vegetarian or vegan diets, offer several benefits over omnivorous diets, including reduced red meat consumption. However, plant-based alternatives to traditional meat products differ from whole-food plant-based diets, which focus on minimally processed foods such as legumes, grains, vegetables, and fruits. Although most PBMSs have lower energy, total fat, and saturated fat contents than meat, their high added salt content may be concerning (39, 85). According to the NOVA classification, PBMSs are categorized as ultra-processed foods (35), and their potential health effects are uncertain. However, their composition can vary in terms of protein, fat, and sodium content, making the Nutri-Score or nutritional profiling potentially more reflective of their

nutritional quality (86, 87). We observed significant variability in the fat content and primary fat sources among PBMSs, resulting in a wide range of FAs and nutritional indices. Currently, there is limited evidence on the long-term benefits or potential adverse effects of replacing meat with PBMS. In an eight-week randomized controlled trial, PBMS improved certain clinical parameters, such as diastolic blood pressure and fasting fructosamine concentration, but its consumption was not superior to that of meat (88). Shifting from an animal-based to a plant-based diet clearly benefits cardiometabolic health and reduces all-cause mortality (15). Additionally, a systematic review of seven randomized clinical studies indicated that incorporating PBMS into the diet lowers total cholesterol and LDL cholesterol (89).

We must also acknowledge that our study has both strengths and limitations. The primary strength of this study lies in its thorough examination of all commercially available plant-based burger patty alternatives in Hungary, which were compared with beef-based products. To account for variability among the different batches, we collected and analyzed each product with three different expiration dates. In addition to analyzing the label information, we conducted analytical measurements to assess the total fat content and FA compositions of these products. To our knowledge, this is the first study to compare a broad range of nutritional indices of lipids, including the latest HFI, rather than being limited to the AI and TI. However, this study has several limitations. While we attempted to reduce variability between productions by using three different expiration dates, it is crucial to highlight that over an extended period, significant differences may arise in both the lipid and FA compositions of products manufactured during various production periods. This could be attributed to factors such as variations in the FA composition of the oils and oil blends used, processing and homogenization methods, and other technological changes. We focused solely on fat content and FA composition, neglecting other macro- and micronutrients, such as proteins, carbohydrates, or minerals, despite previous studies indicating notable differences between plant-based and beef-based products. Our objective was to investigate the composition of beef burgers and their plant-based alternatives, excluding other meat products and their plant-based substitutes, such as sausages, minced meat, meatballs, and other meat burgers (e.g., those made from pork, chicken, or mixed meat). This study focused exclusively on the Hungarian market, which limits the generalizability of the findings to the broader European market. Furthermore, it is important to recognize that the small sample size, consisting of six plant-based and four beef-based products, also represents a limitation of our study.

5 Conclusion

In this study, we observed significant variability in the fatty acid composition of PBMSs, as the oils used directly influenced the fatty acid profiles of the products. While BBPs predominantly contain SFAs and MUFAs, most PBMSs are rich in PUFAs. PBMSs may offer more beneficial physiological effects owing to their lower average fat content and more favorable fatty acid composition. However, PBMSs cannot be regarded as a uniform group because of the diverse types of oils used in each product. Nonetheless, the health implications remain uncertain, underscoring the need for further randomized clinical studies to explore the effects of substituting meat products with plant-based alternatives on human health. Overall, PBMSs present a viable

option for consumers aiming to reduce meat consumption; however, their nutritional quality largely depends on the specific ingredients, including the type of vegetable oil and processing methods employed.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

VK: conceptualization, methodology, writing—original draft preparation. TM: conceptualization, methodology, software, validation, data curation, writing—original draft preparation, writing—review and editing, visualization. ZS: conceptualization, writing—review and editing. TD: software, data curation, writing—original draft preparation, visualization. ÉS: validation, data curation, visualization, writing—review and editing, supervision.

Funding

The author(s) declare that financial support was not received for the research and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of *Frontiers*, at the time of submission. This had no impact on the peer review process and the final decision.

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fnut.2026.1732327/full#supplementary-material>

References

- Mann NJ. A brief history of meat in the human diet and current health implications. *Meat Sci.* (2018) 144:169–79. doi: 10.1016/j.meatsci.2018.06.008
- Leroy F, Smith NW, Adesogan AT, Beal T, Iannotti L, Moughan PJ, et al. The role of meat in the human diet: evolutionary aspects and nutritional value. *Anim Front.* (2023) 13:11–8. doi: 10.1093/af/vfac093
- Tilman D, Clark M. Global diets link environmental sustainability and human health. *Nature.* (2014) 515:518–22. doi: 10.1038/nature13959
- Ramankutty N, Mehrabi Z, Waha K, Jarvis L, Kremen C, Herrero M, et al. Trends in global agricultural land use: implications for environmental health and food security. *Ann Rev Plant Biol.* (2018) 69:789–815. doi: 10.1146/annurev-arplant-042817-040256
- Stoll-Kleemann S, Schmidt UJ. Reducing meat consumption in developed and transition countries to counter climate change and biodiversity loss: a review of influence factors. *Reg Environ Chang.* (2016) 17:1261–77. doi: 10.1007/s10113-016-1057-5
- IARC Working Group on the Evaluation of Carcinogenic Risks to Humans. *Red meat and processed meat.* In: Editors: S Minelga. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans. Volume 114 Lyon, France: International Agency for Research on Cancer (2018). 1–517.
- Abete I, Romaguera D, Vieira AR, Lopez de Munain A, Norat T. Association between Total, processed, red and white meat consumption and all-cause, Cvd and Ihd mortality: a Meta-analysis of cohort studies. *Br J Nutr.* (2014) 112:762–75. doi: 10.1017/S000711451400124X
- Barnard N, Levin S, Trapp C. Meat consumption as a risk factor for type 2 diabetes. *Nutrients.* (2014) 6:897–910. doi: 10.3390/nu6020897
- Cross AJ, Freedman ND, Ren J, Ward MH, Hollenbeck AR, Schatzkin A, et al. Meat consumption and risk of esophageal and gastric cancer in a large prospective study. *Am J Gastroenterol.* (2011) 106:432–42. doi: 10.1038/ajg.2010.415
- Lim WY, Chuah KL, Eng P, Leong SS, Lim E, Lim TK, et al. Meat consumption and risk of lung cancer among never-smoking women. *Nutr Cancer.* (2011) 63:850–9. doi: 10.1080/01635581.2011.589961
- Zhu H, Yang X, Zhang C, Zhu C, Tao G, Zhao L, et al. Red and processed meat intake is associated with higher gastric Cancer risk: a Meta-analysis of epidemiological observational studies. *PLoS One.* (2013) 8:e70955. doi: 10.1371/journal.pone.0070955
- Farvid MS, Stern MC, Norat T, Sasazuki S, Vineis P, Weijenberg MP, et al. Consumption of red and processed meat and breast cancer incidence: a systematic review and meta-analysis of prospective studies. *Int J Cancer.* (2018) 143:2787–99. doi: 10.1002/ijc.31848
- Song M, Fung TT, Hu FB, Willett WC, Longo VD, Chan AT, et al. Association of animal and plant protein intake with all-cause and cause-specific mortality. *JAMA Intern Med.* (2016) 176:1453–63. doi: 10.1001/jamainternmed.2016.4182
- Naghshi S, Sadeghi O, Willett WC, Esmailzadeh A. Dietary intake of Total, animal, and plant proteins and risk of all cause, cardiovascular, and Cancer mortality: systematic review and dose-response Meta-analysis of prospective cohort studies. *BMJ.* (2020) 370:m2412. doi: 10.1136/bmj.m2412
- Neuenschwander M, Stadelmaier J, Eble J, Grummich K, Szczerba E, Kiesswetter E, et al. Substitution of animal-based with plant-based foods on cardiometabolic health and all-cause mortality: a systematic review and Meta-analysis of prospective studies. *BMC Med.* (2023) 21:404. doi: 10.1186/s12916-023-03093-1
- Zhong VW, Allen NB, Greenland P, Carnethon MR, Ning H, Wilkins JT, et al. Protein foods from animal sources, incident cardiovascular disease and all-cause mortality: a substitution analysis. *Int J Epidemiol.* (2021) 50:223–33. doi: 10.1093/ije/dyaa205
- Jahn S, Furchheim P, Strässner A-M. Plant-based meat alternatives: motivational adoption barriers and solutions. *Sustainability.* (2021) 13:13271. doi: 10.3390/su132313271
- Szenderak J, Frona D, Rakos M. Consumer acceptance of plant-based meat substitutes: a narrative review. *Foods.* (2022) 11:1274. doi: 10.3390/foods11091274
- Andreani G, Sogari G, Marti A, Frolidi F, Dagevos H, Martini D. Plant-based meat alternatives: technological, nutritional, environmental, market, and social challenges and opportunities. *Nutrients.* (2023) 15:452. doi: 10.3390/nu15020452
- Grundey SM, Denke MA. Dietary influences on serum lipids and lipoproteins. *J Lipid Res.* (1990) 31:1149–72. doi: 10.1016/s0022-2275(20)42625-2
- Fernandez ML, West KL. Mechanisms by which dietary fatty acids modulate plasma lipids. *J Nutr.* (2005) 135:2075–8. doi: 10.1093/jn/135.9.2075
- Perna M, Hewlings S. Saturated fatty acid chain length and risk of cardiovascular disease: a systematic review. *Nutrients.* (2022) 15:30. doi: 10.3390/nu15010030
- Gillingham LG, Harris-Jan S, Jones PJ. Dietary monounsaturated fatty acids are protective against metabolic syndrome and cardiovascular disease risk factors. *Lipids.* (2011) 46:209–28. doi: 10.1007/s11745-010-3524-y
- Abdelhamid AS, Martin N, Bridges C, Brainard JS, Wang X, Brown TJ, et al. Polyunsaturated fatty acids for the primary and secondary prevention of cardiovascular disease. *Cochrane Database Syst Rev.* (2018) 11:CD012345. doi: 10.1002/14651858.CD012345.pub3
- Schwingshackl L, Zahring J, Beyerbach J, Werner SS, Nagavci B, Hesecker H, et al. A scoping review of current guidelines on dietary fat and fat quality. *Ann Nutr Metab.* (2021) 77:65–82. doi: 10.1159/000515671
- EFSA Panel on Dietetic Products N, and Allergies. Scientific opinion on dietary reference values for fats, including saturated fatty acids, polyunsaturated fatty acids, monounsaturated fatty acids, trans fatty acids, and cholesterol. *EFSA J.* (2010) 8:1461. doi: 10.2903/j.efsa.2010.1461
- Simopoulos AP. Omega-3 fatty acids in health and disease and in growth and development. *Am J Clin Nutr.* (1991) 54:438–63. doi: 10.1093/ajcn/54.3.438
- Innis SM. Dietary omega 3 fatty acids and the developing brain. *Brain Res.* (2008) 1237:35–43. doi: 10.1016/j.brainres.2008.08.078
- Swanson D, Block R, Mousa SA. Omega-3 fatty acids Epa and Dha: health benefits throughout life. *Adv Nutr.* (2012) 3:1–7. doi: 10.3945/an.111.000893
- Lands B. Consequences of essential fatty acids. *Nutrients.* (2012) 4:1338–57. doi: 10.3390/nu4091338
- Biazotto KR, Xavier ACH, de Mattos RR, Furlan JM, Wagner R, Bandoni DH, et al. Plant-based burgers in the spotlight: a detailed composition evaluation and comprehensive discussion on nutrient adequacy. *Foods.* (2025) 14:372. doi: 10.3390/foods14030372
- Romao B, Botelho RBA, Torres ML, Maynard DDC, de Holanda MEM, Borges VRP, et al. Nutritional profile of commercialized plant-based meat: an integrative review with a systematic approach. *Foods.* (2023) 12:448. doi: 10.3390/foods12030448
- Szabo Z, Marosvolgyi T, Szabo E, Koczka V, Verzar Z, Figler M, et al. Effects of repeated heating on fatty acid composition of plant-based cooking oils. *Foods.* (2022) 11:192. doi: 10.3390/foods11020192
- Moubarac JC, Parra DC, Cannon G, Monteiro CA. Food classification systems based on food processing: significance and implications for policies and actions: a systematic literature review and assessment. *Curr Obes Rep.* (2014) 3:256–72. doi: 10.1007/s13679-014-0092-0
- Metz KM, Neumann NJ, Fasshauer M. Ultra-processing markers are more prevalent in plant-based meat products as compared to their meat-based counterparts in a German food market analysis. *Public Health Nutr.* (2023) 26:2728–37. doi: 10.1017/S1368980023002458
- Bleiweiss-Sande R, Chui K, Evans EW, Goldberg J, Amin S, Sackeck J. Robustness of food processing classification systems. *Nutrients.* (2019) 11:1344. doi: 10.3390/nu11061344
- De Marchi M, Costa A, Pozza M, Goi A, Manuelli CL. Detailed characterization of plant-based burgers. *Sci Rep.* (2021) 11:2049. doi: 10.1038/s41598-021-81684-9
- Hernandez MS, Coyle K, Siebecker MG, Woerner DR, Brooks JC, Legako JF. Nutritional profiling of plant-based meat alternatives and ground beef. *J Food Sci.* (2024) 89:9230–42. doi: 10.1111/1750-3841.17579
- Pointke M, Pawelzik E. Plant-based alternative products: are they healthy alternatives? Micro- and macronutrients and nutritional scoring. *Nutrients.* (2022) 14:601. doi: 10.3390/nu14030601
- He J, Liu H, Balamurugan S, Shao S. Fatty acids and volatile flavor compounds in commercial plant-based burgers. *J Food Sci.* (2021) 86:293–305. doi: 10.1111/1750-3841.15594
- Yazdanparast S, Mohammadi-Nasrabadi F, Hashmati A, Rezazadeh R, Taheri M, Alhouei B, et al. Comprehensive assessment of fatty acid profiles of meat products to develop action plan strategies for healthier products. *Sci Rep.* (2025) 15:23188. doi: 10.1038/s41598-025-04749-z
- Szabó E, Boehm G, Beermann C, Weyermann M, Brenner H, Rothenbacher D, et al. Trans octadecenoic acid and trans octadecadienoic acid are inversely related to long-chain polyunsaturates in human Milk: results of a large birth cohort study. *Am J Clin Nutr.* (2007) 85:1320–6. doi: 10.1093/ajcn/85.5.1320
- Chen J, Liu H. Nutritional indices for assessing fatty acids: a Mini-review. *Int J Mol Sci.* (2020) 21:5695. doi: 10.3390/ijms21165695
- Dal Bosco A, Cavallo M, Menchetti L, Angelucci E, Cartoni Mancinelli A, Vaudo G, et al. The healthy fatty index allows for deeper insights into the lipid composition of foods of animal origin when compared with the atherogenic and thrombogenicity indexes. *Foods.* (2024) 13:1568. doi: 10.3390/foods13101568
- Curtain F, Grafenauer S. Plant-based meat substitutes in the flexitarian age: an audit of products on supermarket shelves. *Nutrients.* (2019) 11:2603. doi: 10.3390/nu11112603
- Alessandrini R, Brown MK, Pombo-Rodrigues S, Bhageerutty S, He FJ, MacGregor GA. Nutritional quality of plant-based meat products available in the UK: a Cross-sectional survey. *Nutrients.* (2021) 13:4225. doi: 10.3390/nu13124225
- Romao B, Botelho RBA, Nakano EY, Raposo A, Han H, Vega-Munoz A, et al. Are vegan alternatives to meat products healthy? A study on nutrients and main ingredients of products commercialized in Brazil. *Front Public Health.* (2022) 10:900598. doi: 10.3389/fpubh.2022.900598
- Moonaisur N, Marx-Pienaar N, de Kock HL. Plant-based meat alternatives in South Africa: an analysis of products on supermarket shelves. *Food Sci Nutr.* (2024) 12:627–37. doi: 10.1002/fsn3.3765
- Bryngelsson S, Moshtaghian H, Bianchi M, Hallstrom E. Nutritional assessment of plant-based meat analogues on the Swedish market. *Int J Food Sci Nutr.* (2022) 73:889–901. doi: 10.1080/09637486.2022.2078286
- Petersen T, Hirsch S. Comparing meat and meat alternatives: an analysis of nutrient quality in five European countries. *Public Health Nutr.* (2023) 26:3349–58. doi: 10.1017/S1368980023001945

51. Costa-Catala J, Toro-Funes N, Comas-Baste O, Hernandez-Macias S, Sanchez-Perez S, Latorre-Moratalla ML, et al. Comparative assessment of the nutritional profile of meat products and their plant-based analogues. *Nutrients*. (2023) 15:2807. doi: 10.3390/nu15122807
52. Zhang Q, Liu Y, He C, Zhu R, Li M, Lam HM, et al. Nutritional assessment of plant-based meat products available on Hong Kong market: a Cross-sectional survey. *Nutrients*. (2023) 15:3684. doi: 10.3390/nu15173684
53. Drewnowski A, Bruins MJ, Besselink JFF. Comparing nutrient profiles of meat and fish with plant-based alternatives: analysis of nutrients, ingredients, and fortification patterns. *Nutrients*. (2024) 16:2725. doi: 10.3390/nu16162725
54. Guidance document for competent authorities, tolerances for the control of compliance of nutrient values declared on a label with Eu legislation, (2012). Available online at: https://food.ec.europa.eu/system/files/2016/10/labelling_nutrition-vitamins_minerals-guidance_tolerances_1212_en.pdf
55. Jiménez-Colmenero F, Pintado T, Cofrades S, Ruiz-Capillas C, Bastida S. Production variations of nutritional composition of commercial meat products. *Food Res Int*. (2010) 43:2378–84. doi: 10.1016/j.foodres.2010.09.009
56. Perez-Palacios T, Ruiz J, Martin D, Muriel E, Antequera T. Comparison of different methods for Total lipid quantification in meat and meat products. *Food Chem*. (2008) 110:1025–9. doi: 10.1016/j.foodchem.2008.03.026
57. Howe JC, Trainer D, Holden JM, Douglass LW. Fat content of ground beef: comparison of actual (analytical) to label claim. *FASEB J*. (2007) 21:A318. doi: 10.1096/fasebj.21.5.A318-b
58. Dillitzer N, Thes M, Theis R, Kuchler M, Kienzle E, Dobenecker B. Higher in Fat as Labelled – Raw Meat Products in Focus. European Society of Veterinary & Comparative Nutrition Congress; Munich, Germany(2018).
59. Zapata-Muriel A, Echeverry P, Van Dusseldorp TA, Kurtz J, Monsalves-Alvarez M. Measured versus label declared macronutrient and calorie content in Colombian commercially available whey proteins. *J Int Soc Sports Nutr*. (2022) 19:258–66. doi: 10.1080/15502783.2022.2090828
60. Aly MO, Ghobashy SM, Aborhyem SM. Authentication of protein, fat, carbohydrates, and Total energy in commercialized high protein sports foods with their Labeling data. *Sci Rep*. (2023) 13:15359. doi: 10.1038/s41598-023-42084-3
61. Yuliarti O, Kiat Kovis TJ, Yi NJ. Structuring the meat analogue by using plant-based derived composites. *J Food Eng*. (2021) 288:110138. doi: 10.1016/j.jfoodeng.2020.110138
62. Ismail I, Hwang YH, Joo ST. Meat Analog as future food: a review. *J Anim Sci Technol*. (2020) 62:111–20. doi: 10.5187/jast.2020.62.2.111
63. Smetana S, Mathys A, Knoch A, Heinz V. Meat alternatives: life cycle assessment of most known meat substitutes. *Int J Life Cycle Assess*. (2015) 20:1254–67. doi: 10.1007/s11367-015-0931-6
64. Tso R, Forde CG. Unintended consequences: nutritional impact and potential pitfalls of switching from animal- to plant-based foods. *Nutrients*. (2021) 13:2527. doi: 10.3390/nu13082527
65. Mertens E, Deriemaeker P, Van Beneden K. Analysis of the nutritional composition of ready-to-use meat alternatives in Belgium. *Nutrients*. (2024) 16:1648. doi: 10.3390/nu16111648
66. Bezdard J, Bugaut M, Clement G. Triglyceride composition of coconut oil. *J Am Oil Chem Soc*. (1971) 48:134–9. doi: 10.1007/BF02545736
67. Marina AM, Che Man YB, Nazimah SAH, Amin I. Chemical properties of virgin coconut oil. *J Am Oil Chem Soc*. (2009) 86:301–7. doi: 10.1007/s11746-009-1351-1
68. Barthet VJ. (N-7) and (N-9) Cis-monounsaturated fatty acid contents of 12 Brassica species. *Phytochem*. (2008) 69:411–7. doi: 10.1016/j.phytochem.2007.08.016
69. Szydłowska-Czerniak A, Trokowski K, Karlovits G, Szlyk E. Determination of anti-oxidant capacity, phenolic acids, and fatty acid composition of rapeseed varieties. *J Agric Food Chem*. (2010) 58:7502–9. doi: 10.1021/jf100852x
70. Özcan MM, Yılmaz FG, Uslu N, Kulluk DA, Dursun N, Yılmaz H. Determination of bioactive compounds, phenolic contents, fatty acid and biogenic element profiles of the seeds of sunflower (*Helianthus annuus* L.) genotypes. *Food Human*. (2024) 2:100222. doi: 10.1016/j.foohum.2023.100222
71. Talebi SM, Darbandi N, Naziri F, Matsuyura A. Seed morphometry and fatty acid profile in oilseed and non-oilseed sunflower cultivars. *Biochem Syst Ecol*. (2024) 113:104805. doi: 10.1016/j.bse.2024.104805
72. Daley CA, Abbott A, Doyle PS, Nader GA, Larson S. A review of fatty acid profiles and antioxidant content in grass-fed and grain-fed beef. *Nutr J*. (2010) 9:10. doi: 10.1186/1475-2891-9-10
73. Stender S, Astrup A, Dyerberg J. Ruminant and industrially produced trans fatty acids: health aspects. *Food Nutr Res*. (2008) 52. doi: 10.3402/fnr.v52i0.1651
74. Ran-Ressler RR, Bae S, Lawrence P, Wang DH, Brenna JT. Branched-chain fatty acid content of foods and estimated intake in the USA. *Br J Nutr*. (2014) 112:565–72. doi: 10.1017/S0007114514001081
75. Guillocheau E, Penhoat C, Drouin G, Godet A, Catheline D, Legrand P, et al. Current intakes of trans-palmitoleic (trans-C16:1 N-7) and trans-vaccenic (trans-C18:1 N-7) acids in France are exclusively ensured by ruminant Milk and ruminant meat: a market basket investigation. *Food Chem X*. (2020) 5:100081. doi: 10.1016/j.fochx.2020.100081
76. Gozdzik P, Magkos F, Sledzinski T, Mika A. Monomethyl branched-chain fatty acids: health effects and biological mechanisms. *Prog Lipid Res*. (2023) 90:101226. doi: 10.1016/j.plipres.2023.101226
77. Trefflich I, Dietrich S, Braune A, Abraham K, Weikert C. Short- and branched-chain fatty acids as fecal markers for microbiota activity in vegans and omnivores. *Nutrients*. (2021) 13:1808. doi: 10.3390/nu13061808
78. Wang DH, Yang Y, Wang Z, Lawrence P, Worobor RW, Brenna JT. High levels of branched chain fatty acids in natto and other Asian fermented foods. *Food Chem*. (2019) 286:428–33. doi: 10.1016/j.foodchem.2019.02.018
79. de Souza RJ, Mente A, Maroleanu A, Cozma AI, Ha V, Kishibe T, et al. Intake of saturated and trans unsaturated fatty acids and risk of all cause mortality, cardiovascular disease, and type 2 diabetes: systematic review and Meta-analysis of observational studies. *BMJ*. (2015) 351:h3978. doi: 10.1136/bmj.h3978
80. Wu W, Lin L, Shi B, Jing J, Cai L. The effects of early life polyunsaturated fatty acids and ruminant trans fatty acids on allergic diseases: a systematic review and Meta-analysis. *Crit Rev Food Sci Nutr*. (2019) 59:1802–15. doi: 10.1080/10408398.2018.1429382
81. Ulbricht TL, Southgate DA. Coronary heart disease: seven dietary factors. *Lancet*. (1991) 338:985–92. doi: 10.1016/0140-6736(91)91846-m
82. Organization WH. Saturated fatty acid and trans-fatty acid intake for adults and children: who guideline: World Health Organization. Geneva: World Health Organization (2023).
83. Santos-Silva J, Bessa RJB, Santos-Silva F. Effect of genotype, feeding system and slaughter weight on the quality of light lambs: ii. Fatty acid composition of meat. *Livest Prod Sci*. (2002) 77:187–94. doi: 10.1016/S0301-6226(02)00059-3
84. Lindberg L, Woodside JV, Nugent AP. Are plant-based meat alternatives the stepping stone to healthier and more sustainable diets? A review of the literature. *Proc Nutr Soc*. (2025) 1–12. doi: 10.1017/S0029665125100608
85. Flint M, Bowles S, Lynn A, Paxman JR. Novel plant-based meat alternatives: future opportunities and health considerations. *Proc Nutr Soc*. (2023) 82:370–85. doi: 10.1017/S0029665123000034
86. Locatelli NT, Chen GFN, Batista MF, Furlan JM, Wagner R, Bandoni DH, et al. Nutrition classification schemes for plant-based meat analogues: drivers to assess nutritional quality and identity profile. *Curr Res Food Sci*. (2024) 9:100796. doi: 10.1016/j.crfcs.2024.100796
87. de Las Heras-Delgado S, Shyam S, Cunillera E, Dragusan N, Salas-Salvado J, Babio N. Are plant-based alternatives healthier? A two-dimensional evaluation from nutritional and processing standpoints. *Food Res Int*. (2023) 169:112857. doi: 10.1016/j.foodres.2023.112857
88. Toh DWK, Fu AS, Mehta KA, Lam NYL, Haldar S, Henry CJ. Plant-based meat analogs and their effects on cardiometabolic health: an 8-week randomized controlled trial comparing plant-based meat analogs with their corresponding animal-based foods. *Am J Clin Nutr*. (2024) 119:1405–16. doi: 10.1016/j.ajcnut.2024.04.006
89. Fernandez-Rodriguez R, Bizzozero-Peroni B, Diaz-Goni V, Garrido-Miguel M, Bertotti G, Roldan-Ruiz A, et al. Plant-based meat alternatives and cardiometabolic health: a systematic review and meta-analysis. *Am J Clin Nutr*. (2025) 121:39653176:274–83. doi: 10.1016/j.ajcnut.2024.12.002

Glossary

AA: - arachidonic acid	IARC: - International Agency for Research on Cancer
AI: - atherogenicity index	IQR: - interquartile range
ALA: - alpha-linolenic acid	LA: - linoleic acid
AUC: - area under the curve	LDL: - low-density lipoprotein
BBP: - beef-based products	MUFA: - monounsaturated fatty acid
DHA: - docosahexaenoic acid	OA: - oleic acid
EFA: - essential fatty acid	PA: - palmitic acid
EPA: - eicosapentaenoic acid	PBMS: - plant-based meat substitute
FA: - fatty acid	PTV: - programmed temperature vaporization
FID: - flame ionization detector	PUFA: - polyunsaturated fatty acid
GC: - gas chromatography	SFA: - saturated fatty acid
HFI: - healthy fatty index	TFA: - <i>trans</i> isomeric fatty acid
hHI: - hypocholesterolemic/hypercholesterolemic index	TI: - thrombogenicity index
HPI: - health-promoting index	UFA: - unsaturated fatty acid
	UI: - unsaturation index