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Quality characteristics of beef tallow and pork lard obtained from different adipose tissues by low-temperature vacuum rendering

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ABSTRACT. Animal fats are valuable food ingredients owing to their technological, sensory, and functional properties. This study evaluated the influence of animal species and adipose tissue origin on physicochemical characteristics, fatty acid composition, oxidative stability, volatile compound profile, colour, and thermal behaviour of beef tallow and pork lard obtained by low-temperature vacuum rendering (90 ± 2 °C, 200 mbar). Beef visceral, subcutaneous, and groin fat, as well as pork leaf, back, jowl, and groin fat, were rendered under identical processing conditions. Significant differences in fatty acid composition were observed between the analysed fats ($P < 0.05$). Compared to beef fats, pork fats contained higher proportion of polyunsaturated, omega-3, and omega-6 fatty acids, whereas beef fats had more trans and selected saturated fatty acids. Beef fats were characterised by higher oxidation onset

temperatures, indicating greater thermo-oxidative stability. Significant differences were also found in peroxide value, malondialdehyde (MDA) content, colour parameters, and volatile compound profiles. Principal component analysis differentiated the rendered fats according to their volatile fingerprints, reflecting the effects of both animal species and adipose tissue origin on aroma characteristics. Despite compositional differences, all rendered fats showed low acid values, peroxide values, and MDA contents, indicating limited hydrolytic and oxidative deterioration under the applied rendering conditions. These findings indicate that the quality characteristics of rendered fats varied between samples from different species and anatomical fat depots, while low-temperature vacuum rendering was associated with generally favourable lipid composition and limited oxidative changes.

KEY WORDS: adipose tissue, fatty acid composition, oxidation onset temperature, physicochemical properties, volatile compounds

Introduction

Animal fats are important food ingredients due to their technological, sensory, and nutritional properties. In meat products, they contribute to texture, juiciness, flavour, mouthfeel, and overall acceptability, while their physicochemical characteristics influence processing performance and product stability. These properties are closely related to lipid composition, particularly the fatty acid profile, which affects fat consistency, melting behaviour, oxidative stability, flavour, and colour (Wood et al., 2008).

Fatty acid composition is therefore an important determinant of both the nutritional and technological quality of animal fats. A higher degree of unsaturation increases their susceptibility to lipid oxidation, resulting in the formation of secondary oxidation products, including volatile compounds responsible for undesirable flavours and odours, and consequently reducing product stability and shelf life (Wood et al., 2008; Shahidi and Hossain, 2022).

The composition of animal adipose tissue is influenced by several biological and production-related factors, including species, breed, genetics, age, fat deposition, and feeding strategy. Dietary fatty acids can be incorporated into animal tissues, but genetic background also affects how lipids are deposited and what is their fatty acid composition (Wood et al., 2008;

Zappaterra et al., 2020). Substantial species-related differences in the fatty acid profile of adipose tissue have also been reported, including markedly higher proportions of linoleic acid in pigs compared to cattle (Wood et al., 2008).

Moreover, adipose tissue is not compositionally uniform within an animal. Individual anatomical fat depots differ in their development and metabolic activity, which can result in substantial variation in fatty acid profiles and physicochemical properties. Such depot-specific differences may consequently influence oxidative stability, thermal behaviour, and technological suitability of the extracted fats. Anatomical variation in fatty acid composition among porcine adipose tissues has been reported previously, indicating that adipose tissue origin may influence the characteristics of the resulting fat (Zappaterra et al., 2020).

Edible animal fats are generally obtained by rendering, during which lipids are thermally separated from adipose and connective tissues. Conventional wet and dry rendering involve different mechanisms of heat and moisture transfer and may expose lipids to conditions promoting oxidative and hydrolytic changes. Thermal exposure is particularly relevant because heating accelerates fat oxidation and, under sufficiently severe conditions, may lead to further thermal-oxidative deterioration (Kowalski, 1991). Consequently, the use of milder rendering conditions, including lower temperatures and limited oxygen exposure, may help limit oxidative damage and preserve the quality of edible fats (Wojtasik-Kalinowska et al., 2021).

Although the effects of rendering conditions on animal fat quality have previously been investigated, comparative information on fats originating from different anatomical adipose depots and rendered under identical low-temperature vacuum conditions remains limited. In particular, studies jointly assessing fatty acid composition, oxidative stability, thermal behaviour, volatile profile, colour, and conventional physicochemical quality indices are scarce. Such an integrated approach is necessary to distinguish differences associated with animal species and anatomical origin from those resulting from processing conditions.

Therefore, we hypothesised that both animal species and the anatomical origin of adipose tissue significantly influence the physicochemical characteristics, fatty acid composition, oxidative stability, volatile profile, and colour of fats produced under standardised low-temperature vacuum rendering conditions. The aim of this study was to comprehensively compare the quality traits of beef tallow and pork lard obtained from seven anatomically distinct adipose tissues using identical rendering conditions. The findings demonstrate the combined effects of animal species and adipose tissue origin on the technological quality and oxidative stability of rendered animal fats.

Material and methods

Raw material

The experimental material consisted of rendered beef and pork fats obtained from adipose tissues differing in anatomical origin. Beef adipose tissues included visceral fat (F1), subcutaneous fat (F2), and groin fat (F3). Pork adipose tissues included visceral fat (leaf lard, F4), subcutaneous back fat (F5), jowl fat (F6), and groin fat (F7). In this study, the term “groin fat” refers to adipose tissue collected from the inguinal region of the carcass, near the junction of the abdominal wall and the hind limb. Sample F5 consisted predominantly of the inner layers of dorsal and cervical subcutaneous adipose tissue rather than a standardised backfat depot.

Cattle and pigs were obtained from local suppliers in eastern Poland. The cattle were fed a semi-intensive diet consisting of hay, maize silage, haylage, wheat meal, barley meal, and oatmeal. The cattle were housed indoors without access to pasture. The pig diet was based on barley, wheat, triticale, maize, and rapeseed meal. The pigs were reared under commercial production conditions and housed indoors. Adipose tissue samples from both cattle and pigs were collected during the winter period.

Three independent raw-material batches were obtained from the meat-processing plant on three separate slaughter days. Each batch represented a different pool of commercially reared animals. Within each slaughter batch, adipose tissues from several animals were pooled separately according to anatomical location to obtain approximately 1.5 kg of each tissue type. Beef tissues F1–F3 within a given batch originated from the same cattle slaughter lot, whereas pork tissues F4–F7 originated from the same pig slaughter lot. Each pooled tissue sample was subjected to a separate rendering process. Therefore, the experimental unit was the independent slaughter-day/rendering batch ($n = 3$ per adipose-tissue type). The cattle were young animals of dairy breeds and beef-dairy crosses with an approximate slaughter weight of 600 kg, and the pigs were crossbreeds of the Polish Landrace and Pietrain with an approximate slaughter weight of 115 kg.

Adipose tissue was collected at the meat processing plant where slaughter and carcass deboning were conducted. Beef fat was collected in two stages: subcutaneous fat during slaughter and perivisceral and inguinal fat was collected during deboning. All pork fat samples were collected during deboning. Following collection, the adipose tissues were vacuum-packed, labelled, and stored at 2 °C for up to 24 h before rendering. After rendering, the fats were transferred to plastic containers and allowed to solidify. The solidified fats were then vacuum-packed, frozen at –35 °C in a blast freezer, and stored at –60 °C for up to one month before physicochemical analyses were conducted.

Rendering procedure

Before rendering, adipose tissues were minced using a meat grinder equipped with two knives and two grinding plates with 15-mm perforations. Prior to processing, the material was tempered at 5 ± 0.5 °C. Approximately 1500 g of each adipose tissue type was rendered. All rendering experiments were conducted in triplicate using three independent processing runs for each adipose tissue type.

Rendering was carried out under laboratory conditions using a custom-designed system consisting of a heating chamber, reflux condenser, and vacuum pump. The process was conducted under reduced pressure (200 mbar) at 90 ± 2 °C. The rendering time depended on the type of adipose tissue and ranged from 16.0 ± 0.1 to 90.0 ± 1.6 min. Cattle visceral fat required the shortest processing time (16.0 ± 0.1 min), whereas pork jowl fat the longest (90.0 ± 1.6 min). Subcutaneous beef fat, beef groin fat, and pork leaf fat were rendered in approximately 30 min (30.0 ± 1.0 , 30.0 ± 1.3 , and 30.0 ± 1.1 min, respectively), while pork groin fat and pork back fat required 60.0 ± 0.7 min and 65.0 ± 0.9 min, respectively. During rendering, water released from the adipose tissue was continuously evaporated, condensed, and collected in a condensate vessel. The endpoint of the process was established experimentally and defined as the complete cessation of water evaporation, indicating complete moisture removal under the applied conditions. Rendering time was recorded as a process parameter. The procedure was performed in triplicate for each adipose tissue type, and only minor variation in rendering time was observed between independent runs, indicating good reproducibility of the process.

Determination of fatty acid content

The fatty acid profile was determined using a modified Folch method for lipid extraction, according to the procedure described by Onopiuk et al. (2022). The extracted lipids were converted into fatty acid methyl esters (FAMES). The resulting FAMES were analysed by gas chromatography using an Agilent GC-7890 gas chromatograph (Agilent Technologies, USA) equipped with a 60 m HP-88 capillary column (0.25 mm i.d. $\times$ 0.20 μ m film thickness; Agilent J&W GC Columns, USA). The chromatographic conditions were as follows: injection volume, 1 μ l; split ratio, 1:40; carrier gas, helium; helium flow rate, 50 ml/min; injector and detector temperatures, 260 °C. Individual fatty acids were identified by comparing their retention times with those of a certified fatty acid standard mixture (Supelco 37 Component FAME Mix;

Sigma-Aldrich, USA). The relative content of individual fatty acids was expressed as a percentage of the total identified fatty acids (% total FA). Three analytical replicates were performed for each sample.

Determination of oxidation onset temperature

The oxidation onset temperature (OOT) was determined using a DSC 1 differential scanning calorimeter (Mettler Toledo, Switzerland). The instrument was calibrated for temperature and enthalpy using indium and zinc standards. Samples (5.0 ± 0.1 mg) were placed in 40 μ l aluminium crucibles fitted with perforated lids, while an empty crucible served as the reference. The samples were heated from -50 °C to 250 °C at a rate of 10 °C/min under a continuous flow of air (90 ml/min). The OOT was determined from DSC thermograms as the intersection of the extrapolated baseline and the tangent drawn to the leading edge of the exothermic oxidation peak, according to the procedure described by Wirkowska-Wojdyła et al. (2022). Data acquisition and evaluation were performed using STARe Evaluation Software (version 9.30, Mettler Toledo, Switzerland).

Thiobarbituric acid reactive substance

Lipid oxidation was assessed by measuring thiobarbituric acid reactive substances (TBARS) according to a modified method of Pikul et al. (1989). Fat samples (5 g) were mixed with 50 ml of acidified 20% TCA solution and 2.5 ml of antioxidant solution containing 0.5% propyl gallate and 0.5% EDTA and homogenised for 2 min at 12000 rpm. The homogenate was filtered and diluted to 100 ml. A 5 ml aliquot was mixed with 5 ml of 0.02 M TBA solution and incubated in a boiling water bath for 40 min. Absorbance was measured at 532 nm. TBARS content was calculated using 1,1,3,3-tetramethoxypropane (TEP; 0–11 μ M) as a standard and expressed as mg MDA/kg sample. Analyses were performed in triplicate.

Determination of acid value

The acid value (AV) was determined to assess the free fatty acid content and the extent of hydrolytic deterioration in the lard and beef tallow samples. The AV is defined as the amount of potassium hydroxide needed to neutralise free fatty acids in oils or still fats. Briefly, 2 g of lard/beef tallow was diluted with a solvent consisting of 96% ethanol and diethyl ether (3:1, v/v). A few drops of phenolphthalein indicator were added, and the solution was titrated with 0.1 M potassium hydroxide solution until a pink colour persisted for at least 30 s. For each experimental variant, the acid value was determined in triplicate and calculated according to the following formula:

$$AV = \frac{5.611 \times (a - b)}{m},$$

where: AV – acid value (mg KOH/g), a – volume of 0.1 M potassium hydroxide solution used for titration of the sample (ml), b – volume of 0.1 M potassium hydroxide solution used for the blank determination (ml), m – mass of the analysed sample (g).

Determination of iodine value

The iodine value (IV) was determined to estimate the level of unsaturation in the tested lard/beef tallow samples. Briefly, 0.1 g of fat was placed in a 50 ml twist-off test tube, followed by the addition of 2.5 ml of chloroform and 3.75 ml of Hanus reagent. The mixture was shaken vigorously and placed in the dark for 30 min. Then, 3.75 ml of 10% KI solution, 12.5 ml of distilled water and a few drops of starch solution were added. The mixture was then titrated with 0.1 M sodium thiosulfate solution. For each experimental variant, the iodine value was determined in triplicate and calculated according to the following formula:

$$IV = \frac{1.269 \times (a - b)}{m},$$

where: IV – iodine value (g I₂/100 g fat), a – volume of 0.1 M sodium thiosulfate solution used for titration of the blank sample (ml), b – volume of 0.1 M sodium thiosulfate solution used for titration of the fat sample (ml), m – mass of the analysed sample (g).

Determination of peroxide value

The peroxide value was determined to assess the oxidative status of the tested lard/beef tallow samples. Approximately 0.7 g of fat was placed in a twist-off test tube and mixed with 3.5 ml of chloroform. Then, 5.25 ml of glacial acetic acid and 0.7 ml of saturated KI solution were added. After incubation in the dark for 5 min, a few drops of starch solution were added to the mixture which was then titrated immediately with 0.002 M sodium thiosulfate solution. Peroxide value measurements were carried out using three analytical replicates for each fat sample variant and calculated according to the following equation:

$$PV = \frac{(V_s - V_o) \times C}{m} \times 1000,$$

where: PV – peroxide value (meg O₂/kg fat), V_s – volume of 0.002 M sodium thiosulfate solution used for titration of the fat sample (ml), V_o – volume of 0.002 M sodium thiosulfate solution used for titration of the blank sample (ml), C – molar concentration of sodium thiosulfate solution (mol/L), m – mass of the analysed sample (g), 1000 – conversion factor expressing the result as milliequivalents of active oxygen per kilogram of fat.

Determination of saponification value

The saponification value (SV) was determined to estimate the total content of esterified fatty acids present in the analysed lard and beef tallow samples. Briefly, 0.5 g of the fat sample was mixed with 2.5 ml of distilled water, 5 ml of 0.5 M potassium hydroxide solution, and 25 ml of ethanol. The reaction mixture was heated in a water bath at 95 °C for 40 min to ensure complete saponification and subsequently cooled to room temperature. A blank sample was prepared simultaneously under identical conditions but without the addition of a fat sample. Following cooling, both the sample and blank solutions were titrated with 0.5 M hydrochloric acid in the presence of phenolphthalein indicator until the disappearance of the pink colour. Each experimental variant was analysed in three independent replicates. The saponification value was calculated according to the following equation:

$$SV = \frac{28.55 \times (a - b)}{m},$$

where: SV – saponification value (mg KOH/100 g fat), a – volume of 0.5 M hydrochloric acid used for titration of the blank sample (ml), b – volume of 0.5 M hydrochloric acid used for titration of the fat sample (ml), m – sample mass (g).

Analysis of volatile compound profile

The volatile compound profile was analysed using a Heracles II Electronic Nose (Alpha M.O.S., France) based on ultra-fast gas chromatography with headspace analysis, as previously described by Wojtasik-Kalinowska et al. (2016). The system was equipped with two capillary columns of different polarities (MXT-5 and MXT-1701; 180 μ m $\times$ 10 m) and two flame ionisation detectors (FID). Kovats retention indices were determined using n-alkane standards (n-butane to n-hexadecane). Volatile compounds were tentatively assigned using the AroChemBase database based on retention indices obtained on both columns, with an acceptance tolerance of ± 10 RI units. No authentic reference standards or GC-MS confirmation were used; therefore, all compound assignments were considered tentative.

Fat samples (2 g) were incubated in 20 ml headspace vials at 55 °C for 900 s with agitation (8.33 Hz). Hydrogen was used as the carrier gas. The injector temperature was 200 °C, and the oven programme was 60 °C for 2 s, followed by heating at 3 °C/s to 270 °C and holding for 20 s. FID temperatures were maintained at 280 °C. To minimise individual animal variation, adipose tissues from different animals within each experimental group were pooled before analysis. Three independent headspace vials were prepared from each pooled sample and analysed separately.

Colour measurement

Colour parameters (L*, a*, and b*) were measured using a CR-400 chromameter (Konica Minolta Inc., Japan) with D65 illuminant and a 2° standard observer. Ten measurements were

taken at different locations on the surface of the rendered fat samples, and the results were expressed as mean values. Chroma (C^*) was calculated according to the following equation (Szpicer et al., 2020):

$$C = \sqrt{a^2 + b^2}.$$

Statistical analysis

Three independent slaughter-day batches were produced for each experimental variant and considered biological replicates ($n = 3$), with all analytical measurements performed separately for each batch. Statistical analyses were conducted using STATISTICA 13.3 (TIBCO Software Inc., USA). Data were analysed by one-way ANOVA followed by Tukey's HSD test, with significance set at $P < 0.05$. Results are presented as mean $\pm$ standard deviation (SD). Principal component analysis (PCA) was performed using AlphaSoft 8 (Alpha MOS, France) based on chromatographic fingerprints generated by the Heracles II electronic nose. Software-selected chromatographic peak responses were used as variables without manual peak selection. For each experimental group, three analytical replicates from the pooled sample were included separately in the PCA, corresponding to the multiple points shown in Figure 1. PCA was used as an exploratory technique to visualise similarities and differences between samples; therefore, sample separation was interpreted descriptively rather than as evidence of predictive classification.

Results and discussion

Fatty acid composition

The fatty acid profile is an important determinant of both the nutritional value and technological properties of animal fats. Table 1 presents the fatty acid composition of the rendered animal fats.

In all samples, oleic acid (C18:1n9) and palmitic acid (C16:0) were the predominant fatty acids. Oleic acid accounted for 37.5–43.0% of total fatty acids, whereas palmitic acid represented 21.8–27.4%. No significant differences were observed between the samples for either C18:1n9 or C16:0 ($P \geq 0.05$). The predominance of oleic and palmitic acids observed in the present study is consistent with previous reports on cattle adipose tissue, where these fatty acids also constituted the major fraction of total fatty acids (Gamarra et al., 2018), as well as studies conducted on porcine adipose tissue (Huang et al., 2020; Zappaterra et al., 2020). These results confirm that oleic and palmitic acids are the dominant fatty acids in both rendered pork and beef fats.

Most of the rendered fat samples showed no significant differences in total saturated fatty acid (SFA) content. Although one-way ANOVA indicated a significant overall effect ($P < 0.05$), post hoc Tukey's test showed that only visceral beef fat (F1) differed significantly from pork jowl fat (F6) and pork groin fat (F7), whereas no significant differences were found between the other samples. SFA content in all samples ranged from 33.8% to 49.9% of total fatty acids. Likewise, no statistically significant differences were found in total monounsaturated fatty acid (MUFA) content ($P \geq 0.05$), which ranged from 44.4% to 55.2% of total fatty acids.

In contrast, significant differences ($P < 0.05$) were observed for several individual fatty acids. Compared to pork fats, beef fats generally contained higher proportions of myristic acid (C14:0), myristoleic acid (C14:1), palmitoleic acid (C16:1n7), heptadecanoic acid (C17:0), stearic acid (C18:0), and trans-oleic acid (C18:1n9 trans). These differences may reflect both species-specific lipid metabolism and differences in feeding conditions between cattle and pigs. The extensive biohydrogenation of dietary unsaturated fatty acids in the rumen may also contribute to the fatty acid profile of beef fats. In addition, adipose tissues from various anatomical locations differ in lipid metabolism and fatty acid deposition, which may contribute

to depot-specific variation in fatty acid composition. Previous studies have reported that anatomical fat depots showed distinct lipid accumulation patterns and fatty acid profile owing to their specific physiological functions and metabolic characteristics (Wood et al., 2008; Hocquette et al., 2010). The observed differences in polyunsaturated fatty acid (PUFA) content should therefore be interpreted in the context of both dietary fatty acid availability and species-specific lipid metabolism. In monogastric animals such as pigs, dietary PUFAs are absorbed with little modification and are readily incorporated into adipose tissue, resulting in a fatty acid profile that more closely reflects dietary intake. In contrast, in ruminants, dietary PUFAs undergo extensive microbial biohydrogenation before intestinal absorption, substantially reducing the proportion of unsaturated fatty acids available for tissue deposition. Consequently, the lower PUFA content of the beef fats is consistent with the combined effects of ruminal metabolism and the subsequent deposition of fatty acids into adipose tissues (Wood et al., 2008; Shingfield et al., 2013).

Significant differences were observed in PUFA content ($P < 0.05$). Total PUFA content did not differ between beef fat samples (F1–F3) and ranged from 1.9% to 2.0% of total fatty acids. Among pork fats, PUFA content ranged from 11.4% to 17.5%, with pork leaf fat (F4) and pork jowl fat (F6) reaching the highest values. Pork groin fat (F7) showed intermediate values and did not differ significantly from either F4/F6 or pork back fat (F5). Pork back fat (F5) also had an intermediate PUFA content and differed significantly from both the beef fat samples and the pork depots with the highest PUFA contents. The overlapping significance groups are consistent with intermediate PUFA levels in some adipose depots rather than indicating inconsistencies in the statistical analysis. In particular, pork back fat had fatty acid proportions intermediate between the more highly unsaturated pork depots and the more saturated beef fats, resulting in partial overlap among significance groups. The higher PUFA content in pork fats is consistent with previous reports indicating that monogastric animals

incorporate dietary unsaturated fatty acids into adipose tissue more efficiently than ruminants, in which dietary PUFAs undergo extensive microbial biohydrogenation in the rumen (Wood et al., 2008; Huang et al., 2020). Sample F5 consisted predominantly of inner layers of dorsal and cervical subcutaneous fat rather than a standardised backfat depot. Previous studies have demonstrated that inner backfat layers generally contain lower proportions of C18:2n-6 and total PUFAs and higher proportions of *de novo* synthesised fatty acids compared to outer layers, which may partly explain the comparatively lower PUFA and omega-6 contents observed in F5.

A similar pattern was observed for omega-3 and omega-6 fatty acids. Beef fat samples were characterised by low omega-3 (0.2–0.3%) and omega-6 (1.1–1.2%) contents. Regarding omega-3 fatty acids, pork leaf fat (F4) had the highest values, whereas pork back fat (F5) showed intermediate levels of these acids. Pork jowl fat (F6) and pork groin fat (F7) displayed intermediate values and did not differ significantly from either F4 or F5 due to overlapping significance groups. Nevertheless, all pork fat depots contained significantly higher omega-3 contents than the beef fat samples. For omega-6 fatty acids, pork leaf fat (F4), pork jowl fat (F6), and pork groin fat (F7) had the highest values and differed significantly from the beef fat samples, whereas pork back fat (F5) showed intermediate values and differed significantly from both the beef fat samples and the remaining pork fat depots. These findings are consistent with previous reports demonstrating a greater contribution of essential PUFAs in porcine adipose tissue than in cattle fat (Jiang et al., 2017; Huang et al., 2020). Additionally, previous studies have demonstrated lower proportions of C18:2n-6 and total PUFAs in inner backfat layers than in outer layers, reflecting differences in lipid metabolism and fatty acid deposition patterns (Daza et al., 2007). Moreover, as the present study evaluated rendered fats obtained under mild reduced-pressure conditions (90 °C, 200 mbar), oxidative losses of polyunsaturated fatty acids

during processing may have been lower than those reported for conventional high-temperature rendering procedures.

Trans fatty acid (TFA) content differed significantly among the fat samples ($P < 0.05$). The highest TFA levels were observed in visceral (F1) and subcutaneous (F2) beef fat, which did not differ significantly from each other but contained significantly more TFA than all other samples. Beef groin fat (F3) had an intermediate TFA content, i.e, significantly lower than F1 and F2 but higher than all pork fat samples ($P < 0.05$). In contrast, all pork fat depots (F4–F7) contained similarly low TFA levels (approximately 0.2%) and did not differ significantly from one another ($P \geq 0.05$). The elevated TFA content of beef fat is consistent with ruminal biohydrogenation, during which TFA intermediates are formed by rumen microorganisms (Wood, 2008). It should be noted that individual conjugated linoleic acid (CLA) isomers were not determined in the adipose tissues prior to rendering. As CLAs, particularly cis-9,trans-11 C18:2, are naturally present in ruminant adipose tissue because of ruminal biohydrogenation, their determination could provide additional information on the fatty acid characteristics of the raw material and possible changes associated with rendering. Therefore, assessing the major CLA isomers in adipose tissue before and after rendering should be considered in future research. The TFA levels in the present study were lower than those reported by Lisitsyn et al. (2017), who reported trans-9-C18:1 concentrations of 3.1% in beef and 2.63% in pork intramuscular lipids. These discrepancies may be attributed, at least in part, to the different lipid fractions analysed, as the present study focused on rendered adipose tissues from distinct anatomical depots, whereas Lisitsyn et al. (2017) examined intramuscular fat.

The higher trans fatty acid content in beef fats is consistent with ruminal biohydrogenation, during which rumen microorganisms convert dietary unsaturated fatty acids into TFA intermediates, particularly vaccenic acid (trans-11 C18:1). After intestinal absorption, these intermediates are accumulated in adipose tissue, and their relative abundance may vary in

individual anatomical depots owing to differences in lipid turnover and fat deposition. Therefore, depot-specific variation in TFA content likely reflects not only ruminal biohydrogenation but also tissue-specific post-absorptive lipid metabolism (Wood et al., 2008; Shingfield et al., 2013).

Oxidation onset temperature

Thermo-oxidative stability of fats is strongly influenced by fatty acid composition, particularly the degree of unsaturation, with a higher oxidation onset temperature (OOT) indicating greater resistance to this process (Rastrelli et al., 2002). In the present study, beef fats generally had higher OOT values than pork fats, which corresponded with their substantially lower PUFA contents.

However, fatty acid composition alone did not fully explain the variation in OOT (Table 2). Pork jowl fat (F6) had a significantly lower OOT than all other fats ($P < 0.05$), despite PUFA contents and iodine values comparable to those of pork leaf (F4) and groin fat (F7). In contrast, the relatively high OOT of beef subcutaneous fat (F2) and pork back fat (F5) was consistent with their comparatively low PUFA contents. These findings suggest that thermo-oxidative stability reflects the combined effects of fatty acid composition and the presence of other lipid constituents, including endogenous antioxidants and pro-oxidants (Kowalski et al., 2004; Domínguez et al., 2019). However, as these compounds were not quantified, their contribution cannot be confirmed.

OOT was not fully reflected by MDA content. Although F6 had the lowest OOT, its MDA concentration was lower than that of F7. This difference reflects the distinct information provided by these methods: OOT indicates resistance to oxidation initiation during controlled heating, whereas MDA represents secondary oxidation products already present in the fat. Therefore, OOT and MDA should be regarded as complementary indicators of oxidative stability.

Chemical quality

During thermal processing, fats undergo hydrolytic and oxidative changes that may affect their chemical composition and quality, depending on factors such as fatty acid unsaturation, pro-oxidant content, and oxidative stability (Zhang et al., 2012). The acid, iodine, saponification, and peroxide values, as well as TBARS expressed as MDA, are presented in Table 3.

Acid values differed significantly between the fat samples ($P < 0.05$), with visceral beef fat (F1) showing a significantly lower value than subcutaneous beef fat (F2), pork leaf fat (F4), and pork groin fat (F7). Nevertheless, all values remained below the maximum permissible level of 1.0 mg KOH/g specified for edible animal fats by the Polish Committee for Standardisation (PN-A-86908:2000), indicating limited hydrolytic deterioration. This is consistent with previous reports of low free fatty acid levels in properly rendered animal fats (Meeker, 2020).

The iodine value reflects the degree of unsaturation of fats and is directly related to the content of unsaturated fatty acids. Significant differences in iodine value were observed among the fat samples ($P < 0.05$). Pork groin fat (F7) had a higher iodine value than all beef fat samples (F1–F3), whereas the remaining samples displayed intermediate values. No significant differences were detected in the beef (F1–F3) or pork samples (F4–F7), indicating a generally similar degree of unsaturation in each species despite differences between individual fat depots. The variation in iodine value was consistent with the fatty acid composition determined by gas chromatography. Samples with higher iodine values generally contained greater proportions of unsaturated fatty acids, particularly PUFAs and omega-6 fatty acids, whereas lower iodine values were associated with higher percentage of saturated fatty acids. These findings indicate that iodine value adequately reflects differences in the degree of fat unsaturation between the samples.

Peroxide values differed significantly between the experimental groups ($P < 0.05$). The highest peroxide values were observed in visceral beef fat (F1) and beef groin fat (F3), which did not differ significantly from one another ($P \geq 0.05$) but contained higher levels of primary oxidation products than the remaining groups ($P < 0.05$). In contrast, all other fat samples had peroxide values below 2 meq O_2 /kg fat, indicating a relatively low degree of primary lipid oxidation. Since peroxide value reflects the concentration of lipid hydroperoxides formed during the initial stages of oxidation, these results suggest greater susceptibility of F1 and F3 to oxidative changes compared to the other analysed fats. Despite these differences, all peroxide values remained relatively low, indicating limited primary lipid oxidation. Similar observations were reported for freshly rendered fats and lipid systems exposed to mild thermal treatment, where peroxide values generally remained below the threshold associated with advanced oxidative deterioration (Domínguez et al., 2019).

No significant differences were observed in saponification values ($P \geq 0.05$), suggesting similar average fatty acid chain lengths in the analysed fats. The obtained values (191.11–206.42 mg KOH/g fat) were comparable to those reported by Sharma et al. (2013) for pork fat and beef tallow.

The extent of secondary lipid oxidation was evaluated using the TBARS assay and expressed as MDA content. Significant differences in MDA concentration were observed between the experimental groups ($P < 0.05$). The highest MDA content was recorded in subcutaneous beef fat (F2), indicating the greatest accumulation of secondary oxidation products. The lowest values were recorded in visceral beef fat (F1), beef groin fat (F3), and pork back fat (F5), which did not differ significantly from one another, while intermediate MDA levels were found in pork leaf fat (F4), pork jowl fat (F6), and pork groin fat (F7). The distribution of MDA concentrations did not correspond directly to that of peroxide values. The samples with the highest peroxide values (F1 and F3) did not reach the highest MDA

concentrations. This can be explained by the different stages of lipid oxidation measured by the two assays. Peroxide value (PV) measures the accumulation of lipid hydroperoxides, which are primary oxidation products formed during the propagation stage of lipid oxidation, whereas TBARS reflects MDA and other carbonyl compounds associated with the decomposition of hydroperoxides into secondary oxidation products (Meeker, 2020; Abeyrathne et al. 2021). Consequently, PV and MDA concentrations do not necessarily increase in parallel, as hydroperoxide formation and decomposition can occur simultaneously at different rates (Meeker, 2020; Zhang et al., 2021). The elevated PV and relatively low MDA concentrations in F1 and F3 may therefore indicate greater accumulation of primary oxidation products with limited conversion into secondary oxidation products at the time of analysis, whereas the opposite pattern in F2 may be consistent with more advanced decomposition of these primary oxidation products. However, this interpretation cannot establish the progression of oxidation over time because the measurements were performed at a single post-rendering time point. The results therefore provide information on the oxidative state of the fats at the time of analysis rather than on the kinetics of lipid oxidation. PV and TBARS should consequently be regarded as complementary measures of lipid oxidation, reflecting different groups of oxidation products rather than directly interchangeable indicators of oxidative deterioration (Domínguez et al., 2019; Abeyrathne et al., 2021; Zhang et al., 2021). Although naturally occurring antioxidants may also affect the oxidative stability of the fats, their concentrations were not directly determined in the present study, and thus their contribution cannot be established.

The low levels of both primary (peroxide value) and secondary (TBARS) oxidation products may be attributed to the mild rendering conditions applied in the present study. Rendering was performed under reduced pressure (200 mbar) at a relatively low temperature (90 ± 2 °C), conditions that may have limited oxygen exposure and thermal degradation of lipids. These conditions are consistent with low-temperature rendering systems described by

Sharma et al. (2013) as advantageous for preserving fat quality and minimising thermal damage. The lower oxygen availability under reduced pressure, together with the relatively low rendering temperature, may have limited lipid oxidation compared to conventional rendering at atmospheric pressure and higher temperatures. However, because the study did not include a conventional rendering treatment as a control, the specific contribution of reduced pressure and temperature to the observed oxidative stability cannot be assessed. Similar effects of reduced oxygen exposure and mild processing temperatures on lipid stability were described in previous studies evaluating oxidative changes in edible fats and oils (Shahidi and Zhong, 2010; Shahidi and Hossain, 2022). Thus, peroxide value and TBARS should be regarded as complementary indicators of different stages of lipid oxidation rather than as parameters expected to change proportionally. This may explain why some samples with relatively high peroxide values did not simultaneously showed elevated TBARS values, indicating that lipid oxidation in the individual rendered fat samples may have been at different stages.

Volatile compound profile

Aroma characteristics are closely related to lipid composition and oxidation, as the degradation of unsaturated fatty acids generates volatile compounds contributing to the sensory properties of fats (Wood et al., 2008; Bleicher et al., 2022).

The principal volatile markers differentiating the beef tallow and pork lard samples were tentatively assigned using the HERACLES II electronic nose and are presented in Table 4.

Aldehydes are considered important secondary products of lipid oxidation and contributors to volatile flavour formation in meat and meat products due to their low odour thresholds and high sensory impact (Shahidi and Zhong, 2010). They are formed mainly through the oxidation and subsequent degradation of unsaturated fatty acids, generating aroma notes that may be perceived as fatty, green, grassy, roasted or rancid depending on their structure and concentration (Mogilnicka et al., 2020; Bleicher et al., 2022). Compounds tentatively assigned

as propanal and (E)-2-butenal were detected in all samples. Their tentative assignment is consistent with volatile compounds previously reported as products of unsaturated fatty acid oxidation during rendering (Mogilnicka et al., 2020). The tentative detection of aldehydes in all samples suggests that lipid oxidation products may contribute to aroma formation during rendering. According to Bleicher et al. (2022), aldehydes represent one of the major classes of aroma-active compounds in meat and fat products and are often responsible for characteristic species-specific sensory notes. Differences in the abundance of tentatively identified aldehydes between adipose depots may result from variations in fatty acid composition and susceptibility to oxidative reactions.

Amines represented another important class of volatile compounds. A compound tentatively identified as trimethylamine was detected in all samples. Trimethylamine is commonly associated with ammoniacal and fishy odour notes and has previously been reported as a volatile compound occurring in animal-derived products (Bekhit et al., 2021). Additionally, 1-butanamine was detected in subcutaneous beef fat (F2) and pork jowl fat (F6), indicating differences in the occurrence of this compound between adipose depots.

Alcohols were tentatively assigned only in selected samples. A compound tentatively identified as 2-propanol was present in beef groin fat (F3) and pork groin fat (F7), whereas n-butanol was identified in pork leaf fat (F4) and pork back fat (F5). Alcohols are generally formed through the reduction of aldehydes or the decomposition of lipid hydroperoxides and may contribute green, fatty, fruity, or alcoholic aroma notes. Although their odour thresholds are usually higher than those of aldehydes, they may influence overall aroma complexity and the perception of other volatile compounds (Bleicher et al., 2022).

Several additional volatile compounds were tentatively identified in specific fat depots. Dimethyl sulphide was tentatively detected in subcutaneous beef fat (F2) and in pork back, jowl, and groin fat samples (F5–F7). Sulphur-containing compounds are characterised by low

odour thresholds and may contribute cabbage-like, sulphurous, and cooked aroma notes. Acetic acid was identified in pork leaf fat (F4) and pork groin fat (F7), while ethyl isobutyrate was tentatively detected in pork leaf, back, and jowl fat samples (F4–F6), and may add fruity aroma notes. Limonene was identified only in pork jowl and groin fat (F6 and F7), whereas undecane was detected in subcutaneous and groin beef fat and in pork leaf and back fat (F2–F5).

A compound tentatively identified as 2,3-dimethylpyrazine was detected exclusively in pork fat samples (F4–F7). Pyrazines belong to a group of aroma-active compounds characterised by low odour thresholds and high sensory impact (Chao et al., 2020; Wojtasik-Kalinowska et al., 2021;). Pyrazines are commonly formed during Maillard reactions and contribute roasted, caramelised, nutty, and meaty odour notes to thermally processed foods. Therefore, the presence of 2,3-dimethylpyrazine may be associated with heat-induced reactions occurring during the rendering process. Pyrazines has previously been reported in rendered goose fat, where they were associated with thermal processing conditions and the development of characteristic aroma attributes (Wojtasik-Kalinowska et al., 2021).

According to the AroChemBase database, these tentatively assigned compounds are associated with green, fatty, fruity, or alcoholic odour descriptors. However, no sensory analysis was performed; therefore, these descriptors should not be interpreted as evidence of the perceived aroma of the fat samples.

PCA showed differences in the volatile profiles of the fat samples (Figure 1). The first two principal components explained 71.367% of the total variance (PC1 = 48.885%, PC2 = 22.482%). Samples F1 and F2 were located on the negative side of PC1, whereas samples F3, F4, F5, and F7 were positioned on the positive side. Sample F3 was the most clearly separated from the others, indicating a distinct volatile composition. The distribution of the samples on the PCA plot suggests that the observed variation in volatile profiles was associated with both animal species and anatomical origin.

Colour parameters

Significant differences ($P < 0.05$) were observed between the samples for L^* , a^* , b^* , and C^* (Table 5). F4 had the highest lightness (L^*), whereas F6 showed the lowest. All samples had negative a^* values, while F3 was characterised by the highest yellowness (b^*) and chroma (C^*). In contrast, F7 showed the lowest b^* value. Overall, beef fats generally had higher yellowness and chroma than pork fats, which could be related to differences in carotenoid accumulation in cattle adipose tissue (Dunne et al., 2009). However, as carotenoid content was not determined in the present study, this interpretation remains hypothetical.

It should be noted that the current study was conducted under commercial production conditions using raw materials collected directly from a slaughter line. The cattle and pigs were raised under different, species-specific feeding regimes, as described in Section 2.1, and diet is an important factor influencing the fatty acid composition of adipose tissue. Consequently, the differences observed between the beef and pork fats cannot be attributed solely to animal species. Both species-related metabolic characteristics and feeding conditions may have contributed to the observed fatty acid profiles. As the study was not designed to separate the effects of species and diet experimentally, these factors cannot be considered independently when interpreting the observed differences in fatty acid composition.

Conclusions

Low-temperature vacuum rendering resulted in animal fats with favourable physicochemical parameters and low levels of primary and secondary oxidation products under the conditions applied in this study. Differences in quality characteristics were observed between the evaluated combinations of animal species and adipose depots, indicating that raw material origin may be an important consideration in edible fat production and technological applications. However, as the effects of animal species, feeding conditions, adipose tissue

depot, and rendering duration were not experimentally separated, their individual contributions to the observed differences cannot be determined independently.

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Conflict of interest

The Authors declare that there is no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

- Abeyrathne E.D.N.S., Nam K., Ahn D.U., 2021. Analytical methods for lipid oxidation and antioxidant capacity in food systems. *Antioxidants* 10, 1587, <https://doi.org/10.3390/antiox10101587>
- Bekhit A.E.D.A., Giteru S.G., Holman B.W.B., Hopkins D.L., 2021. Total volatile basic nitrogen and trimethylamine in muscle foods: Potential formation pathways and effects on human health. *Compr. Rev. Food Sci. Food Saf.* 20, 3620–3666, <https://doi.org/10.1111/1541-4337.12764>
- Bleicher J., Ebner E.E., Bak K.H., 2022. Formation and analysis of volatile and odor compounds in meat—A review. *Molecules* 27, 6703, <https://doi.org/10.3390/molecules27196703>
- Chao Z., Hui C., Jianbo X., 2020. Pyrazines in food. In: J. Xiao, S. Sarker, Y. Asakawa (Editors). *Handbook of Dietary Phytochemicals*. Springer Nature. Singapore, pp. 1–25, https://doi.org/10.1007/978-981-13-1745-3_44-1
- Daza A., Ruiz-Carrascal J., Olivares A., Menoyo D., López-Bote C.J., 2007. Fatty acids profile of the subcutaneous backfat layers from Iberian pigs raised under free-range conditions. *Food Sci. Technol. Int.* 13, 135–142, <https://doi.org/10.1177/1082013207077925>
- Domínguez R., Pateiro M., Gagaoua M., Barba F.J., Zhang W., Lorenzo J.M., 2019. A comprehensive review on lipid oxidation in meat and meat products. *Antioxidants* 8, 429, <https://doi.org/10.3390/antiox8100429>
- Dunne P.G., Monahan F.J., O'Mara F.P., Moloney A.P., 2009. Colour of bovine subcutaneous adipose tissue: A review of contributory factors, associations with carcass and meat quality and its potential utility in authentication of dietary history. *Meat Sci.* 81, 28–45, <https://doi.org/10.1016/j.meatsci.2008.06.013>
- Gamarra D., Aldai N., Arakawa A., Barron L.J.R., Lopez-Oceja A., de Pancorbo M.M., Taniguchi M., 2018. Distinct correlations between lipogenic gene expression and fatty acid composition of subcutaneous fat among cattle breeds. *BMC Vet. Res.* 14, 167, <https://doi.org/10.1186/s12917-018-1481-5>
- Hocquette J.F., Gondret E., Médale H., Jurie C., Pethick D.W., 2010. Intramuscular fat content in meat-producing animals: Development, genetic and nutritional control, and identification of putative markers. *Animal* 4, 303–319, <https://doi.org/10.1017/S1751731109991091>
- Huang Y., Zhou L., Zhang J. et al., 2020. A large-scale comparison of meat quality and intramuscular fatty acid composition among three Chinese indigenous pig breeds. *Meat Sci.* 168, 108182, <https://doi.org/10.1016/j.meatsci.2020.108182>
- Jiang J., Tang X., Xue Y., Lin G., Xiong Y.L., 2017. Dietary linseed oil supplemented with organic selenium improved the fatty acid nutritional profile, muscular selenium deposition, water retention, and tenderness of fresh pork. *Meat Sci.* 131, 99–106, <https://doi.org/10.1016/j.meatsci.2017.03.014>
- Kowalski B., 1991. Thermal-oxidative decomposition of edible oils and fats. DSC studies. *Thermochim. Acta* 184, 49–57, [https://doi.org/10.1016/0040-6031\(91\)80134-5](https://doi.org/10.1016/0040-6031(91)80134-5)
- Kowalski B., Ratusz K., Kowalska D., Bekas W., 2004. Determination of the oxidative stability of vegetable oils by Differential Scanning Calorimetry and Rancimat measurements. *Eur. J. Lipid Sci. Technol.* 106, 165–169, <https://doi.org/10.1002/ejlt.200300915>

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- Lisitsyn A.B., Chernukha I.M., Lunina O.I., 2017. Fatty acid composition of meat from various animal species and the role of technological factors in transisomerization of fatty acids. *Foods Raw Mater.* 5, 54–61, <https://doi.org/10.21603/2308-4057-2017-2-54-61>
- Meeker D., 2020. Rendering. In: F. Shahidi (Editor). *Bailey's Industrial Oil and Fat Products*. John Wiley & Sons. Hoboken, NJ (USA), <https://doi.org/10.1002/047167849X.bio073.pub2>
- Mogilnicka I., Bogucki P., Ufnal M., 2020. Microbiota and malodor—Etiology and management. *Int. J. Mol. Sci.* 21, 2886, <https://doi.org/10.3390/ijms21082886>
- Onopiuk A., Kołodziejczak K., Szpicer A., Marcinkowska-Lesiak M., Wojtasik-Kalinowska I., Stelmasiak A., Półtorak A., 2022. The effect of partial substitution of beef tallow on selected physicochemical properties, fatty acid profile and PAH content of grilled beef burgers. *Foods* 11, 1986, <https://doi.org/10.3390/foods11131986>
- Pikul J., Leszczynski D.E., Kummerow F.A., 1989. Evaluation of three modified TBA methods for measuring lipid oxidation in chicken meat. *J. Agric. Food Chem.* 37, 1309–1313, <https://doi.org/10.1021/jf00089a022>
- Polish Committee for Standardization (PKN), 2000. PN-A-86908:2000. Vegetable and Animal Oils and Fats—Refined Vegetable Oils. PKN. Warsaw (Poland)
- Rastrelli L., Passi S., Ippolito F., Vacca G., De Simone F., 2002. Rate of degradation of α -tocopherol, squalene, phenolics, and polyunsaturated fatty acids in olive oil during different storage conditions. *J. Agric. Food Chem.* 50, 5566–5570, <https://doi.org/10.1021/jf011063j>
- Shahidi F., Hossain A., 2022. Role of lipids in food flavor generation. *Molecules* 27, 5014, <https://doi.org/10.3390/molecules27155014>
- Shahidi F., Zhong Y., 2010. Lipid oxidation and improving the oxidative stability. *Chem. Soc. Rev.* 39, 4067–4079, <https://doi.org/10.1039/B922183M>
- Sharma H., Giriprasad R., Goswami M., 2013. Animal fat—Processing and its quality control. *J. Food Process. Technol.* 4, 252, <https://doi.org/10.4172/2157-7110.1000252>
- Shingfield K.J., Bonnet M., Scollan N.D., 2013. Recent developments in altering the fatty acid composition of ruminant-derived foods. *Animal* 7, 132–162, <https://doi.org/10.1017/S1751731112001681>
- Szpicer A., Onopiuk A., Półtorak A., Wierzbicka A., 2020. The influence of oat β -glucan content on the physicochemical and sensory properties of low-fat beef burgers. *CyTA J. Food* 18, 315–327, <https://doi.org/10.1080/19476337.2020.1750095>
- Wirkowska-Wojdyła M., Ostrowska-Ligeża E., Górską A., Bryś J., 2022. Application of chromatographic and thermal methods to study fatty acids composition and positional distribution, oxidation kinetic parameters and melting profile as important factors characterizing amaranth and quinoa oils. *Appl. Sci.* 12, 2166, <https://doi.org/10.3390/app12042166>
- Wojtasik-Kalinowska I., Górską-Horczyk E., Stelmasiak A., Marcinkowska-Lesiak M., Onopiuk A., Wierzbicka A., Półtorak A., 2021. Effect of temperature and oxygen dose during rendering of goose fat to promote fatty acid profiles. *Eur. J. Lipid Sci. Technol.* 123, 2100085, <https://doi.org/10.1002/ejlt.202100085>
- Wojtasik-Kalinowska I., Guzek D., Górską-Horczyk E., Głąbska D., Brodowska M., Sun D.-W., Wierzbicka A., 2016. Volatile compounds and fatty acids profile in

-
- Longissimus dorsi* muscle from pigs fed with feed containing bioactive components. LWT Food Sci. Technol. 67, 112–117, <https://doi.org/10.1016/j.lwt.2015.11.023>
- Wood J.D., Enser M., Fisher A.V., Nute G.R., Sheard P.R., Richardson R.I., Hughes S.I., Whittington F.M., 2008. Fat deposition, fatty acid composition and meat quality: A review. Meat Sci. 78, 343–358, <https://doi.org/10.1016/j.meatsci.2007.07.019>
- Zappaterra M., Catillo G., Belmonte A.M., Fiego D.P.L., Zambonelli P., Steri R., Buttazzoni L., Davoli R., 2020. Genetic parameters of muscle fatty acid profile in a purebred Large White heavy pig population. Meat Sci. 163, 108057, <https://doi.org/10.1016/j.meatsci.2020.108057>
- Zhang N., Li Y., Wen S., Sun Y., Chen J., Gao Y., Sagymbek A., Yu X., 2021. Analytical methods for determining the peroxide value of edible oils: A mini-review. Food Chem. 358, 129834, <https://doi.org/10.1016/j.foodchem.2021.129834>
- Zhang Q., Saleh A.S.M., Chen J., Shen Q., 2012. Chemical alterations taken place during deep-fat frying based on certain reaction products: A review. Chem. Phys. Lipids 165, 662–681, <https://doi.org/10.1016/j.chemphyslip.2012.07.002>

Table 1. Fatty acid composition of animal rendered fat samples (% total fatty acids), n = 3

ITEM	F1	F2	F3	F4	F5	F6	F7
C14:0	2.3 ± 0.2 ^{bc}	3.3 ± 0.3 ^{cd}	4.1 ± 0.4 ^d	1.6 ± 0.2 ^a	1.1 ± 0.1 ^a	1.2 ± 0.1 ^a	1.4 ± 0.1 ^{ab}
C14:1	0.3 ± 0.1 ^a	1.8 ± 0.2 ^b	1.6 ± 0.2 ^b	<0.1 ^a	<0.1 ^a	<0.1 ^a	<0.1 ^a
C16:0	26.5 ± 2.7 ^a	26.6 ± 2.7 ^a	27.4 ± 2.7 ^a	24.3 ± 2.4 ^a	24.0 ± 2.4 ^a	21.8 ± 2.2 ^a	22.0 ± 2.2 ^a
C16:1n7	2.5 ± 0.3 ^b	6.8 ± 0.7 ^c	6.8 ± 0.7 ^c	1.5 ± 0.2 ^a	2.1 ± 0.2 ^a	1.9 ± 0.2 ^a	2.0 ± 0.2 ^a
C17:0	1.4 ± 0.1 ^c	0.8 ± 0.1 ^b	0.8 ± 0.1 ^b	0.4 ± 0.1 ^a	0.3 ± 0.1 ^a	0.4 ± 0.1 ^a	0.4 ± 0.1 ^a
C17:1	0.6 ± 0.1 ^{bc}	0.9 ± 0.1 ^c	0.9 ± 0.1 ^c	0.3 ± 0.1 ^{ab}	0.2 ± 0.1 ^a	0.3 ± 0.1 ^{ab}	0.3 ± 0.1 ^{ab}
C18:0	19.7 ± 2.0 ^b	8.5 ± 0.8 ^a	9.6 ± 1.0 ^a	12.9 ± 1.3 ^a	14.1 ± 1.4 ^{ab}	10.4 ± 1.0 ^a	10.2 ± 1.0 ^a
C18:1n9 <i>trans</i>	1.6 ± 0.2 ^c	1.3 ± 0.1 ^c	0.8 ± 0.1 ^b	0.2 ± 0.1 ^a	0.2 ± 0.1 ^a	0.2 ± 0.1 ^a	0.2 ± 0.1 ^a
C18:1n9	38.7 ± 3.9 ^a	42.1 ± 4.2 ^a	41.2 ± 4.1 ^a	37.5 ± 3.8 ^a	41.6 ± 4.2 ^a	42.7 ± 4.3 ^a	43.0 ± 4.3 ^a
C18:1n7	1.0 ± 0.1 ^a	2.1 ± 0.2 ^b	1.8 ± 0.2 ^b	2.2 ± 0.2 ^b	3.2 ± 0.3 ^c	3.2 ± 0.3 ^c	3.1 ± 0.3 ^c
C18:2 <i>trans</i>	0.4 ± 0.1 ^b	0.5 ± 0.1 ^b	0.4 ± 0.1 ^b	<0.1 ^a	<0.1 ^a	<0.1 ^a	<0.1 ^a
C18:2n6	1.2 ± 0.1 ^a	1.1 ± 0.1 ^a	1.2 ± 0.1 ^a	15.6 ± 2.0 ^c	10.1 ± 1.3 ^{ab}	14.0 ± 1.8 ^c	14.0 ± 1.8 ^c
C20:1n9	0.2 ± 0.1 ^a	0.2 ± 0.1 ^a	0.1 ± 0.1 ^a	0.7 ± 0.1 ^{ab}	0.8 ± 0.1 ^b	1.0 ± 0.1 ^b	0.8 ± 0.1 ^b
C18:3n3	0.3 ± 0.1 ^a	0.3 ± 0.1 ^a	0.2 ± 0.1 ^a	1.3 ± 0.2 ^b	0.7 ± 0.1 ^b	1.1 ± 0.1 ^c	1.1 ± 0.1 ^b
C20:2n6	<0.1 ^a	<0.1 ^a	<0.1 ^a	0.5 ± 0.1 ^b	0.5 ± 0.1 ^b	0.6 ± 0.1 ^b	0.5 ± 0.1 ^b
C20:3n3	<0.1 ^a	<0.1 ^a	<0.1 ^a	0.1 ± 0.1 ^b	0.1 ± 0.1 ^{ab}	0.2 ± 0.1 ^b	0.1 ± 0.1 ^{ab}
ΣSFA	49.9 ± 5.0 ^b	39.2 ± 3.9 ^{ab}	41.9 ± 4.2 ^{ab}	39.2 ± 4.0 ^{ab}	39.5 ± 4.0 ^{ab}	33.8 ± 3.4 ^a	34.0 ± 3.4 ^a
ΣMUFA	44.9 ± 4.8 ^a	55.2 ± 5.6 ^a	53.2 ± 5.5 ^a	42.4 ± 4.5 ^a	48.1 ± 5.0 ^a	49.3 ± 5.1 ^a	49.4 ± 5.1 ^a
ΣPUFA	2.0 ± 0.3 ^a	2.0 ± 0.3 ^a	1.9 ± 0.3 ^a	17.5 ± 2.4 ^c	11.4 ± 1.6 ^b	15.9 ± 2.1 ^c	15.7 ± 2.1 ^{bc}
ΣTFA	2.0 ± 0.3 ^c	1.8 ± 0.2 ^c	1.2 ± 0.2 ^b	0.2 ± 0.1 ^a	0.2 ± 0.1 ^a	0.2 ± 0.1 ^a	0.2 ± 0.1 ^a
Omega-3	0.3 ± 0.1 ^{ab}	0.3 ± 0.1 ^{ab}	0.2 ± 0.1 ^a	1.4 ± 0.3 ^d	0.8 ± 0.2 ^{bc}	1.3 ± 0.2 ^{cd}	1.2 ± 0.2 ^{cd}
Omega-6	1.2 ± 0.1 ^a	1.1 ± 0.1 ^a	1.2 ± 0.1 ^a	16.1 ± 2.1 ^c	10.6 ± 1.4 ^b	14.6 ± 1.9 ^c	14.5 ± 1.9 ^c
Omega-9	38.9 ± 4.0 ^a	42.3 ± 4.3 ^a	41.3 ± 4.2 ^a	38.2 ± 3.9 ^a	42.4 ± 4.3 ^a	43.7 ± 4.4 ^a	43.8 ± 4.4 ^a

F1 – visceral beef fat, F2 – subcutaneous beef fat, F3 – beef groin fat, F4 – pork leaf fat, F5 – pork back fat, F6 – pork jowl fat, F7 – pork groin fat, SFA – saturated fatty acids, MUFA – monounsaturated fatty acids, PUFA – polyunsaturated fatty acids, TFA – trans fatty acids; ΣSFA = C14:0 + C16:0 + C17:0 + C18:0, ΣMUFA = C14:1 + C16:1n7 + C17:1 + C18:1n9 *trans* + C18:1n9 + C18:1n7 + C20:1n9, ΣPUFA = C18:2 *trans* + C18:2n6 + C18:3n3 + C20:2n6 + C20:3n3, ΣTFA = C18:1n9 *trans* + C18:2 *trans*, Omega-3 = C18:3n3 + C20:3n3, Omega-6 = C18:2n6 + C20:2n6, Omega-9 = C18:1n9 + C20:1n9; ^{abc} – values are reported as mean ± standard deviation (n = 3)

independent rendering batches); different lowercase superscript letters in the same row indicate statistically significant differences between experimental groups ($P < 0.05$)

Table 2. Oxidation onset temperature of rendered animal fat samples determined by differential scanning calorimetry

Group	Oxidation onset temperature, °C
F1	211.05 ± 1.01 ^{cd}
F2	213.25 ± 0.86 ^d
F3	213.12 ± 2.01 ^d
F4	208.30 ± 1.09 ^{bc}
F5	214.00 ± 2.05 ^d
F6	184.26 ± 1.15 ^a
F7	205.03 ± 1.99 ^b

F1 – visceral beef fat, F2 – subcutaneous beef fat, F3 – beef groin fat, F4 – pork leaf fat, F5 – pork back fat, F6 – pork jowl fat, F7 – pork groin fat; ^{a-d} – values are reported as mean ± standard deviation (n = 3 independent rendering batches); different lowercase superscript letters in the same column indicate statistically significant differences between experimental groups ($P < 0.05$)

Table 3. Acid value, iodine value, saponification value, peroxide value and malondialdehyde (MDA) content of selected animal fats

Group	Acid value, mg KOH/g	Iodine value, g I ₂ /100 g fat	Peroxide value, meq O ₂ /kg fat	Saponification value, mg KOH/100 g fat	MDA, mg/kg sample
F1	0.37 ± 0.12 ^a	32.14 ± 0.73 ^a	3.81 ± 0.15 ^b	203.04 ± 15.87 ^a	0.13 ± 0.004 ^a
F2	0.67 ± 0.01 ^b	32.96 ± 1.86 ^{ab}	1.22 ± 0.17 ^a	206.42 ± 10.75 ^a	0.77 ± 0.024 ^d
F3	0.52 ± 0.13 ^{ab}	31.99 ± 1.90 ^a	3.80 ± 0.51 ^b	200.46 ± 11.07 ^a	0.15 ± 0.005 ^a
F4	0.88 ± 0.15 ^b	34.85 ± 1.53 ^{abc}	1.44 ± 0.69 ^a	198.90 ± 5.22 ^a	0.28 ± 0.038 ^c
F5	0.81 ± 0.13 ^{ab}	36.04 ± 1.68 ^{bc}	0.65 ± 0.43 ^a	205.79 ± 7.71 ^a	0.11 ± 0.027 ^a
F6	0.47 ± 0.27 ^{ab}	36.72 ± 0.30 ^{bc}	1.61 ± 0.7 ^a	191.11 ± 15.74 ^a	0.21 ± 0.018 ^b
F7	0.86 ± 0.11 ^b	37.82 ± 2.4 ^c	1.45 ± 0.65 ^a	194.01 ± 6.28 ^a	0.31 ± 0.036 ^c

F1 – visceral beef fat, F2 – subcutaneous beef fat, F3 – beef groin fat, F4 – pork leaf fat, F5 – pork back fat, F6 – pork jowl fat, F7 – pork groin fat; ^{a-d} – values are reported as mean ± standard deviation (n = 3 independent rendering batches); different lowercase superscript letters in the same column indicate statistically significant differences between experimental groups ($P < 0.05$)

Table 4. Tentatively assigned volatile compounds detected in rendered animal fats using an electronic nose based on Kovats retention indices and the AroChemBase database

IR DB-5	IR DB-17-01*	Tentatively assigned compound	Chemical group	Sensory descriptor	F1	F2	F3	F4	F5	F6	F7
490	650	Trimethylamine	Amine	Ammoniacal	+	+	+	+	+	+	+
510	600	Propanal	Aldehyde	Green	+	+	+	+	+	+	+
516	550	Dimethyl sulfide	Sulfur compound	Cabbage-like		+			+	+	+

IR DB-5	IR DB-17-01*	Tentatively assigned compound	Chemical group	Sensory descriptor	F1	F2	F3	F4	F5	F6	F7
520	630	2-propanol	Alcohol	Alcoholic			+				+
563	688	Butane-2,3-dione	Ketone	Buttery	+	+	+			+	
564	661	Butanal	Aldehyde	Malty		+	+	+	+	+	+
570	720	1-butanamine	Amine	Ammoniacal		+				+	
620	700	2-methylfuran	Furan	Grassy	+		+				
636	779	Acetic acid	Organic acid	Acidic				+			+
655	778	n-butanol	Alcohol	Alcoholic				+	+		
660	830	(E)-but-2-enal	Aldehyde	Roasted	+	+	+			+	+
726	822	Ethyl isobutyrate	Ester	Fruity			+	+	+		
937	1020	2,3-dimethylpyrazine	Pyrazine	Roasted				+	+	+	+
1047	1082	Limonene	Terpene	Fruity						+	+
1100	1100	Undecane	Hydrocarbon	Alkane		+	+	+	+		

F1 – visceral beef fat, F2 – subcutaneous beef fat, F3 – beef groin fat, F4 – pork leaf fat, F5 – pork back fat, F6 – pork jowl fat, F7 – pork groin fat; * retention indexes for DB-5 and DB-17 columns. Sensory descriptors were automatically assigned by the AlphaSoft database to tentatively assigned volatile compounds based on retention indices. They are indicative only and should not be interpreted as evidence of the perceived aroma of the samples, since no sensory evaluation was performed.

Table 5. Instrumental color characteristic of beef and pork fat tissues

PARAMETER	F1	F2	F3	F4	F5	F6	F7
L*	78.87 ± 0.32 ^c	83.97 ± 0.41 ^f	83.06 ± 0.19 ^e	84.13 ± 0.06 ^f	77.96 ± 0.16 ^b	73.32 ± 0.11 ^a	80.83 ± 0.14 ^d
a*	-3.03 ± 0.06 ^e	-3.77 ± 0.09 ^c	-4.76 ± 0.05 ^a	-4.56 ± 0.02 ^b	-2.83 ± 0.01 ^f	-3.66 ± 0.03 ^d	-3.82 ± 0.02 ^c
b*	0.71 ± 0.12 ^b	12.95 ± 0.29 ^d	19.92 ± 0.35 ^f	13.99 ± 0.03 ^e	1.32 ± 0.02 ^c	1.39 ± 0.05 ^c	-0.90 ± 0.06 ^a
C*	3.11 ± 0.03 ^a	13.49 ± 0.25 ^c	20.48 ± 0.33 ^e	14.72 ± 0.02 ^d	3.12 ± 0.01 ^a	3.92 ± 0.01 ^b	3.92 ± 0.03 ^b

F1 – visceral beef fat, F2 – subcutaneous beef fat, F3 – beef groin fat, F4 – pork leaf fat, F5 – pork back fat, F6 – pork jowl fat, F7 – pork groin fat, L* – lightness, a* – red-green coordinate, b* – yellow-blue coordinate, C* – chroma; ^{a-f} – values are reported as mean ± standard deviation (n = 3 independent rendering batches); different lowercase superscript letters in the same row indicate statistically significant differences between experimental groups ($P < 0.05$)

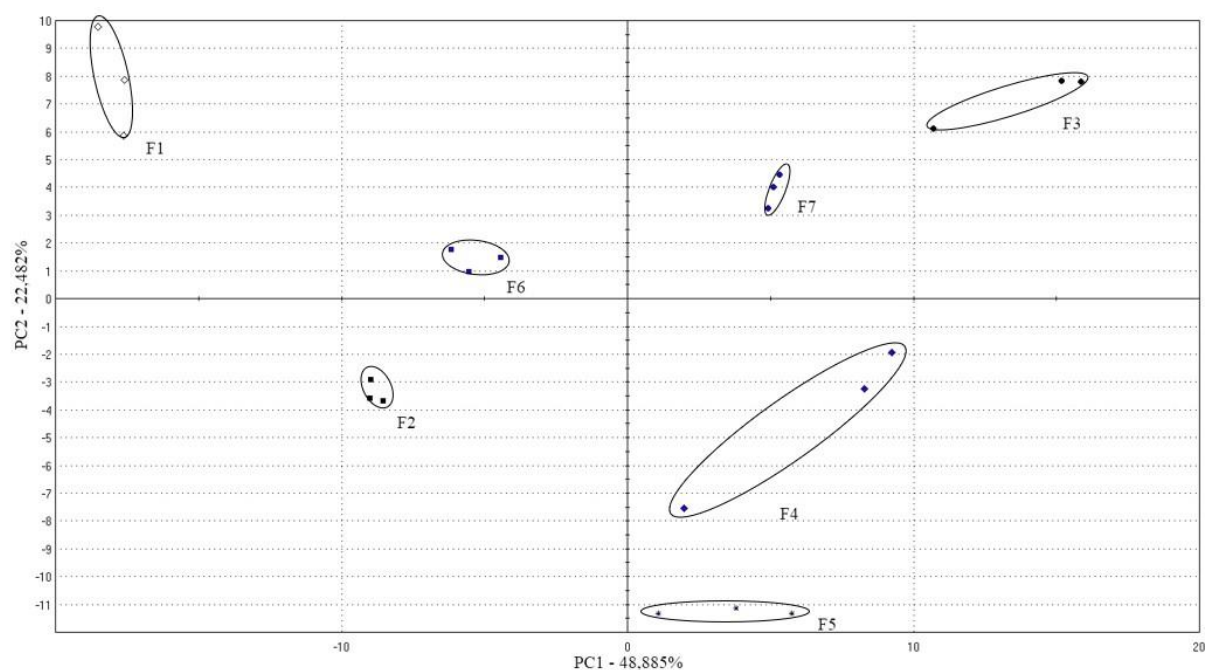


Figure 1. Principal Component Analysis (PCA) of volatiles from selected animal fats.

F1 – visceral beef fat, F2 – subcutaneous beef fat, F3 – beef groin fat, F4 – pork leaf fat, F5 – pork back fat, F6 – pork jowl fat, F7 – pork groin fat