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Research Article

Growth performance, ruminal fermentation, and lipid metabolism of lambs fed bergamot (*Citrus* × *bergamia* Risso) by-products

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ABSTRACT

The aim of this study was to evaluate the impacts of dietary bergamot (*Citrus* × *bergamia* Risso) by-products partially replacing maize on growth performance, rumen fermentation, and lipid metabolism in rumen, abomasum and meat. Moreover, for assessing the contribution of bergamot bioactive compounds, unprocessed bergamot pulp was compared with pulp from which these compounds had been extracted. Thirty-six 2-month-old lambs were divided into 3 groups and fed for 50 days: a maize-based diet (CON), or the same CON diet with 200 g/kg DM of dried bergamot pulp, or the same CON diet with 200 g/kg DM of dephenolized bergamot pulp. Dietary treatments did not affect growth performance, carcass traits, and ruminal fermentation. The chemical characteristics of bergamot pulps influenced the ruminal lipid metabolism, reducing the accumulation of undesirable C18:1 *t*10 in meat. However, the overall fatty acid composition of meat remained unaltered.

1. Introduction

Feeding livestock with by-products derived from crops residues and food processing is a common practice which dates back to the earliest stages of animal domestication. This alimentation technique of using agro-industrial by-products in substitution of conventional feedstuffs offers several advantages (Salami et al., 2019). Firstly, it helps to reduce the feed-food competition, and consequently the use of agricultural land that could otherwise be allocated to food production (Sandström et al., 2022). Secondly, from an economic perspective, this strategy allows to contain disposal costs, for processing industries, and diminish the expenditure on herd diets, for farmers (Dominguez Aldama et al., 2023). Thirdly, the replacement of cultivated feeds can mitigate the environmental impact related to their cultivation and transportation (K. Wang et al., 2024). Finally, feeding livestock with agro-industrial residues can enhance the quality of animal products, given their richness in bioactive compounds (Mapiye et al., 2026).

In the last years, a number of by-products have been proposed to be valorised as innovative ingredients for animal feed, such as that derived from nuts (Musati et al., 2023), pomegranates (Hoseini et al., 2025), olives (Tzamaloukas et al., 2021), or grapes (Wang et al.,

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2024). Particularly ruminants are able to exploit by-products, often rich in fibre, such as hemicellulose, pectin, and cellulose, to meet their energy needs. In this context, by-products derived from citrus industry processing could be a valid alternative to conventional feedstuffs, as their chemical composition is rich in fibres, mainly pectins and soluble carbohydrates, which are easily fermentable (Bampidis and Robinson, 2006). Furthermore, citrus by-products are widely available, as citrus fruits are the most produced fruit worldwide, with a global production of over 166 million tons in 2024 (FAOSTAT, 2026). Roughly one-third of citrus fruits are processed (FAO, 2021), mainly to produce juice, but also to extract pectin and essential oils. This process generates a large amount of waste, mostly made up of peels, pulp residues, and seeds. In fact, these by-products can represent between 50% and 70% of the original fresh fruit weight, depending on the type of fruit and the processing methods used (Zema et al., 2018).

The impacts of using citrus by-products in animal nutrition have been explored under different perspectives, investigating different animal species, metabolism, and quality of meat, milk, and dairy products. For instance, including up to 100 g/kg dry matter (DM) of citrus pulp in dairy rations improves milk yield and fat yield, however, higher doses may reduce feed intake while still sustaining the overall energy output of the milk (Hartinger et al., 2024). Feeding steers with 150 g/kg DM dried citrus pulp increased the proportion of several polyunsaturated fatty acids (PUFA) in beef, including linoleic acid (LA; C18:2 *c*9,12), arachidonic acid (C20:4 *c*5,8,11,14), α-linolenic acid (ALA; C18:3 *c*9,12,15), and total conjugated linoleic acids (CLA; Tayengwa et al., 2021). Moreover, dietary citrus pulp at high doses (up to 350 g/kg DM) reduces lamb oxidation of lipids and proteins, thanks to the supply of bioactive molecules deriving from citrus by-product (Gravador et al., 2015; Inserra et al., 2014).

However, citrus fruits are a large and diverse group, encompassing varieties with markedly different chemical properties and a wide range of bioactive compounds, mainly represented by flavonoids (Janda et al., 2016; Russo et al., 2024). Among these, bergamot (*Citrus* × *bergamia* Risso) has attracted interest due to its high content of bioactive compounds and its concentrated cultivation area in the Mediterranean region. Global bergamot production in 2024 was approximately 25,000 tonnes on an area of 1500 ha (ARSAC Azienda Regionale per lo Sviluppo dell'Agricoltura Calabrese, 2024), 90% of which was concentrated in the province of Reggio Calabria in southern Italy (Navarra et al., 2015). These fruits are processed for the extraction of juice, essential oils, and bioactive compounds, generating pulp as the main by-product. In recent years, studies have investigated the inclusion of selected bergamot processing residues in sheep, goat, pig, and rabbit diets to evaluate their effects on growth performance and meat quality (Scerra et al., 2018; Scerra et al., 2021; Scerra et al., 2024a; Scerra et al., 2024b). These studies demonstrated that the use of certain bergamot by-products in ruminant and monogastric animal feed did not compromise growth performance or carcass characteristics, but rather led to improved meat quality. Specifically, an increase in beneficial fatty acids, especially n-3 fatty acids, a more favourable n-6/n-3 ratio, and greater resistance to oxidative processes were observed. However, several other bergamot-derived by-products remain largely unexplored, and their potential application in animal nutrition has yet to be investigated.

In the present study, two different bergamot by-products were analysed: bergamot pulp, generated after the extraction of essential oils; and dephenolized bergamot pulp, obtained by processing bergamot pulp to extract the polyphenolic fraction, used as a dietary supplement for humans. In light of above, in the present study maize was replaced with bergamot by-products, as this cultivation typically requires substantial inputs of water, pesticides, and fertilizers. Accordingly, this study investigated the effects of including 200 g/kg DM of bergamot pulp and dephenolized bergamot pulp in the diets of lambs on growth performance, ruminal fermentation, and fatty acid profile in rumen, abomasum and meat. Furthermore, by comparing bergamot pulp with its dephenolized counterpart, the study sought to determine the specific role of bergamot bioactive compounds in modulating these responses. We hypothesised that replacing maize with bergamot by-products would not impair growth performance and that bergamot polyphenols could modulate ruminal biohydrogenation and improve the fatty acid profile of meat.

2. Material and methods

2.1. Bergamot by-products

Both bergamot by-products used in this study were provided in dried form by H&AD srl (Herbal and Antioxidant Derivatives; industrial area, località Chiusi, Bianco, RC, Italy), a company specialized in the extraction of bioactive plant compounds for the production of dietary supplements and nutraceuticals. Fresh bergamot pulp was generated during citrus essential oil extraction (therefore consisted of the fruit after removal of the outer peel) and supplied to H&AD by agricultural companies located in the Bova areas (Bova Marina, RC, Italy). Upon receipt, H&AD dried the fresh bergamot pulp in a ventilated oven at 42 °C until constant weight, obtaining dried bergamot pulp. Another portion of the same fresh pulp was subjected by H&AD to polyphenol extraction through adsorption on polystyrene resin columns. Following recovery of the phenolic fraction, the resulting dephenolized pulp was dried under the same conditions (42 °C until constant weight), yielding dried dephenolized bergamot pulp.

Representative samples of both by-products were collected and subjected to chemical characterization using the analytical procedures described for the experimental diets in Section 2.2.

2.2. Experimental design and dietary treatments

In the present trial, 36 male lambs (Valle del Belice × Pinzirita crossbred) were selected from a local dairy sheep farm based on their uniformity in age and body weight (2-month-old and 15.0 ± 1.67 kg). The lambs were housed in individual pens with straw litter at the experimental farm of the University of Catania. After an adaptation period of 7 days with progressive substitution of weaning diet with experimental one, lambs were allocated to 3 dietary treatments balanced for body weight ($n = 12$):

- Control group (CON) was fed with a standard maize-based diet for growing lambs;
- Bergamot pulp group (BP) received the same CON diet, but part of maize was substitute with 200 g/kg DM of dried bergamot pulp;
- Dephenolized bergamot pulp group (DBP) was offered the CON diet, but 200 g/kg DM of dephenolized bergamot pulp partially replaced the maize.

Representative feed samples were collected at the beginning, middle, and end of the trial for analysing chemical composition of experimental diets. More details on the chemical composition and ingredients of the bergamot by-products and experimental diets are given in Tables 1 and 2. We decided to include 200 g/kg of DM of bergamot by-products, as this percentage was considered the highest possible to maintain adequate protein and energy levels. Furthermore, based on the chemical composition of these fibre-rich ingredients, particularly their high content of fermentable carbohydrates such as pectin, maize was chosen as the ingredient to be partially replaced in the experimental diets.

The lambs were fed *ad libitum* and had free access to fresh water. Individual feed intake was recorded daily by measuring the difference between feed offered and refusals. The lambs were weighed weekly throughout the trial. After 50 days on feeding trial, the animals were transferred to a commercial abattoir 30 km far from experimental facilities where they were immediately slaughtered following European regulation (Council Regulation n. 1099/2009).

2.3. Sampling and procedures at the slaughterhouse

The whole ruminal and abomasal content was collected 10 min after sacrifice and pH was immediately recorded using a pH meter Orion 9106 (Orion Research Incorporated, Boston, MA, USA). For fatty acid profile, samples of abomasal and unfiltered ruminal contents were collected and immediately frozen with dry ice. These samples were subsequently lyophilized and stored at −80°C until analyses. Another aliquot of ruminal fluid was collected, filtered, and centrifuged for volatile fatty acids (VFA) and ammonia analyses, as detailed in Musati et al. (2024) and Reardon et al. (1966), respectively.

After evisceration, carcasses were weighed (hot carcass weight) and stored in a cool room set at 4°C. Twenty-four hours later, the carcasses were weighed again (cold carcass weight). Then, *longissimus thoracis et lumborum* muscle was removed by both side of the carcasses, vacuum packed, and stored at −80°C until analyses of fatty acid profile.

2.4. Analyses of by-products and diets

Equal amount of feed samples collected during the trial were mixed in order to obtain representative samples. The diets and the by-products were finely milled at 1 mm (Powteq Twister TW200, Beijing Grinder Instrument Co., Beijing, China) and stored at −20°C. For each sample, DM, crude protein, ash, and ether extract were determined using the official AOAC methods (1995; methods 930.15, 984.13, 942.05, and 920.39, respectively). In addition, amylase-treated neutral detergent fibre (aNDF), acid detergent fibre (ADF), and acid detergent lignin (ADL) were analysed according to Van Soest et al. (1991), and the results were expressed on a residual ash basis. According to Makkar et al. (1993), total polyphenols and total tannins were extracted in combination of polyvinylpolypyrrolidone in order to precipitate tannins, and then quantified following the Folin-Ciocalteu method with modifications (Luciano et al., 2019). The fatty acid profile of diets and by-products were estimated as described by Shingfield et al. (2003) and modified by Valenti et al. (2018). In brief, lipids were extracted using chloroform and immediately converted to fatty acids methyl esters with sulfuric acid in methanol. Further details on fatty acids identification are reported in Section 2.6.

Table 1
Chemical composition (g/kg DM) of bergamot by-products.

	Bergamot pulp	Dephenolized bergamot pulp
Chemical composition		
DM (g/kg FM)	906	919
CP	129	59.4
aNDF	387	306
ADF	357	219
ADL	303	149
Ash	96.2	118
Total polyphenols (g TA/kg DM)	24.2	9.38
Total tannins (g TA/kg DM)	7.64	2.03
Total fatty acids	60.0	39.6
Individual fatty acids		
C16:0	15.6	15.5
C18:0	2.60	2.10
C18:1 *c*9	11.7	11.4
C18:2 *c*9,12	17.0	5.88
C18:3 *c*9,12,15	5.66	1.19

Abbreviations: ADF, acid detergent fibre; ADL, acid detergent lignin; aNDF, amylase treated neutral detergent fibre; DM, dry matter; EE, ether extract; FA, fatty acid; TA, tannic acid.

Table 2
Ingredients and chemical composition of experimental diets (g/kg DM).

	Experimental diets[a]		
	CON	BP	DBP
Ingredients			
Maize	430	230	230
Alfalfa hay	320	320	320
Soybean meal	200	200	200
Molasses	30	30	30
Vitamin-mineral integrator[b]	20	20	20
Dried bergamot pulp	-	200	-
Dephenolized bergamot pulp	-	-	200
Chemical composition			
DM (g/kg FM)	900	905	906
Ash	191	200	195
CP	161	167	166
aNDF	242	325	288
ADF	159	230	217
ADL	79.4	111	130
Total polyphenols (g TA/kg DM)	3.70	7.05	4.78
Total tannins (g TA/kg DM)	0.65	1.38	< 0.01
Total fatty acids	85.0	99.8	66.0
Individual fatty acids			
C16:0	13.9	24.7	12.9
C18:0	2.87	10.3	2.74
C18:1 *c*9	20.9	22.0	16.1
C18:2 *c*9,12	41.3	34.9	28.7
C18:3 *c*9,12,15	2.42	3.45	2.21

Abbreviations: ADF, acid detergent fibre; ADL, acid detergent lignin; aNDF, amylase treated neutral detergent fibre; DM, dry matter; EE, ether extract; FA, fatty acid; FM, fresh matter; TA, tannic acid.

[a] CON: control diet; BP: diet including 200 g/kg DM of bergamot pulp; DBP: diet including 200 g/kg DM of dephenolized bergamot pulp.

[b] Vitamins: vitamin A 3000000 UI, vitamin D3 400000 UI, vitamin E 5000 UI, vitamin B2 1000 mg/kg, vitamin B5 1000 mg/kg, vitamin B6 800 mg/kg, vitamin K3 400 mg/kg, vitamin B1 400 mg/kg, vitamin B9 100 mg/kg, vitamin B7 10 mg/kg, vitamin B12 4 mg/kg, choline chloride 100000 mg/kg; Trace elements: zinc 15000 mg/kg, manganese 10000 mg/kg, iron 8000 mg/kg, iodium 120 mg/kg, selenium 20 mg/kg

2.5. Analyses of ruminal and abomasal digesta

Following the protocol described in Reardon et al. (1966), the concentration of ruminal ammonia of centrifuged samples was determined spectrophotometrically reading the absorbance at 690 nm (UV-1601; Shimadzu Corporation, Milan, Italy). The quantification was estimated with a 6-point calibration curve (0 – 3.06 mg/L ammonium solution). Concerning the VFA analysis, the samples were centrifuged at 16000 × *g* for 15 min and the supernatant transferred in gas chromatograph vials. The identification and quantification of individual VFA was achieved using a gas chromatograph Shimadzu GC-2030 (Shimadzu Corporation) with flame ionization detector coupled with fused silica capillary column (30 m length × 0.25 mm internal diameter × 0.25 μm film thickness, Supelco, Bellafonte, PA). A 1 μL sample was injected in splitless mode with the injector set to 250 °C. The oven operated under isothermal conditions at 140 °C. Helium served as the carrier gas at a constant flow of 2 mL/min, with an additional helium makeup flow of 30 mL/min. The flame ionization detector was maintained at 250 °C, and the flame was fuelled with 350 mL/min of air and 35 mL/min of hydrogen. For the quantification of VFA, crotonic acid was used as an internal standard, whereas for the identification, the retention time of individual VFA was compared with that of a standard mixture (Volatile Free Acid Mix, CRM46975, Sigma). Regarding the fatty acid profile of ruminal and abomasal content, an aliquot of lyophilized sample was directly methylated with a double step: basic and acid transesterification (Natalello et al., 2019). Individual fatty acids were identified using a gas chromatograph set as detailed subsequently in the Section 2.6.

2.6. Analyses of intramuscular fat

A sample of *longissimus thoracis et lumborum* muscle was prepared for fatty acid profile analysis by removing the covering fat. Intramuscular fat was then extracted using a chloroform–methanol mixture and directly subjected to base-catalysed methylation, following the original protocols of Folch et al. (1957) and Christie (1982) and modified by Valenti et al. (2018). Methylated fatty acids of feedstuffs, rumen, abomasum, and meat were separated using a Shimadzu GC-2030 (Shimadzu Corporation) with flame ionization detector equipped with a capillary column 100 m × 0.25 mm × 0.20 μm (Supelco SP-2560, Supelco, Bellafonte, PA). The fatty acid was profiled in 1 μL sample injected with a split ratio 1:80. The oven operated as follow: 50 °C for 4 min, then increased to 170 °C at 7.5 °C/min, held for 58 min, then increased up to 200 °C at 5 °C/min, held for 20 min, finally increased to 230°C at 3 °C/min and held for 7 min. Samples were carried along the column with helium at a constant flow of 1 mL/min. The temperatures of injector and flame

ionization detector were maintained at 250 and 300 °C, respectively, with the flame supplied by 350 mL/min of air and 35 mL/min of hydrogen. Peaks of individual fatty acids were identified by comparing retention times with those of commercially available methylated fatty acid standards (Larodan Fine Chemicals, Malmo, Sweden; Nu-Chek Prep Inc., Elysian, MN, USA) and by comparing with chromatograms published by Alves and Bessa (2007) and Kramer et al. (2008).

2.7. Calculation and statistical analyses

Biohydrogenation (BH) of the main fatty acids (oleic, linoleic, and α-linolenic acids) was assessed in both the rumen and the abomasum following the equation proposed by Oliveira et al. (2016). In addition, BH completeness and the formation of intermediates were evaluated for each compartment (rumen and abomasum) according the equations described in Musati et al. (2025). We also calculated the atherogenic index of meat (Ulbricht and Southgate, 1991).

The statistical software SPSS (v27; SPSS Inc., Chicago) was used for analysing all the studied parameters (animal performance, rumen fermentation, and fatty acid profile of rumen, abomasum, and meat). The experimental unit considered was the individual animal and a generalized linear model was used to test the dietary treatment. When significant effects were detected, means were compared using Tukey's adjustment. Statistical significance was set at $P < 0.05$, while $0.05 \leq P < 0.10$ was interpreted as a trend.

3. Results

3.1. Growth performance and carcass traits

Table 3 reports the results relating to growth performance and carcass traits. The replacement of 200 g/kg DM of dried bergamot pulp or dephenolized bergamot pulp did not affect growth performance, including body weight, average daily gain, DM intake, or hot and cold carcass weight ($P > 0.05$). However, the feed conversion ratio tended to be higher in lambs fed bergamot by-products compared to CON ($P = 0.062$).

3.2. Ruminal fermentation parameters

The effects of dietary bergamot by-products on rumen fermentation parameters are shown in Table 4. The concentration of ruminal ammonia was comparable in all dietary treatments ($P = 0.105$), as well as the total VFA production ($P = 0.496$). Nevertheless, the molar proportion of individual VFA was slightly changed, with the acetate proportion being higher in lambs fed BP and DBP than CON ($P = 0.004$), while that of caproate was higher in DBP compared to CON ($P = 0.017$). The proportion of propionate tended to be lower in lambs fed bergamot by-products ($P = 0.095$), whereas butyrate, valerate, sum of *iso* VFA, and acetate:propionate ratio did not show significance ($P > 0.05$).

3.3. Fatty acid profile of ruminal content

The substitution of 46.5% dietary maize with bergamot by-products modified the fatty acid profile of ruminal content (Table 5). Particularly, the quantity of total fatty acids was lower in DBP treatment compared to BP ($P = 0.008$). While, feeding lambs with BP increased the amount of SFA and C16:0 compared to CON and DBP ($P = 0.019$ and 0.002, respectively) and the C14:0 concentration compared to DBP ($P = 0.049$). Regarding the monounsaturated fatty acids (MUFA), the ruminal quantity of C18:1 *t*6 + 7 + 8 and C18:1 *c*11 was higher in CON lambs compared to DBP ($P = 0.009$ and 0.005, respectively), while the C18:1 *t*9 was greater in CON than BP ($P = 0.015$). Conversely, the concentration of C16:1 *c*9 was lower in CON ruminal content compared to BP ($P = 0.013$). Concerning summation of PUFA, the inclusion of dried bergamot pulp reduced their concentration of about 29% compared to CON ($P = 0.027$), and a similar pattern was observed also for the concentration of LA ($P = 0.031$). The group of lambs fed CON showed higher values of ALA than that with BP or DBP (+33%; $P = 0.013$), while the quantity of rumenic acid (RA, C18:2 *c*9,*t*11) was higher in CON than BP

Table 3
Growth performance and carcass traits of lambs fed diets with bergamot by-products.

	Dietary treatment[a]			SEM	*P*-value
	CON	BP	DBP		
Final BW (kg)	25.7	24.2	25.8	0.67	0.533
BW gain (kg)	10.8	9.1	10.8	0.58	0.419
ADG (g/d)	220	186	220	11.9	0.419
FCR	3.54	4.67	4.01	0.20	0.062
Hot carcass weight (kg)	11.7	11.3	11.6	0.34	0.420
Cold carcass weight (kg)	11.5	11.1	11.4	0.34	0.855
Chilling loss (%)	1.68	1.86	2.00	0.094	0.464
DM intake (g FM/d)	763	798	807	31.2	0.838

Abbreviations: ADG, average daily gain; BW, body weight; DM, dry matter; FCR, feed conversion ratio; FM, fresh matter; SEM, standard error of the means.

[a] CON: control diet; BP: diet including 200 g/kg DM of bergamot pulp; DBP: diet including 200 g/kg DM of dephenolized bergamot pulp.

Table 4
Rumen fermentation parameters of lambs fed diets with bergamot by-products.

	Dietary treatment[c]			SEM	*P*-value
	CON	BP	DBP		
Ammonia (mg/L)	104	182	175	17.3	0.105
Total VFA (mmol/L)	108	103	119	5.6	0.496
Individual VFA (mol/mol)					
Acetate	53.4[b]	58.0[a]	57.8[a]	0.67	0.004
Propionate	25.9	21.6	21.0	1.00	0.095
Butyrate	17.3	16.4	16.1	0.88	0.845
Valerate	1.68	1.46	2.00	0.124	0.205
Caproate	0.285[b]	0.399[ab]	0.778[a]	0.0761	0.017
Σ *iso*	1.42	2.11	2.28	0.344	0.572
Acetate:propionate ratio	2.27	2.81	2.89	0.130	0.106

Abbreviations: SEM, standard error of the means; VFA, volatile fatty acid.
[a] Means in the same row lacking a common superscript differ ($P < 0.05$).
[b] Means in the same row lacking a common superscript differ ($P < 0.05$).
[c] CON: control diet; BP: diet including 200 g/kg DM of bergamot pulp; DBP: diet including 200 g/kg DM of dephenolized bergamot pulp.

($P = 0.002$). When examining BH indices, none were affected by dietary treatment ($P > 0.05$), except for BH index of ALA (BH C18:3 *c*9,12,15) which was lower in CON than in animals fed with bergamot by-products ($P < 0.001$).

3.4. Fatty acid profile of abomasal content

The fatty acid composition of abomasal content was quite similar to that of the rumen, but with slight differences, as shown in Table 6. For instance, total quantity of fatty acids was not affected by dietary treatment ($P > 0.05$), while the SFA sum and C24:0 concentration were higher in BP than CON ($P = 0.018$ and 0.005, respectively). The quantity of C16:0 was higher in abomasal content of lambs fed BP compared to the other treatments ($P < 0.001$), whereas that of C17:0 *anteiso* was higher in DBP ($P = 0.002$). Contrary to rumen content, feeding lambs with 200 g/kg DM of dried bergamot pulp reduced the quantity of MUFA by 16% compared to CON group ($P = 0.027$). The concentration of C18:1 *t*10 was higher in CON than in BP and DBP ($P = 0.041$), however, Tukey's multiple-comparison test did not identify significant pairwise differences among groups ($P > 0.05$). The amounts of C18:1 *t*6 + 7 + 8, C18:1 *t*9, and C18:1 *c*11 were greater in lambs fed CON diet compared to DBP ($P = 0.014$, 0.032, and 0.038, respectively), whereas, in case of the C16:1 *c*9, the CON lambs had lower value than BP animals ($P = 0.007$). Similarly to MUFA, also the content of abomasal PUFA was higher in CON lambs than BP ones ($P = 0.009$), and other PUFA showed a comparable pattern. For example, LA quantity was higher in CON than BP ($P = 0.009$), and the concentrations of RA and C18:2 *t*10,*c*12 were greater in CON compared to BP and DBP ($P = 0.040$ and 0.001, respectively). Finally, feeding lambs with BP increased the index of BH of ALA in abomasum compared to CON, as indicated by BH C18:3 *c*9,12,15 ($P = 0.032$).

3.5. Fatty acid profile of intramuscular fat

In Table 7 the results of intramuscular fat and its fatty acid composition are presented. Dietary inclusion of 200 g/kg DM of either dried or dephenolized bergamot pulp did not influence intramuscular fat or total fatty acid content in lambs ($P > 0.05$). Likewise, the overall levels of SFA, MUFA, and PUFA, as well as n-6 and n-3 PUFA remained unaffected by the dietary treatment ($P > 0.05$). Moreover, none of the SFA detected was influenced by experimental diets ($P > 0.05$). The content of C18:1 *t*9 was higher in lambs fed BP than DBP ones ($P = 0.015$), for C18:1 *t*10 was higher in CON than DBP ($P = 0.019$), and for C18:1 *c*11 higher in CON than BP ($P < 0.001$). While, the amounts of C18:1 *c*10 and *c*14 in meat were greater in animals fed with 200 g/kg DM bergamot pulp compared to the other treatments ($P < 0.001$ and $P = 0.003$, respectively). Finally, the group fed with BP showed higher values of C18:1 *c*6 compared to CON and followed by DBP ($P < 0.001$). Regarding the individual PUFA, feeding lambs with 200 g/kg DM of dried bergamot pulp increased the concentration of C18:2 *t*9,12 in meat compared to other diets ($P = 0.006$), while the CON increased the concentration of C18:2 *t*10,*c*12 than DBP ($P = 0.049$), and the DBP group showed higher value of C22:5 n-6 compared to BP ($P = 0.041$).

4. Discussion

The use of locally available agro-industrial by-products in ruminant feeding can enhance livestock sustainability by reducing environmental impact, feed costs, and reliance on conventional feed resources (Salami et al., 2019). This is particularly relevant for maize, a high-demand crop extensively used for food, feed, and biofuel production and frequently imported in Mediterranean region. Furthermore, ruminants can efficiently valorise fibrous residues, transforming them into high-quality animal products while exploiting the potential benefits of their bioactive compounds (Mapiye et al., 2026). Therefore, the aim of the present study was to assess the feasibility of replacing maize with bergamot by-products in lamb diet studying the effects on growth performance and lipid metabolism. Particularly, for estimating the role of bergamot bioactive compounds, lambs were fed either unprocessed bergamot pulp or

Table 5
Rumen fatty acid profile (mg/100 g DM freeze-dried ruminal content) of lambs fed diets with bergamot by-products.

	Dietary treatment[c]			SEM	*P*-value
	CON	BP	DBP		
pH	6.00	6.20	5.93	0.069	0.266
Total FA	943[ab]	1073[a]	851[b]	31.5	0.008
Σ SFA	526[b]	716[a]	524[b]	33.4	0.019
C14:0 *iso*	1.95	3.20	2.32	0.437	0.498
C14:0	13.3[ab]	15.8[a]	10.5[b]	0.922	0.049
C15:0 *iso*	6.63	9.74	8.28	0.679	0.189
C15:0 *anteiso*	13.3	16.1	14.5	1.06	0.578
C15:0	9.14	13.6	9.79	1.58	0.472
C16:0 *iso*	3.73	6.20	5.51	0.699	0.363
C16:0	194[b]	292[a]	195[b]	14.3	0.002
C17:0 *iso*	2.72	3.79	3.44	0.513	0.712
C17:0 *anteiso*	0.499	0.658	0.461	0.050	0.217
C17:0	3.87	5.45	4.62	0.452	0.383
C18:0	259	329	252	20.4	0.227
C20:0	5.32	6.32	5.43	0.244	0.187
C22:0	3.38	3.74	3.34	0.147	0.466
C24:0	3.67	4.23	3.64	0.146	0.173
Σ *iso*	15.0	22.9	19.5	2.04	0.309
Σ *anteiso*	13.8	16.7	15.0	1.09	0.558
Σ OBCFA	44.8	62.1	52.0	4.99	0.382
Σ MUFA	285	263	220	14.1	0.168
C16:1 *c*7	1.12	1.57	1.29	0.126	0.351
C16:1 *c*9	4.29[b]	7.71[a]	5.88[ab]	0.484	0.013
C18:1 *t*5	0.761	0.715	0.585	0.042	0.206
C18:1 *t*6 + 7 + 8	9.70[a]	7.97[ab]	6.06[b]	0.500	0.009
C18:1 *t*9	5.76[a]	5.37[b]	3.74[ab]	0.313	0.015
C18:1 *t*10	35.7	17.7	19.2	3.33	0.056
C18:1 *t*11	62.9	68.8	45.4	6.27	0.275
C18:1 *c*6	7.59	7.41	5.80	0.376	0.094
C18:1 *c*9	116	105	98.3	6.29	0.549
C18:1 *c*10	4.48	4.83	3.66	0.253	0.140
C18:1 *c*11	10.5[a]	8.73[ab]	6.16[b]	0.579	0.005
C18:1 *c*12	5.77	4.86	3.83	0.661	0.514
C18:1 *c*13	0.470	0.480	0.531	0.031	0.708
C18:1 *c*14	3.89	4.78	3.60	0.280	0.187
C20:1 *c*11	7.39	8.51	7.80	0.314	0.352
Σ PUFA	132[a]	93.8[b]	107[ab]	5.95	0.027
C18:2 *t*9.12	2.12	1.93	2.93	0.298	0.342
C18:2 *c*9,12	125[a]	87.8[b]	100[ab]	5.92	0.031
C18:2 *c*9,*t*11	1.67[a]	1.22[ab]	0.675[b]	0.120	0.002
C18:2 *t*10,*c*12	0.768	0.355	0.458	0.076	0.078
C18:3 *c*9,12,15	1.51[a]	1.14[b]	1.14[b]	0.059	0.013
C20:4 n-6	0.751	0.768	0.750	0.038	0.975
C20.3 n-3	0.483	0.633	0.575	0.041	0.348
Calculations					
C18:1 *t*10/*t*11 ratio	0.601	0.379	0.557	0.086	0.350
BH completeness (%)[d]	39.2	41.9	42.7	2.91	0.888
Intermediate production (%)[d]	22.7	23.0	18.3	1.22	0.204
BH C18:1 *c*9 (%)[e]	43.0	48.0	44.1	2.87	0.765
BH C18:2 *c*9,12 (%)[e]	69.7	72.4	67.7	1.62	0.490
BH C18:3 *c*9,12,15 (%)[e]	93.7[b]	96.3[a]	95.2[a]	0.29	< 0.001

Abbreviations: BH, biohydrogenation, FA, fatty acid; MUFA, monounsaturated fatty acid; OBCFA, odd- and branched-chain fatty acid; PUFA, polyunsaturated fatty acid; SEM, standard error of the means; SFA, saturated fatty acid.

[a] Means in the same row lacking a common superscript differ ($P < 0.05$).

[b] Means in the same row lacking a common superscript differ ($P < 0.05$).

[c] CON: control diet; BP: diet including 200 g/kg DM of bergamot pulp; DBP: diet including 200 g/kg DM of dephenolized bergamot pulp.

[d] Calculated as reported by Musati et al. (2025).

[e] Calculated as reported by Oliveira et al. (2016).

dephenolized bergamot pulp, obtained after the extraction of these compounds.

4.1. Growth performance

Previous studies on ruminants fed various citrus by-products have not revealed significant impacts on animal growth (Bampidis and Robinson, 2006). For instance, feeding steers with fresh citrus pulp did not affect final body weight or average daily gain (Luzardo

Table 6
Abomasum fatty acid profile (mg/100 g DM freeze-dried abomasum content) of lambs fed diets with bergamot by-products.

	Dietary treatment[c]			SEM	*P*-value
	CON	BP	DBP		
pH	2.88[b]	2.99[ab]	3.55[a]	0.110	0.024
Total FA	991	1041	926	24.2	0.151
Σ SFA	563[b]	735[a]	588[ab]	27.6	0.018
C14:0 *iso*	2.12	3.12	2.64	0.341	0.501
C14:0	14.3	13.7	11.3	0.706	0.179
C15:0 *iso*	6.71	9.31	8.24	0.459	0.062
C15:0 *anteiso*	13.4	14.1	14.9	0.758	0.732
C15:0	8.60	11.74	9.81	0.966	0.419
C16:0 *iso*	2.38	4.26	4.39	0.601	0.319
C16:0	158[b]	242[a]	171[b]	8.838	< 0.001
C17:0 *iso*	2.06	3.19	2.88	0.369	0.444
C17:0 *anteiso*	0.235[b]	0.184[b]	0.353[a]	0.022	0.002
C17:0	4.39	5.95	5.74	0.392	0.218
C18:0	328	402	334	18.6	0.195
C20:0	7.04	8.29	7.03	0.271	0.089
C22:0	4.45	4.95	4.74	0.128	0.271
C24:0	4.63[b]	5.77[a]	5.12[ab]	0.151	0.005
Σ *iso*	13.3	19.9	18.2	1.435	0.148
Σ *anteiso*	13.6	14.3	15.2	0.757	0.694
Σ OBCFA	43.2	55.6	52.5	3.288	0.280
Σ MUFA	297[a]	227[b]	228[ab]	12.61	0.027
C16:1 *c*7	1.01	1.05	1.18	0.071	0.610
C16:1 *c*9	3.06[b]	5.37[a]	4.37[ab]	0.312	0.007
C18:1 *t*5	1.05	0.887	0.748	0.060	0.110
C18:1 *t*6 + 7 + 8	12.1[a]	9.23[ab]	7.60[b]	0.652	0.014
C18:1 *t*9	6.75[a]	5.88[ab]	4.64[b]	0.337	0.032
C18:1 *t*10	43.5	22.7	22.9	3.93	0.041*
C18:1 *t*11	68.6	50.4	43.8	4.98	0.108
C18:1 *c*6	8.94	8.49	7.46	0.501	0.479
C18:1 *c*9	110	82.6	97.6	4.937	0.081
C18:1 *c*10	5.43	6.06	5.10	0.346	0.529
C18:1 *c*11	10.6[a]	7.92[ab]	6.80[b]	0.636	0.038
C18:1 *c*12	7.58	5.38	4.62	0.760	0.262
C18:1 *c*13	0.660	0.628	0.568	0.040	0.655
C18:1 *c*14	4.95	5.80	5.04	0.343	0.551
C20:1 *c*11	7.23	7.42	8.21	0.437	0.638
Σ PUFA	131[a]	78.6[b]	110[ab]	7.240	0.009
C18:2 *t*9.12	2.11	2.27	3.39	0.386	0.342
C18:2 *c*9,12	121[a]	71.0[b]	99.8[ab]	7.008	0.009
C18:2 *c*9,*t*11	2.01[a]	1.40[b]	1.29[b]	0.128	0.040
C18:2 *t*10,*c*12	1.16[a]	0.410[b]	0.512[b]	0.096	0.001
C18:3 *c*9,12,15	1.61	1.18	1.32	0.080	0.082
C20:4 n-6	0.947	0.940	0.999	0.057	0.903
C20:3 n-3	0.658	0.721	1.04	0.075	0.080
Calculations					
C18:1 *t*10/*t*11 ratio	0.663	0.522	0.622	0.077	0.385
BH completeness (%)[d]	47.4	48.5	51.4	2.67	0.823
Intermidiate (%)[d]	22.4	22.3	16.9	1.29	0.138
BH C18:1 *c*9 (%)[e]	55.7	58.0	54.6	2.15	0.809
BH C18:2 *c*9,12 (%)[e]	75.5	76.3	74.0	1.69	0.858
BH C18:3 *c*9,12,15 (%)[e]	94.3[b]	96.1[a]	95.5[ab]	0.29	0.032

Abbreviations: BH, biohydrogenation, FA, fatty acid; MUFA, monounsaturated fatty acid; OBCFA, odd- and branched-chain fatty acid; PUFA, polyunsaturated fatty acid; SEM, standard error of the means; SFA, saturated fatty acid.
*In the pairwise analysis, no significant differences ($P > 0.05$) were found after adjustment for multiple comparisons using Tukey's correction.
[a] Means in the same row lacking a common superscript differ ($P < 0.05$).
[b] Means in the same row lacking a common superscript differ ($P < 0.05$).
[c] CON: control diet; BP: diet including 200 g/kg DM of bergamot pulp; DBP: diet including 200 g/kg DM of dephenolized bergamot pulp.
[d] Calculated as reported by Musati et al. (2025).
[e] Calculated as reported by Oliveira et al. (2016).

et al., 2021). Similarly, Scerra et al. (2018) found that feeding lambs with fresh bergamot by-products had no significant effects on final body weight, average daily gain, dry matter intake, or carcass weight. Therefore, consistent with previous findings, the dietary inclusion of bergamot by-products, either as bergamot pulp (BP) or dephenolized bergamot pulp (DBP), did not adversely affect lamb growth performance. Indeed, DM intake, final body weight, body weight gain, average daily gain, and both hot and cold carcass weights were comparable among dietary treatments. These results suggests that the experimental diets were well balanced in terms of

Table 7
Meat fatty acid profile (mg/100 g fresh meat) of lambs fed diets with bergamot by-products.

	Dietary treatment[d]			SEM	*P*-value
	CON	BP	DBP		
IMF (g/100 g fresh meat)	2.08	2.07	1.81	0.096	0.439
Total FA	1784	1708	1716	33.9	0.621
ΣSFA	818	810	796	18.0	0.886
C12:0	4.26	5.19	4.55	0.330	0.508
C14:0 *iso*	0.459	0.546	0.472	0.030	0.455
C14:0	60.6	65.8	62.2	2.67	0.733
C15:0 *iso*	1.54	1.79	1.46	0.077	0.188
C15:0 *anteiso*	1.78	2.01	1.80	0.089	0.525
C15:0	5.79	6.03	5.48	0.184	0.491
C16:0 *iso*	2.13	2.34	2.24	0.103	0.730
C16:0	451	445	445	11.8	0.967
C17:0 *iso*	6.32	6.36	5.76	0.168	0.271
C17:0 *anteiso*	5.84	4.95	4.92	0.617	0.799
C17:0	18.1	16.9	16.0	0.49	0.228
C18:0	251	245	238	5.2	0.584
C20:0	1.77	1.72	1.61	0.057	0.537
C21:0	0.186	0.201	0.183	0.013	0.830
C22:0	0.495	0.474	0.505	0.024	0.865
C23:0	2.12	1.93	2.08	0.104	0.761
C24:0	0.091	0.074	0.065	0.009	0.501
Σ *iso*	10.5	11.0	9.93	0.337	0.423
Σ *anteiso*	7.61	6.96	6.72	0.624	0.842
Σ OBCFA	44.8	43.6	40.9	1.01	0.286
Σ MUFA	761	711	706	20.4	0.486
C16:1 *c*7	4.68	4.88	4.40	0.128	0.326
C16:1 *c*9	28.1	27.9	28.1	1.22	0.996
C18:1 *t*5	0.195	0.194	0.180	0.013	0.860
C18:1 *t*6 + 7 + 8	4.31	4.36	3.54	0.165	0.072
C18:1 *t*9	3.83[ab]	4.21[a]	3.19[b]	0.151	0.015
C18:1 *t*10	18.2[a]	11.1[ab]	10.1[b]	1.31	0.019
C18:1 *t*11	18.8	18.6	13.1	1.29	0.127
C18:1 *c*6	5.00[b]	5.78[a]	4.12[c]	0.168	< 0.001
C18:1 *c*9	623	583	590	17.2	0.605
C18:1 *c*10	1.58[b]	2.13[a]	1.41[b]	0.070	< 0.001
C18:1 *c*11	23.4[a]	18.7[b]	19.4[ab]	0.83	0.039
C18:1 *c*12	4.71	4.70	4.09	0.197	0.357
C18:1 *c*13	1.56	1.29	1.17	0.074	0.082
C18:1 *c*14	2.17[b]	2.70[a]	2.05[b]	0.086	0.003
C20:1 *c*11	5.37	6.55	5.51	0.222	0.055
Σ PUFA	204	186	215	7.9	0.341
C18:2 *t*9.12	3.68[b]	4.67[a]	3.47[b]	0.171	0.006
C18:2 *c*9,12	115	101	118	4.0	0.190
C18:2 *c*9,*t*11	9.00	8.58	6.57	0.482	0.086
C18:2 *t*10,*c*12	0.360[a]	0.303[ab]	0.230[b]	0.022	0.049
C18:3 *c*9,12,15	1.89	1.79	2.00	0.054	0.286
C20:4 n-6	0.372	0.360	0.357	0.019	0.949
C20.3 n-3	45.4	42.0	54.5	3.35	0.295
C20:5 n-3	3.49	3.70	3.41	0.276	0.908
C22:4 n-6	4.40	3.85	5.35	0.321	0.158
C22:5 n-6	1.24[ab]	1.10[b]	1.73[a]	0.109	0.041
C22:5 n-3	9.09	9.28	9.04	0.650	0.988
C22:6 n-3	3.33	3.60	3.18	0.204	0.708
Calculations					
Σ n-6	131	115	134	4.6	0.194
Σ n-3	63.2	60.4	72.1	4.26	0.513
n-6/n-3	2.28	2.04	1.95	0.081	0.219
PUFA/SFA	0.260	0.236	0.280	0.015	0.505
Atherogenic index[e]	0.727	0.792	0.765	0.020	0.440
Desaturation index[f]	0.337	0.325	0.330	0.004	0.491

Abbreviations: BH, biohydrogenation, FA, fatty acid; IMF, intramuscular fat; MUFA, monounsaturated fatty acid; OBCFA, odd- and branched-chain fatty acid; PUFA, polyunsaturated fatty acid; SEM, standard error of the means; SFA, saturated fatty acid.

[a] Means in the same row lacking a common superscript differ ($P < 0.05$).

[b] Means in the same row lacking a common superscript differ ($P < 0.05$).

[c] Means in the same row lacking a common superscript differ ($P < 0.05$).

[d] CON: control diet; BP: diet including 200 g/kg DM of bergamot pulp; DBP: diet including 200 g/kg DM of dephenolized bergamot pulp.

[e] Calculated as reported by Ulbricht and Southgate (1991).

[f] Calculated as C17:1 *c*9/(C17:1 *c*9 +C17:0).

energy and protein supply, allowing the replacement of maize with bergamot by-products without compromising animal performance. However, the feed conversion ratio tended to be higher in lambs fed bergamot by-products, indicating that animals tended to need higher quantities of feed for each kg of body weight gain. This effect may be attributable to the greater fibre content of bergamot pulps, which could have slightly reduced the efficiency of nutrient utilization without ultimately affecting growth performance (Sousa et al., 2014). In this context, acetate is commonly regarded as a fermentation end-product associated with fibre digestion. Accordingly, in the present study, the proportion of acetate was higher in lambs fed bergamot pulps compared with the CON group, suggesting a shift towards a more fibrolytic fermentation pattern. Overall, the experimental diets containing BP and DBP appeared to adequately meet both energy and protein requirements. Indeed, total VFA production was similar between treatments, indicating comparable energy availability among diets. Likewise, ruminal ammonia concentrations did not differ among treatments, suggesting similar dietary protein utilization efficiency (Dewhurst and Newbold, 2022).

4.2. Lipid metabolism

To the best of our knowledge, this is the first study to evaluate lipid metabolism in ruminants fed bergamot by-products. Among studies evaluating the effects of dietary citrus by-products, several have investigated the fatty acid profile of lamb meat (e.g., Bampidis and Robinson, 2006; Francisco et al., 2018). However, only one study has comprehensively investigated fatty acid metabolism across rumen digesta, plasma, and meat in lambs fed diets containing 240 or 350 g/kg FM dried citrus pulp (Lanza et al., 2015). Overall, these authors reported that dietary citrus pulp induced only minor changes in the ruminal fatty acid profile, whereas the most pronounced effects were observed in plasma, considered as an indirect measure of post-ruminal fatty acid flow. Lambs receiving citrus pulp exhibited a plasma fatty acid profile indicative of altered ruminal BH, characterized by lower proportion of stearic acid (SA; C18:0) and higher ones of vaccenic acid (VA; C18:1 *t*11), RA, LA, and ALA (Lanza et al., 2015). Consistent with these findings, the present study detected only slight differences in ruminal fatty acid composition, while more pronounced changes were observed in the abomasum. In this context, abomasal fatty acid composition can be considered a proxy for post-ruminal fatty acid flow, reflecting the pool of fatty acids available for subsequent absorption and tissue deposition. Specifically, dietary inclusion of BP or DBP did not impact the abomasal concentrations of SA and VA, which are end of intermediate products of BH. In contrast, the amounts of RA, LA, and ALA were significantly or tendentially lowered in abomasal digesta from lambs receiving bergamot pulps, both BP and DBP. This finding may be explained by the fatty acid composition of the experimental diets, as the CON treatment contained higher levels of PUFA than the BP and DBP diets. Thus, differences in the dietary supply of fatty acid substrates may have contributed to the lower concentrations of these fatty acids observed in the abomasal digesta of lambs fed bergamot by-products. In addition, the absence of differences in the fatty acid profiles of the rumen and abomasum between the BP and DBP treatments suggests that the polyphenolic fraction of bergamot pulp did not exert a measurable effect on ruminal BH. The similar fatty acid composition, together with the lack of differences in BH completeness and intermediate production indices, indicates that the polyphenolic compounds present in bergamot pulp had only a limited influence on ruminal PUFA metabolism under the conditions of the present study. Probably, the inclusion level adopted in the present experiment (200 g/kg DM) may have been insufficient to elicit detectable changes in ruminal lipid metabolism.

The alteration of BH pathway from *trans*-11 to *trans*-10, commonly referred to as the "*trans*-10 shift" (Bessa et al., 2015), leads to the accumulation of C18:1 *t*10 in animal products at the expense of VA. This shift is considered undesirable since C18:1 *t*10 has been associated with an increased risk of coronary heart diseases (Ferlay et al., 2017), while VA has been reported to exert antitumoral and anticarcinogenic effects (Fan et al., 2023). In the present study, dietary treatments did not appear to inhibit the BH process or affect VA concentrations. However, lambs fed bergamot pulps exhibited lower concentrations of C18:1 *t*10 and its precursor C18:2 *t*10,*c*12 in the abomasal contents, suggesting a potential modulation of the BH pathway. On the one hand, this shift is often associated with the presence of bioactive compounds, including tannins (Frutos et al., 2020). However, the concentrations of these compounds in the BP and DBP diets were very low, making it unlikely that they were responsible for the observed effects. Moreover, the similar responses observed in lambs fed the BP and DBP diets suggest that polyphenols were not the primary drivers of the effects detected. On the other hand, high-fibre diets, such as those based on forage or pasture, have been shown to reduce the accumulation of *trans*-10 isomers in animal products (Sterk et al., 2011). In the present study, the replacement of maize with bergamot pulp may have altered the dietary starch:fibre ratio, creating ruminal conditions more favourable to fibre fermentation and, consequently, limiting the formation of *trans*-10 intermediates. In this context, the higher abomasal pH observed in lambs fed dephenolized bergamot pulp is more likely to be associated with the substitution of dietary starch by highly fermentable fibre, particularly pectins, and the consequent changes in ruminal fermentation and digesta characteristics. Furthermore, given the similar ash content, bergamot pulp-based diets may have a different mineral profile compared to the CON group, which may have enhanced the buffering capacity of the digesta through an increased supply of minerals (Genther and Hansen, 2015). Nevertheless, the relative contribution of this mechanism remains unclear. Further research investigating the mineral composition of bergamot by-products, as well as the effects of higher dietary inclusion levels, would help elucidate the factors underlying the observed increase in abomasal pH.

The consumption of red meat rich in saturated fatty acids (SFA) is strictly related to a higher risk of cardiovascular diseases, diabetes, and cancer (Mei et al., 2024; Pan et al., 2022; Shi et al., 2023). The manipulation of animal diets may be a successful strategy to enhance the fatty acid profile of meat towards healthier products. Several nutritional strategies have been successfully employed to enrich meat with unsaturated fatty acids, including the use of pasture-based feeding systems, oilseed supplementation, and diets containing bioactive compounds (Jerónimo et al., 2009; Stanišić et al., 2024; Valenti et al., 2021). The inclusion of agro-industrial by-products in ruminant diets may represent an effective strategy to enhance the nutritional quality of animal products, as these feeds are often rich in bioactive compounds and unsaturated fatty acids (Nudda et al., 2025). For instance, Lanza et al. (2015) observed that lambs fed up to 350 g/kg FM dried citrus pulp exhibited an improved meat fatty acid profile, including higher proportions of

MUFA, RA, C20:5 n-3, C22:6 n-3, as well as a reduction in SFA and PUFA/SFA ratio. The authors attributed these effects to the presence of unsaturated fatty acids and polyphenols in the diets, that may have impaired ruminal BH. In contrast, in the present study, none of the meat fatty acids involved in BH were affected by dietary treatment. However, it should be taken into account that the inclusion level of the by-product used by Lanza et al. (2015) was approximately 75% higher than that adopted in the present trial, and that differences in the citrus species of origin (orange vs. bergamot) and in the type of by-product employed (juice-processing residue vs. essential oil extraction residue) may also have contributed to the observed discrepancies. Similarly, Scerra et al. (2018) evaluated the effects of feeding lambs with diets containing 200 or 350 g/kg DM fresh bergamot pulp. Meat from lambs receiving the higher inclusion level showed increased proportions of VA, RA, and ALA, together with a lower n-6/n-3 ratio. In contrast, no differences in meat fatty acid composition were detected between lambs fed 200 g/kg DM fresh bergamot pulp and those in the control group. In our study, the only improvement observed in lambs fed bergamot pulp was a reduction in the concentration of C18:1 *t*10 in DBP meat. This finding is relevant because the consumption of products rich in C18:1 *t*10 has been associated with an increased risk of coronary heart disease (Ferlay et al., 2017). The lower concentration of this fatty acid in meat was consistent with the results obtained from the abomasal contents, where reduced levels of C18:1 *t*10 suggested a lower activity of the *trans*-10 BH pathway. This effect was subsequently reflected in the meat fatty acid profile, indicating that bergamot pulp supplementation may selectively influence specific pathways of ruminal lipid metabolism, with limited effects on the overall fatty acid composition of the meat.

5. Conclusion

The inclusion of 200 g/kg DM of dried bergamot pulp or dephenolized bergamot pulp in partial replacement of maize did not negatively affect growth performance, carcass traits, and ruminal fermentation. The chemical characteristics of bergamot pulps influenced the ruminal lipid metabolism, reducing the accumulation of undesirable C18:1 *t*10 in meat of lambs fed dephenolized bergamot pulp. However, the overall fatty acid composition of meat remained unaltered. These results could be primarily attributed to the higher fibre content of the diet, whereas the bioactive compounds present in bergamot pulp appear to have played a limited role, as no significant differences were observed between lambs fed dephenolized pulp and those fed untreated pulp.

The partial replacement of conventional feedstuffs, as maize, with bergamot pulps may be a profitable strategy to reduce environmental impact of livestock sector and feed-food competition, without detrimental effects on growth performance and meat quality. A limitation of the present study is that only a single inclusion level of bergamot pulps was evaluated. Therefore, it cannot be excluded that higher doses may elicit additional effects on ruminal lipid metabolism and meat fatty acid profile. Further research should explore a wider range of dietary inclusion levels and assess additional meat quality parameters, such as oxidative stability. In addition, the effects of bergamot polyphenolic extracts should be evaluated independently to better elucidate their specific role in modulating ruminal metabolism and meat quality. Future studies should also assess the economic feasibility of bergamot pulps as feed ingredients, considering their cost and availability.

CRediT authorship contribution statement

Martino Musati: Writing – original draft, Visualization, Formal analysis, Data curation. **Fabrizio Mangano:** Writing – review & editing, Formal analysis. **Antonino Bertino:** Writing – review & editing, Formal analysis, Data curation. **Marco Sebastiano Cannone:** Writing – review & editing, Formal analysis. **Salvatore Privitera:** Formal analysis. **Alessandro Priolo:** Writing – review & editing, Supervision, Project administration, Investigation, Conceptualization. **Giuseppe Luciano:** Writing – review & editing, Investigation, Conceptualization. **Manuel Scerra:** Writing – review & editing, Conceptualization. **Paolo Fortugno:** Writing – review & editing. **Antonella Della Malva:** Writing – review & editing, Investigation. **Marzia Albenzio:** Writing – review & editing. **Guido Mangione:** Writing – review & editing, Formal analysis. **Antonio Natalello:** Writing – review & editing, Supervision, Investigation, Conceptualization.

Ethical approval

All animal experimental procedures were carried out in compliance with European Union regulations on the protection of animals used for scientific purposes (Directive 2010/63/EU) and were reviewed and approved by the Research Ethics Committee of the University of Reggio Calabria (Protocol No. 0000723).

Ethics declaration

This study was conducted in accordance with the following guidelines for animal welfare and/or reporting: 2010/63/EU. This study was approved by the Research Etichs commitee of the University of Reggio Calabria. (Approval No. 0000723)

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Declaration of Competing Interest

The authors declare no competing interests.

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