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RESEARCH ARTICLE

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Effect of dietary administration of red orange and lemon extract on volatile compounds: profile and sensory parameters of lamb meat

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ABSTRACT

The aim of this work was to study the effects of red orange and lemon extract (RLE) inclusion on volatile organic compounds (VOCs) and sensory profile of lamb meat aged seven days. A total of 44 Merino lambs were randomly divided into two experimental groups: one that received the RLE ($n = 22$) and the control group (CON; $n = 22$). The RLE extract was orally and individually administered (90 mg/kg of live weight) to each lamb every day from colostrum assumption until slaughter (40 ± 1 days). *Longissimus lumborum* muscle was sampled and dry aged at 4°C for seven days. The VOC and sensorial analyses were carried out at 1, 3 and 7 days. A total of 65 VOCs were detected. Aldehyde family was the most abundant, followed by ketones and alcohols in both groups. Extending ageing period, content of aldehydes and thiols increased only in control group ($p < 0.01$), but no differences were observed 24 h after slaughtering ($p > 0.05$). Regardless of dietary treatment, sensory evaluation, tenderness and juiciness showed a similar trend in both groups. Along ageing days, a significant improvement in these patterns was observed ($p < 0.05$). Our results showed that RLE inclusion did not have effects on both volatile compounds and sensory profile after slaughtering; ageing improves some sensory characteristics of lamb meat and the inclusion of RLE also seems to have a positive effect on the production of VOCs and on sensory properties such as meaty odour and overall liking.

HIGHLIGHTS

- Anthocyanins extracted from red orange and lemon extract have antioxidant properties.
- Red orange and lemon extract is reported to exert antioxidant effect as feed additive in ruminants.
- Anthocyanins affect volatile compounds (VOCs) of meat only after some ageing days.
- Anthocyanins can improve VOCs and sensory profile of lamb meat.

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Introduction

Flavour is one of the key factors affecting consumers' choice of food. Many studies have focused on improving meat flavour compounds, particularly of small ruminant species, from the standpoint of animal nutrition. Lipid can easily deteriorate, leading to the reduction of meat oxidative stability and the production of various volatile components (Wood et al. 2004). In fact, certain secondary oxidation products are characterised by odours that consumers can detect as rancidity flavour if their threshold is exceeded (Li et al. 2020). It is well known that antioxidants can inhibit

lipid oxidation, and these substances, both synthetic and natural, have been widely used in meat production (Tian et al. 2021). The use of synthetic products has been discouraged because of their potential toxic effects, so meat industry has turned attention to new economical and effective natural antioxidants that can replace synthetic antioxidants without adversely affecting the quality of finished products and consumer perceptions (Shah et al. 2014). Moreover, there is a growing research interest in natural antioxidants to be introduced into animal feed in order to improve not only the quality of the meat but also animal welfare and their immune status, thus enabling the reduction

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of antibiotic use on farms (Zeng et al. 2015). In fact, it is reported that the use of natural vegetable additives also in ruminant diet can help improve the chemical–physical and sensory characteristics of livestock products such as meat (Tsiplakou et al. 2021).

Citrus (*Citrus spp*) is one of the most important fruits crop worldwide (the second most produced fruit worldwide in 2021), accounting for 161.8 million tons produced in more than 10.2 million hectares (Gonzatto and Santos 2023). Oranges account for over 50% and the major producing countries are Brazil, China, India and the United States of America, followed by mandarin, grapefruit, lemon and lime (Agustí et al. 2014). Europe produces about 28% of world production and the major producing countries are Spain, Italy and Greece. About 30% of the production of citrus fruits (and 40% of orange production) is processed, principally to make juice, and large amounts of by-products are obtained (Alnaimy et al. 2017).

In several previous studies, it has been observed that the red orange and lemon extract (RLE) obtained from processed waste is rich in flavanones and anthocyanins (Damiano et al. 2020; Caruso et al. 2021). If included as additive in the diet, it is able to improve muscle oxidative status in kids (Salzano et al. 2021) and lambs (Maggiolino et al. 2021), it is able to inhibit the growth of potentially pathogenic bacteria in the faecal microbiota (Ferrara et al. 2021) and to induce a significant reduction in oxidative stress-induced damage in lambs (Damiano et al. 2022). A recent study on kid meat has shown that RLE inclusion in the diet of lactating lambs can affect volatile organic compounds (VOCs) production during the ageing, although were not enough to be perceived by panellists at the sensory test (Sgarro et al. 2022).

Given the current knowledge regarding the effects of RLE on the meat of small ruminants, particularly kid's meat, the aim of the work is to evaluate the effect of RLE supplementation in lamb diet on VOC composition and meat flavour during a seven-day ageing time.

Materials and methods

Ethics statement

The trial was carried out in compliance with D.Lgs. n. 26/2014 and it was authorised by the Animal Welfare Body of the University of Naples Federico II (protocol number 2019/0028161 of 03/19/2019).

Relative composition of red orange and lemon extract

The dry powder phytoextract, which was rich in bioflavonoids (flavanones and anthocyanins) and other polyphenols, was obtained according to a patented extraction process (Italian Patent No. 102017000057761) from red orange and lemon processing wastes, exclusively for experimental purpose (Salzano et al. 2021). The relative concentrations of individual flavanones and anthocyanins were identified by HPLC-PDA-ESI/MSⁿ as described in previous studies (Damiano et al. 2020; Maggiolino et al. 2021). Separation of anthocyanins content in the RLE extract was quantified using an ultra-Fast HPLC system coupled with a photodiode array (PDA) detector and Finnigan LXQ equipped with an electrospray ionisation (ESI) interface in series configuration (Thermo Electron, San Jose, CA). The anthocyanins were quantified by UHPLC according to a method described by Fabroni et al. (2016). The individual abundances of each anthocyanin are reported in Table 1.

Table 1. Anthocyanin content of the experimental feed (red orange and lemon extract, RLE).

Components	[M] ⁺ (m/z)	MS ⁿ (m/z)	Anthocyanin	Relative composition (%) ^a
1	611	449/287	Cyanidin 3,5-diglucoside	1.29
2	465	303	Delphinidin 3-glucoside	2.67
3	611	287	Cyanidin 3-sophoroside	0.41
4	449	287	Cyanidin 3-glucoside	39.97
5	595	287	Cyanidin 3-rutinoside	1.30
6	479	317	Petunidin 3-glucoside	1.59
7	551	465/303	Delphinidin 3-(6''-malonyl) glucoside	1.43
8	463	301	Peonidin 3-glucoside	2.98
9	565	479/317	Petunidin 3-(6''-malonyl) glucoside	1.45
10	535	449/287	Cyanidin 3-(6''-malonyl) glucoside	21.76
11	–	271	Pelargonidin derivative	1.44
12	549	463/301	Peonidin 3-(6''-malonyl) glucoside	13.80
13	–	287	Cyanidin derivative	2.39
14	–	301	Peonidin derivative	1.82
Total anthocyanins (g CGE/100 g)				2.66 ± 0.01

[M]⁺ (m/z): mass peak; MSⁿ (m/z): MS fragmentation model.

^aRelative composition of anthocyanins calculated from peak areas recorded at 520 nm. The total anthocyanin content was expressed as mg of cyanidin 3-glucoside equivalents (CGE)/100 mL.

Animal management and feeding

The experimental procedures were carried out at the experimental farm of the Council for Agricultural Research and Economics, Research Centre of Animal Production and Aquaculture (CREA, Bella Muro, Italy). The trial involved 44 Merino male lambs, all born as singletons. All lambs were managed as described by Maggiolino et al. (2021). After colostrum assumption, lambs were randomly divided into two groups of 22 animals each using a complete random block design. One was treated as experimental group (RLE; $n = 22$) that received orally the feed additive (90 mg/kg of live weight) and the other one, the control group, who was given a 0.90% NaCl solution (control; $n = 22$). The RLE extract was administered to each lamb every day and once a day from birth until slaughter (40 ± 1 days). Lambs received RLE that was mixed with water to obtain a cream (Maggiolino et al. 2021), and saline solution using a large syringe. All animals were weighed once every two days to daily amount of RLE to be fed.

Meat sampling

As all the lambs were slaughtered at 40 ± 2 days of age. Lambs were transported to a European Community-approved abattoir, far 15 km from the farm, in compliance with European Community laws on Animal Welfare in transport (1/2005EC) and the European Community regulation on Animal Welfare for slaughter of commercial animals (1099/2009EC). Slaughter procedures were the same described in a previous study (Maggiolino et al. 2021).

The *Longissimus thoracis et lumborum* muscles were collected (from the 1st thoracic to the 5th lumbar vertebra) at the slaughter day, after 4 h chilling at 4 °C. It was cut into three parts and each part was randomly assigned to one of the three experimental storage days: 1, 3 or 7. All sections were placed in extruded polystyrene trays (AERpack PCM0330 produced by Coopbox Italia, Bibbiano, Italy), wrapped in film (Cryovac LID2050, Passirana di Rho, Milano, Italy) and stored until the preassigned storage day at a temperature of 4 °C in the dark as described by Maggiolino et al. (2020).

Volatile compounds (VOCs) analysis

Five grams meat samples were grilled at temperature of 130–150 °C on each surface, using an electrical griddle (Delonghi, Mod. CG660, Treviso, Italy) until 70 °C at core was reached. Temperature was measured with a

copper constantan fine wire thermocouple fixed in the geometrical centre of the sample (model 5SCTT-T-30-36; Omega Engineering Inc., Norwalk, CT) as described by Maggiolino et al. (2019). Then, samples were minced and analysed for VOC determination as reported by Maggiolino et al. (2021).

The VOCs were extracted by solid-phase micro-extraction (SPME) as reported by Natrella et al. (2020). The samples were weighed (1 ± 0.05 g) into 20 mL vials, closed by a rubber septum and an aluminium cap. All samples were added with internal standard (82 ng 2-octanol) to perform a semi-quantitation and loaded into an autosampler Triplus RSH (Thermo Fisher Scientific, Rodano, Italy). The vials were kept at 35 °C for 15 min for equilibration, the extraction was carried out using a divinylbenzene/carboxen/polydimethylsiloxane 50/30 mm SPME fibre assembly (Supelco, Bellefonte, PA) at 35 °C for 30 min. The fibre was desorbed at 250 °C for 5 min in the injection port of the Trace1300 gas chromatograph (Thermo Fisher Scientific, Rodano, Italy), operating in splitless mode. The gas chromatograph was equipped with a mass spectrometer ISQ Series 3.2 SP1. The compounds were separated on a Thermo capillary column VF-WAX MS (60 m, 0.25 mm, 0.25 mm), under the following conditions: injection port temperature, 250 °C; oven temperatures, 35 °C for 5 min then 1.5 °C min⁻¹ to 45 °C, then 4 °C min⁻¹ to 160 °C, a final increase up to 210 °C at 20 °C min⁻¹, the final temperature was held for 7 min. Mass detector was set at the following conditions: detector voltage, 1700 V; source temperature, 250 °C; ionisation energy, 70 eV; and scan range 40–300 amu. Tentative identification of the peaks was done by means of Xcalibur V2.0 software, in particular Qual Browse, by matching their spectra with the reference mass spectra of NIST library. The semi-quantitation of the compounds was carried out using the internal standard method, and the amounts were expressed as ng/g.

Sensory analysis

A panel of seven trained evaluators carried out the sensory analysis test. The selection of the expert assessors was carried out following the British Standards Institution (BSI 1993) methods. The meat samples for sensory analysis were cut into slices (about 2 cm thin) and grilled at temperature of 130–150 °C on each surface, using an electrical griddle (Delonghi, Mod. CG660, Treviso, Italy) until 70 °C at core was reached. After fat and connective tissue removal, the sample was cut into about 1.5 cm³ pieces, then wrapped in

pre-labelled foils and placed in a heated incubator until offered to the evaluators. In order to balance the carryover effects among the meat samples, the tasting was designed as reported by MacFie et al. (1989).

Each expert evaluator performed four different sessions in each of which 11 samples were tasted for a total of 88 meat samples per panellist (one sample for each of the 44 lambs). The order of the samples was randomised by the sensory panel software (Compusense 5 software; Compusense, Inc., Guelph, Canada), ensuring a different sequence for each panellist. Tested samples were scored on a 1–10-point scale for tenderness (1 = extremely tough to 10 = extremely tender), juiciness (1 = extremely dry to 10 = extremely juicy), overall liking (1 = extremely disliking to 10 = extremely liking), sweetness, unpleasant taste, meaty odour and unpleasant odour (1 = extremely weak to 10 = extremely strong for each descriptor).

Statistical analysis

The data set was tested for normal distribution and variance homogeneity (Shapiro–Wilk and Bartlett test).

Each lamb represented an experimental unit. All data were processed with analysis of variance (ANOVA) using GLM procedure of SAS software, according to the following model:

$$y_{ijk} = \mu + \alpha_i + A_j + T_k + (A \times T)_{jk} + \varepsilon_{ijkl},$$

where y_{ijk} are dependent variables; μ is the overall mean; α_i is the i th lamb random effect ($i = 1, \dots, 44$), A was the effect of the j th dietary RLE inclusion ($j = 1, 2$), T is the effect of the k th ageing ($k = 1, \dots, 3$), $(A \times T)_{jk}$ is the binary interaction of dietary treatment and ageing time and ε_{ijkl} is the error term. A Tukey test for repeated measures was applied to evaluate the differences according to ageing time.

For the analysis of factors affecting each sensory trait, fixed terms for full models included ageing and time, as well as additional covariates of panellist age, income level, gender, the number of adults in the household and preferred degree of doneness were added to the model in turn. The experimental design factors of panellist, tasting round and session were fitted as random effects. All means were expressed as

Table 2. Effect of red orange and lemon extract dietary supplementation and ageing time on alcohol volatile compounds of grilled meat from lambs ($n = 22$ samples for each experimental group).

	Group	Ageing time			SEM ¹	<i>p</i> Value		
		Day 1	Day 3	Day 7		<i>G</i> ²	<i>T</i> ³	<i>G</i> × <i>T</i>
1-Heptanol	CON	14.27	13.25	15.26	0.64	0.2369	0.5487	0.6633
	RLE	10.51	11.56	15.46				
1-Hexanol	CON	52.05	60.25	70.25	8.96	0.3325	0.3489	0.5622
	RLE	66.16	71.36	76.33				
1-Hexanol, 2-ethyl-	CON	7.23	8.21	7.36	1.25	0.5456	0.2895	0.6789
	RLE	2.44	4.25	5.99				
1-Nonen-4-ol	CON	2.13	3.58	4.89	0.85	0.4899	0.5688	0.4993
	RLE	4.52	5.02	5.96				
1-Octanol	CON	13.64	15.68	18.25	1.76	0.3695	0.4799	0.8123
	RLE	19.96	20.15	24.26				
1-Octen-3-ol	CON	167.44a	254.68	302.58b	11.36	0.4344	0.0109	0.3325
	RLE	196.33	205.26	237.65				
1-Pentanol	CON	156.54a	205.36	296.47b	11.65	0.5955	0.0312	0.8156
	RLE	179.89a	201.25	236.89b				
1-Penten-3-ol	CON	58.95	62.35	66.98	7.89	0.4944	0.3397	0.6335
	RLE	62.32	65.35	71.25				
1-Propanol	CON	–	–	–	3.12	–	0.9654	–
	RLE	28.67	29.66	35.26				
1-Undecanol	CON	–	–	–	2.58	–	0.4578	–
	RLE	23.06	28.95	30.65				
2-Hexen-1-ol	CON	–	–	–	3.95	–	0.5488	–
	RLE	37.62	40.25	45.36				
2,7-Octadien-1-ol	CON	2.56	3.26	4.25	0.71	0.6665	0.7715	0.6324
	RLE	3.21	4.58	6.36				
2-Octen-1-ol	CON	7.75	8.36	9.68	0.99	0.4996	0.3398	0.4295
	RLE	8.83	9.35	10.25				
2-Penten-1-ol	CON	10.63a	15.62	48.98b,x	1.29	0.7441	0.0132	0.0432
	RLE	11.96	12.36	14.66y				

CON: control; RLE: red orange and lemon extract.

Results are expressed as ng/g of meat.

¹Standard error of the means.

²Group.

³Ageing time.

Different letters in the same row show statistical differences during time in the same group^{a,b} = $p < 0.05$.

Different letters in the same column show statistical differences between groups at the same ageing time^{x,y} = $p < 0.05$.

Table 3. Effect of red orange and lemon extract dietary supplementation and ageing time on aldehyde volatile compounds of grilled meat from lambs ($n = 22$ samples for each experimental group).

	Group	Ageing time			SEM ¹	<i>p</i> Value		
		Day 1	Day 3	Day 7		<i>G</i> ²	<i>T</i> ³	<i>G</i> × <i>T</i>
2,4-Decadienal	CON	2.86a	3.68	7.65b,x	0.23	0.0322	0.0051	0.0072
	RLE	2.34	2.98	4.52y				
2,4-Dodecadienal	CON	1.91a	2.02	4.12 ^b	0.15	0.2452	0.0325	0.1254
	RLE	1.94	2.41	3.02				
2,4-Heptadienal	CON	2.64	3.02	3.24	0.09	0.4158	0.5222	0.6812
	RLE	2.97	3.24	3.54				
2-Nonenal	CON	5.84a	8.24	16.57b,x	0.98	0.1592	0.0441	0.2126
	RLE	5.44	6.25	7.66y				
2-Octenal	CON	5.85a	7.12	15.65b	0.62	0.4032	0.0299	0.1878
	RLE	5.34	6.52	9.15				
4-Heptenal	CON	18.41	19.52	20.65	0.88	0.2358	0.6512	0.4456
	RLE	14.52	19.49	22.16				
4-Nonenal	CON	5.04a	9.02 ^b	14.25c,x	0.91	0.0258	0.0369	0.0159
	RLE	3.44	4.25	5.82y				
Benzaldehyde	CON	14.92a	21.02	28.18b	1.03	0.6195	0.0126	0.5208
	RLE	16.95a	18.66	26.28b				
Butanal	CON	3.66	3.98	4.02	0.06	0.8482	0.6554	0.9102
	RLE	3.77	4.21	4.01				
Butanedial	CON	6.67	10.25	12.56	1.01	0.6548	0.3589	0.7029
	RLE	7.31	6.89	9.23				
Dodecanal	CON	13.36a	16.25	25.69b,X	1.26	0.0025	<0.0001	<0.0001
	RLE	–	–	3.25 ^y				
Heptanal	CON	444.76A	548.35	702.54B,X	18.63	0.0010	<0.0001	<0.0001
	RLE	332.79	352.58	421.89Y				
Hexanal	CON	4801.67A	7598.33B,X	12548.32C,X	27.03	0.0057	<0.0001	<0.0001
	RLE	4571.78	5262.58 ^y	5321.85Y				
Nonanal	CON	452.58	502.23	752.95	14.96	0.2548	0.3456	0.2289
	RLE	414.28	426.39	521.65				
Octanal	CON	161.69a	206.35	321.85b	17.39	0.3956	0.0235	0.4556
	RLE	149.02	180.25	204.98				
Pentanal	CON	193.18a	196.36 ^a	395.63b,x	14.36	0.0459	0.0369	0.0288
	RLE	158.99	168.25	172.36y				
Propanal	CON	63.22	71.25	70.65	1.96	0.1266	0.2485	0.3368
	RLE	39.49	39.29	45.27				

CON: control; RLE: red orange and lemon extract.

Results are expressed as ng/g of meat.

¹Standard error of the means.²Group.³Ageing time.Different letters in the same row show statistical differences during time in the same group: ^{A,B,C} $p < 0.01$ and ^{a,b,c} $p < 0.05$.Different letters in the same column show statistical differences between groups at the same ageing time: ^{x,y} $p < 0.01$ and ^{x,y} $p < 0.05$.

square means and mean standard error. The significance was set at $p < 0.05$.

Results

Volatile organic compounds

Alcohol concentration in VOC from the grilled experimental lambs is reported in Table 2. The value of 1-octen-3-ol and 2-penten-1-ol was lower ($p < 0.05$) at day 1 (D1) than day 7 (D7) only in CON group. Also 1-pentanol showed the same trend in both the dietary experimental thesis ($p < 0.05$). Moreover, 2-penten-1-ol ($p < 0.05$) was higher in CON samples than RLE at D7.

Table 3 shows aldehyde VOCs detected in VOCs. Levels of 2,4-decadienal, 2-nonenal, 4-nonenal, dodecanal, heptanal ($p < 0.01$) and pentanal

($p < 0.05$) increased after seven days of ageing in CON group and the same values were higher at D7 in CON group compared to RLE samples ($p < 0.05$). Furthermore, 2,4-dodecadienal, 2-octenal ($p < 0.05$) raised at D7 in CON group, but no differences were observed between experimental groups. In both groups, benzaldehyde ($p < 0.05$) and hexanal ($p < 0.01$) raised over ageing time, and hexanal ($p < 0.01$) was almost 25% and 225% higher on day 3 (D3) and D7, respectively, in the CON group than in the RLE one.

Carboxylic acid level in VOC from the grilled lamb meat is described in Table 4. Ethanoic acid, hexyl ester increased up to D7 in the samples of the RLE group ($p < 0.05$), while no trace of such compound was detected in the meat from CON group. Similarly, pentanoic and propanoic acid raised at D7 than D1 in

Table 4. Effect of red orange and lemon extract dietary supplementation and ageing time on carboxylic acid volatile compounds of grilled meat from lambs ($n = 22$ samples for each experimental group).

	Group	Ageing time			SEM ¹	<i>p</i> Value		
		Day 1	Day 3	Day 7		<i>G</i> ²	<i>T</i> ³	<i>G</i> × <i>T</i>
Butanoic acid	CON	4.42	5.23	5.96	0.25	0.3256	0.5855	0.4596
	RLE	7.56	8.23	7.98				
Butanoic acid, 4-hydroxy-	CON	2.60	3.65	4.02	0.41	0.6632	0.2589	0.5423
	RLE	3.92	4.03	4.52				
Ethanoic acid	CON	16.05	20.25	26.98	1.68	0.4896	0.4722	0.3694
	RLE	17.79	18.65	20.58				
Ethanoic acid, hexyl ester	CON	–	–	–	21.36	–	0.0269	–
	RLE	220.45a	260.25	379.36b				
Heptanoic acid	CON	25.72	26.69	27.45	1.98	0.4496	0.9521	0.4792
	RLE	21.13	22.58	24.65				
Hexanoic acid	CON	26.95	32.25	35.89	0.54	0.6854	0.3952	0.7235
	RLE	26.80	30.21	31.54				
Hexanoic acid, ethenyl ester	CON	98.14	102.36	108.66	8.56	0.5326	0.5963	0.8123
	RLE	86.98	92.54	100.58				
Nonanoic acid	CON	38.24	42.65	44.89	0.65	0.3698	0.4562	0.3649
	RLE	31.71	35.68	38.69				
Octanoic acid	CON	11.49	13.58	16.98	0.98	0.2356	0.2215	0.1598
	RLE	12.77	15.25	18.47				
Pentanoic acid	CON	5.13a	15.23	30.25b,x	1.98	0.0258	0.0366	0.0412
	RLE	4.52	5.26	8.48y				
Propanoic acid	CON	7.97a	15.69	29.35b,x	0.69	0.0415	0.0158	0.0129
	RLE	6.50	8.02	9.66y				

CON: control; RLE: red orange and lemon extract.

Results are expressed as ng/g of meat.

¹Standard error of the means.²Group.³Ageing time.Different letters in the same row show statistical differences during time in the same group: ^{a,b} = $p < 0.05$.Different letters in the same column show statistical differences between groups at the same ageing time: ^{x,y} = $p < 0.05$.**Table 5.** Effect of red orange and lemon extract dietary supplementation and ageing time on ketone volatile compounds of grilled meat from lambs ($n = 22$ samples for each experimental group).

	Group	Ageing time			SEM ¹	<i>p</i> Value		
		Day 1	Day 3	Day 7		<i>G</i> ²	<i>T</i> ³	<i>G</i> × <i>T</i>
1-Octen-3-one	CON	7.65a	15.32	32.25b,x	1.54	0.0245	0.0356	0.0189
	RLE	6.49	8.21	10.89y				
2-Butanone,3-hydroxy	CON	401.75A	602.35B	809.63C,X	25.68	<0.0001	<0.0001	<0.0001
	RLE	487.53A	568.24	601.98B,Y				
2,3-Pentanedione	CON	92.37a	102.58	124.69b	9.65	0.5524	0.0410	0.2954
	RLE	98.50	100.58	102.36				
2-Heptanone	CON	14.71	15.63	18.36	1.25	0.2698	0.3245	0.7412
	RLE	13.79	14.25	15.98				
2-Heptanone,6-methyl	CON	7.69	8.25	9.65	0.87	0.4511	0.6582	0.3254
	RLE	8.88	8.95	10.25				
2-Hexanone,4-methyl	CON	8.07a	9.65	15.32b	1.98	0.4788	0.0410	0.3233
	RLE	7.24	8.45	9.25				
2-Octanone	CON	11.9A	18.45	35.68B,X	2.01	0.0026	0.0005	0.0030
	RLE	11.46	12.45	15.28Y				
2-Propanone	CON	34.81A	49.35	87.40B,X	6.33	<0.0001	<0.0001	<0.0001
	RLE	31.80	36.52	41.24Y				
3,5-Octadien-2-one	CON	15.84a	23.56	36.58b	2.99	0.4878	0.0369	0.7128
	RLE	15.50	17.25	20.47				
3-Hepten-2-one	CON	132.53a	168.65	258.99b,x	18.58	0.0258	0.0365	0.0410
	RLE	131.65	154.25	152.98y				
5-Hepten-2-one,6-methyl	CON	19.41	22.56	24.98	3.68	0.7354	0.6184	0.5222
	RLE	20.71	28.32	30.45				
6,7-Dodecanedione	CON	515.63A	702.56B	874.66B	36.89	0.4554	<0.0001	0.3527
	RLE	563.58A	602.33	709.88B				

CON: control; RLE: red orange and lemon extract.

Results are expressed as ng/g of meat.

¹Standard error of the means.²Group.³Ageing time.Different letters in the same row show statistical differences during time in the same group: ^{A,B,C} = $p < 0.01$; ^{a,b} = $p < 0.05$.Different letters in the same column show statistical differences between groups at the same ageing time: ^{x,y} = $p < 0.01$; ^{x,y} = $p < 0.05$.

Table 6. Effect Of red orange and lemon extract dietary supplementation and ageing time on aromatic hydrocarbons, furans and hydrocarbons of grilled meat from lambs ($n = 22$ samples for each experimental group).

		Ageing time			p Value			
	Group	Day 1	Day 3	Day 7	SEM1	G ²	T ³	G × T
Aromatic hydrocarbons								
Benzene, 1,2-dimethyl	CON	36.53A	48.35	78.54B	5.24	0.4215	0.0025	0.3898
	RLE	30.01	38.45	49.24				
Benzene, 1,3-dimethyl	CON	47.14A	84.25	102.89B,X	8.35	<0.0001	<0.0001	<0.0001
	RLE	40.64	50.21	62.47Y				
Ethylbenzene	CON	27.63A	35.25A	75.14B,X	6.23	<0.0001	<0.0001	<0.0001
	RLE	29.05	32.05	39.78Y				
Furans								
Furan, 2-ethyl-	CON	7.17	10.25	12.56	1.68	0.4889	0.5266	0.7125
	RLE	11.46	12.54	13.98				
Furan, 2-pentyl	CON	18.34	20.35	22.58	3.32	0.2689	0.6335	0.4822
	RLE	20.01	22.58	26.78				
Hydrocarbons								
Heptane	CON	68.79A	152.58B	203.65C	8.95	–	<0.0001	–
	RLE	–	–	–				
Octane	CON	88.98A	145.36B,X	210.54C,X	10.52	<0.0001	<0.0001	<0.0001
	RLE	74.89	85.35Y	92.58Y				
Pentane, 1-cyclopropyl	CON	20.13a	32.25	48.58b	2.59	0.7442	0.0388	0.4229
	RLE	25.28	30.25	35.47				

CON: control; RLE: red orange and lemon extract.

Results are expressed as ng/g of meat.

¹Standard error of the means.²Group.³Ageing time.Different letters in the same row show statistical differences during time in the same group: ^{A,B,C} = $p < 0.01$; ^{a,b} = $p < 0.05$.Different letters in the same column show statistical differences between groups at the same ageing time: ^{x,y} = $p < 0.01$.**Table 7.** Effect of red orange and lemon extract dietary supplementation and ageing time on volatile organic compounds of grilled meat from lambs ($n = 22$ samples for each experimental group).

	Group	Ageing time			SEM ¹	p Value		
		Day 1	Day 3	Day 7		G ²	T ³	G × T
Alcohols	CON	490.19A	662.6	846.95B	68.69	0.4985	0.0025	0.4968
	RLE	658.42	729.35	836.33				
Aldehydes	CON	6135.04A	9155.74B,X	14873.87C,X	247.25	<0.0001	<0.0001	<0.0001
	RLE	5690.88	6464.95Y	6736.85Y				
Aromatic hydrocarbons	CON	111.3	167.85	256.57	33.85	0.6558	0.5487	0.6933
	RLE	99.7	121.71	151.49				
Furans	CON	27.54	30.58	36.24	2.58	0.2368	0.5478	0.3669
	RLE	31.29	35.64	41.98				
Carboxylic acids	CON	236.71	277.58	330.43	20.98	0.6638	0.8124	0.7395
	RLE	440.13	500.70	644.51				
Hydrocarbons	CON	177.92	332.65	462.85	34.32	0.3956	0.6252	0.7488
	RLE	100.78	115.65	129.56				
Lactones	CON	6.30	7.58	8.25	0.54	0.7559	0.5189	0.3678
	RLE	6.04	6.58	7.41				
Sulphur compounds	CON	18.46	20.58	22.35	1.06	0.1598	0.2878	0.3718
	RLE	15.29	18.78	20.58				
Thiols	CON	34.04A	54.98	70.85B ^x	5.65	<0.0001	<0.0001	<0.0001
	RLE	38.90	42.58	43.58Y				
Ketones	CON	1262.36A	1738.91	2328.13B	221.25	0.4588	<0.0001	0.8852
	RLE	1397.13	1559.8	1721.01				

CON: control; RLE: red orange and lemon extract.

Results are expressed as ng/g of meat.

¹Standard error of the means.²Group.³Ageing time.Different letters in the same row show statistical differences during time in the same group: ^{A,B,C} = $p < 0.01$.Different letters in the same column show statistical differences between groups at the same ageing time: ^{x,y} = $p < 0.01$.

CON group ($p < 0.05$) and reaching higher values than in the RLE group at the same day ($p < 0.05$).

Table 5 shows values of ketones found in VOCs. Levels of 1-octen-3-one ($p < 0.05$), 2-octanone

($p < 0.01$), 2-propanone ($p < 0.01$), 5-hepten-2-one, 6-methyl ($p < 0.05$) 2,3-pentanedione ($p < 0.05$), 2-hexanone, 4-methyl- ($p < 0.05$) and 3,5-octadien-2-one ($p < 0.05$) increased until D7 of ageing in CON group.

Table 8. Effect of red orange and lemon extract dietary supplementation and ageing time on sensory evaluation of grilled meat from lambs ($n = 22$ samples for each experimental group).

	Group	Ageing time			SEM ¹	<i>p</i> Value		
		Day 1	Day 3	Day 7		<i>G</i> ²	<i>T</i> ³	<i>G</i> × <i>T</i>
Tenderness	CON	6.15a	6.87	7.52b	0.06	0.6653	0.0254	0.2323
	RLE	6.21a	6.91	7.65b				
Juiciness	CON	6.96a	7.58b	7.24	0.05	0.4455	0.0349	0.7115
	RLE	6.92a	7.49	7.61b				
Sweetness	CON	6.21	6.32	6.41	0.06	0.5544	0.7125	0.3991
	RLE	6.15	6.28	6.35				
Unpleasant taste	CON	3.93	3.56	3.61	0.07	0.5123	0.8125	0.2277
	RLE	4.02	3.85	3.66				
Unpleasant odor	CON	4.23	4.52	4.65	0.05	0.2895	0.4912	0.5128
	RLE	4.33	4.38	4.36				
Meaty odor	CON	7.21a	8.35b	7.27a,x	0.06	0.0235	0.0158	0.0122
	RLE	7.35a	8.35b	8.23b,y				
Overall assessment	CON	7.55a	8.52b	7.66a,x	0.07	0.0325	0.0245	0.0147
	RLE	7.42a	8.56b	8.51b,y				

CON: control; RLE: red orange and lemon extract.

¹Standard error of the means.²Group.³Ageing time.Different letters in the same row show statistical differences during time in the same group: ^{a,b} = $p < 0.05$.Different letters in the same column show statistical differences between groups at the same ageing time: ^{x,y} = $p < 0.05$.

This trend led to reaching higher values at D7 of 1-octen-3-one ($p < 0.05$), 2-octanone ($p < 0.01$), 2-propanone ($p < 0.01$) and 3-hepten-2-one ($p < 0.05$) in CON group than in RLE one. In both the experimental groups, 6,7-dodecanedione ($p < 0.01$) and 2-butanone, 3-hydroxy ($p < 0.01$) raised during ageing time. The latter compounds, moreover, had lower concentration at D7 in the RLE group ($p < 0.01$).

Results of aromatic hydrocarbons, furans, hydrocarbons, lactones, sulphur compounds and thiols by grilled lamb meat are shown in Table 6. Benzene, 1,2-dimethyl-, benzene, 1,3-dimethyl- and ethylbenzene tended to grow in concentration over ageing time ($p < 0.01$) and the values of the last two compounds were higher at D7 in CON group ($p < 0.01$). No traces of heptane were found in the RLE samples. Heptane, octane ($p < 0.01$) and pentane-1-cyclopropyl ($p < 0.05$) grew up to D7 only in CON sample. Besides, the octane concentrations were lower in RLE group compared to CON one, both at D3 and D7 ($p < 0.01$).

Table 7 shows the effect of dietary supplementation with RLE on VOC chemical families. Alcohols, aldehydes, thiols and ketones raised ($p < 0.01$) until D7 in CON group; moreover, aldehydes (at D3 and D7) and thiols (at D7) were lower in RLE samples ($p < 0.01$).

Sensory profile

The results of the sensory evaluation are shown in Table 8. Tenderness, juiciness, meaty odour and overall liking increased with ageing in both experimental groups ($p < 0.05$). Furthermore, meaty odour and

overall liking were greater at D7 in meat from RLE group than CON ($p < 0.05$).

Discussion

Volatile organic compounds

Raw meat has an extremely weak taste, while the cooking process enhances its flavour. Among the processes involved in the production of VOCs in meat, Maillard reaction, lipid oxidation and thermal degradation of vitamins are the main ones (Khan et al. 2015). Some compounds derive from chemical precursors present in raw meat, while other ones derive from secondary degradation/oxidation processes of meat molecules during ageing and/or storage.

A total of 65 VOCs were detected and recognised using SPME/GC-MS from grilled lamb meat. These compounds were assigned to 10 families according to chemical structure: 17 aldehydes, 14 alcohols, 12 ketones, 11 carboxylic acids, three hydrocarbons, three aromatic hydrocarbon, two furans, one lactone, one sulphur compound and one thiol. Very similar results were found in a previous study on 40-day-old kids (Sgarro et al. 2022), whereas a reduced number of chemical families was detected in our samples compared to a recent study conducted on 100-day-old Comisana breed lambs (Natalello et al. 2023). Volatile compound composition can be strongly influenced by breed, sex, age, animal feeding and fatty acid composition of meat as well as by the procedures for slaughtering, ageing, storage and cooking technique (Drumm and Spanier 1991; Aaslyng and Meinert 2017).

In the muscle, there are several water-soluble non-VOCs with low molecular weight, which act as precursors of VOCs and indirectly influence the meat aroma. These include amino acids, peptides, reducing sugars, vitamins and nucleotides, although the composition of muscle fat and sulphur amino acids such as cysteine and methionine are the main components that affect the flavour of cooked meat (Resconi et al. 2013). Some chemical families of VOCs generally detected in beef, horse and donkey meat as nitrogen compound (Ba et al. 2014; Maggiolino et al. 2020) and esters (Domínguez et al. 2014) were not detected in the meat samples examined in the present study. Indeed, no trace of pyrazines has been found in the trial, although they have been reported in well-done grilled meat (Watanabe et al. 2015). Regardless of the dietary treatment and ageing time, consistently with other studies conducted on beef (Ma et al. 2012), pork (Ramírez et al. 2004), lamb (Vasta et al. 2013) and equids meat (Maggiolino et al. 2019, 2020), in our trial, the aldehyde family was the most representative among VOCs, followed by ketones and alcohols. Aldehydes and ketones are the products of the early lipid oxidation, while compounds such as alcohols and esters were derived from secondary oxidation processes (Soncin et al. 2007). Furans, lactones, sulphur compounds and thiols in our samples have been detected in limited extent. Sensory detection thresholds of VOC from lipid oxidation are significantly higher compared to those of heterocyclic compounds containing nitrogen or sulphur that belong to Maillard reaction pathways (Kosowska et al. 2017).

Extending ageing period, the meat content of aldehydes, ketones, alcohols and thiols increased only in control group; the effect of ageing or storage on VOCs concentration is consistent with results reported by several authors (Ba et al. 2014; Sgarro et al. 2022). Furthermore, total thiols (D3) and, mostly, aldehydes (D3 and D7) were significantly lower in the meat of animals receiving RLE than CON group. In a previous study, the RLE dietary supplementation improved the activity of antioxidant enzymes, as catalase, glutathione peroxidase and superoxide dismutase in plasma of lambs. Oranges, lemons, grapefruits and mandarins, widely used for ruminant feeding due to high amount of pectin and soluble carbohydrates (Hadjipanayiotou and Louca 1976; Inserra et al. 2014), contain high levels of bioactive compounds with significant antioxidant properties (Abeyasinghe et al. 2007; Zou et al. 2016). The antioxidant property of these compounds will depend on the oxidation-reduction of the hydroxyphenolic group and on the chemical structure.

However, the antioxidant capacity of some fruits is not simply given by the sum of the antioxidant capacities of each of its components but also by the interaction between them, which can produce synergistic or antagonistic effects (Abeyasinghe et al. 2007). However, the biochemical pathways able to describe the effect of RLE and other similar additive on meat quality are unclear. It is clear that the RLE administration is not able to affect VOC profile soon after slaughtering, but during ageing it seems to reduce the production of those VOC that derives from oxidative processes, particularly on lipid components.

Hexanal, the most detected aldehyde in all samples, is the primary VOC obtained from cooked meat of different species as pork, beef, horse and goat (Brodowska et al. 2016; Maggiolino et al. 2019; Maggiolino et al. 2021; Sgarro et al. 2022). Hexanal, as well as heptanal and pentanal, was derived from the lipid oxidation (Ha et al. 2019). Thus hexanal production is strongly correlated to the amount of intramuscular fat, and therefore dietary treatment did not show effects on these VOCs for the low fat content of suckling or weaned lamb meat (Guzmán et al. 2020). Generally, aldehyde threshold values of perception are very high and they are able to give the meat an unpleasant rancid flavour (Huang et al. 2013), although this threshold varies among aldehydes. The threshold value for the perception of hexanal by the human nose is considered 5000 ng/g (% ppm) (Brewer and Vega 1995; Bonaccorsi et al. 2022), and it is reached soon after one day after slaughtering, remaining stable during ageing in RLE group, but considerably increased in the CON group. While good concentrations impart the typical meaty odour, high concentrations are instead an indication of the onset of meat degradation processes (Ajuyah et al. 1993; Bonaccorsi et al. 2022). Also heptanal, characterised by a threshold value for human nose of about 230 ng/g (0.23 ppm) (Resconi et al. 2013), showed values over the threshold just one day after slaughtering, and increased only in CON group. Stability of hexanal and heptanal concentration, as well as of other aldehyde compounds, during the ageing of meat from animals fed with RLE, compared to the control group, can be due to the positive effect of RLE dietary administration on the enzymatic antioxidant mechanisms in lamb meat (Maggiolino et al. 2021). In fact, improvement of the oxidative stability of meat lipid component in small ruminants has been reported after the administration of diets rich in substances characterised by antioxidant activity (phenolic compounds, saponins, essential oils, anthocyanins) (Vasta and Luciano 2011;

Qwele et al. 2013), reporting also a reduction in the TBARS and hydroperoxides production during storage (Maggiolino et al. 2021).

The alcohol and carboxylic acid content profiles were very similar between the two experimental groups for almost all compounds. The alcohols detected are secondary products from aldehydes with the exception of 1-penten-3-ol, that belongs to 18:3n-3 autoxidation (Morán et al. 2013). In the present study, alcohols were produced in small amounts. The perception threshold values of alcohols are usually high and only some of these compounds can affect meat sensory profile. Precisely, 1-pentanol can be placed as aged meat contributors to a mild, fuel oil, fruit and balsamic odour notes, while 1-octen-3-ol can be detected as mushroom-like, earth, fatty and rancid notes (Sirtori et al. 2020). The 2-penten-1-ol was the only compound that on D7 was significantly lower in the RLE group than in control group. Minor differences were detected in carboxylic acids. These compounds were produced in moderate quantities. Ethanoic, pentanoic and propanoic acid increased after seven days of ageing. Generally, the production of these compounds is affected by composition of the fatty acids and the lipid content of meat. They mainly belong to the thermal degradation of meat triglycerides and phospholipids (Wong et al. 1975). Furthermore, no compounds deriving from the degradation of branched chain fatty acids and associated with the 'goaty/sweaty' odour such as 4-methyloctanoic, 4-ethyloctanoic and 4-methylnonanoic acids were detected in the present study. Probably, the early age of slaughtering and feeding system may have affected the accumulation and composition of intramuscular fat in lambs (Miller et al. 1986; Madruga et al. 2009). As described for aldehydes, alcohols and carboxylic acids, compounds belonging to the chemical family of ketones also derive from lipid oxidation processes (Maggiolino et al. 2019). In this study, the most abundant ketones detected were 2-butanone and 6,7-dodecanedione. The abundance of 2-butanone may be associated with grain-based diet in lambs (Vasta et al. 2007). Generally, in animals fed with a high quantity of concentrates, a high presence of ketones and precisely of 2-butanone and 2-heptanone was observed (Echegaray et al. 2021). However, 2-heptanone levels detected in our study were not relevant. This group was the third most abundant family for both experimental groups. Taking into account that the threshold level of perception for these compounds is quite low, this group could have had a significant influence on the sensory quality of meat (Casaburi

et al. 2015). The 2-ketones have a distinctive aroma that can be perceived as ethereal, buttery, spicy, blue cheese notes (Lorenzo 2014).

Among furans, 2-pentyl and 2-ethyl were the only compounds detected. Consistent with Echegaray et al. (2021), such furans are frequently found in lamb meat as a results of the oxidation in lipid fraction (Gkarane et al. 2018; Del Bianco et al. 2020).

Compared to other studies conducted on lamb (Echegaray et al. 2021), beef (Maggiolino et al. 2021) and horse meat (Tateo et al. 2020), low concentrations of hydrocarbons were recorded in the present study. Heptane, octane and pentane are the only linear aliphatic hydrocarbons detected. However, these compounds have a high olfactory threshold value (Bianchi et al. 2007) and poorly contribute to the sensory meat perception. Octane concentration in lamb meat tended to increase during storage only in the control group. The dietary treatment with RLE seemed to delay the production of hydrocarbons deriving from oxidation products. This hypothesis is consistent with a previous study, where lambs fed with RLE had low concentration of TBARS (lipid oxidation products) in muscle (Maggiolino et al. 2021).

Finally, the aromatic hydrocarbons detected in the study belong to benzene-derivatives. These compounds contribute to the sensory patterns of meat, due to low perception threshold value (Karabagias 2018). Some of these compounds, and in particular benzene, are intermediate products which are converted into aldehydes via oxidation pathways (Guo et al. 2021). This phenomenon may explain the low concentrations of aromatic hydrocarbons and the high levels of aldehydes in lamb meat. Consistent with our results about aldehydes, in lamb meat, the RLE dietary administration would affect the content of benzoic compounds, which produce a buttery aroma flavour (Maggiolino et al. 2019).

Sensory profile

The RLE inclusion in lactating lambs' diet was not able to modify the sensory evaluation of the meat. Nevertheless, ageing shows differences in sensory perception, particularly after seven days, in line with main effects on VOCs production. A significant improvement was observed in tenderness and juiciness in both experimental groups during ageing, with similar trend regardless of dietary treatment. The discussed differences in VOC levels may have influenced meaty odour and overall assessment. The prolongation of ageing from 3 to 7 days has induced a better perception of

the RLE meat, particularly referred to meaty odour and overall assessment. Although there were no changes in unpleasant odours, most likely the high release of compounds deriving from lipid oxidation during storage in the meat of the control group could have negatively affected the lamb meat sensory perception. Lipid peroxidation processes produce unpleasant odours and change tastes, as well as cause loss of water holding capacity and shorten shelf life (Domínguez et al. 2019). The higher aldehydes production, and particularly the great hexanal production after seven days in CON meat, really over the threshold considered for human perception, may have resulted in a worse evaluation of the CON meat at the sensory test. Therefore, this positive effect of the inclusion of RLE on the meat sensory perception could be an indirect phenomenon linked to the ability of RLE to improve the antioxidant capacity of the muscle even post-mortem directly or indirectly.

Conclusions

The results highlighted that the RLE inclusion in suckling lamb diet is not able to affect both VOCs production and sensory profile of lamb meat. However, the ageing favoured an increase in VOC production, contributing to the aroma of meat in lambs. Addition of RLE in the diet of lambs positively affected the production of VOCs during ageing. Although the experimental trial was carried out in a fairly short time (both for the *in vivo* feeding test and the meat ageing), RLE dietary supplementation positively reduced the production of compounds deriving from the lipid oxidation reaction, perceived as rancid taste. Furthermore, lamb meat obtained by animals dietary supplemented with RLE recorded a better meaty odour and overall liking score after 7 ageing days. These results showed that the use of RLE with high concentration of bioactive compounds such as anthocyanins can be considered an effective tool for the improvement of meat quality and sensory properties of suckling lamb meat after ageing.

Ethical approval

The research was approved by the Animal Welfare Body of the University of Naples Federico II (PG/2019/0028161 of 03/19/2019).

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

Not applicable.

References

- Aslyng MD, Meinert L. 2017. Meat flavour in pork and beef – from animal to meal. *Meat Sci.* 132:112–117. doi: [10.1016/j.meatsci.2017.04.012](https://doi.org/10.1016/j.meatsci.2017.04.012).
- Abeyasinghe D, Li X, Sun C, Zhang W, Zhou C, Chen K. 2007. Bioactive compounds and antioxidant capacities in different edible tissues of citrus fruit of four species. *Food Chem.* 104(4):1338–1344. doi: [10.1016/j.foodchem.2007.01.047](https://doi.org/10.1016/j.foodchem.2007.01.047).
- Agustí M, Mesejo C, Reig C, Martínez-Fuentes A. 2014. Citrus production. *Horticulture: plants for people places*. Vol. 1, Dordrecht (Netherlands): Springer; p. 159–195.
- Ajuyah AO, Fenton TW, Hardin RT, Sim JS. 1993. Measuring lipid oxidation volatiles in meats. *J Food Sci.* 58(2):270–273. doi: [10.1111/j.1365-2621.1993.tb04253.x](https://doi.org/10.1111/j.1365-2621.1993.tb04253.x).
- Alnaimy A, Gad A, Mustafa M, Atta M, Basuony H. 2017. Using of citrus by-products in farm animals feeding. *Open Access J Sci.* 1(3):58–67.
- Ba HV, Park K, Dashmaa D, Hwang I. 2014. Effect of muscle type and vacuum chiller ageing period on the chemical compositions, meat quality, sensory attributes and volatile compounds of Korean native cattle beef. *Anim Sci J.* 85(2): 164–173. doi: [10.1111/asj.12100](https://doi.org/10.1111/asj.12100).
- Bianchi F, Cantoni C, Careri M, Chiesa L, Musci M, Pinna A. 2007. Characterization of the aromatic profile for the authentication and differentiation of typical Italian dry-sausages. *Talanta.* 72(4):1552–1563. doi: [10.1016/j.talanta.2007.02.019](https://doi.org/10.1016/j.talanta.2007.02.019).
- Bonaccorsi L, Donato A, Fotia A, Frontera P, Gnisci A. 2022. Competitive detection of volatile compounds from food degradation by a zinc oxide sensor. *Appl Sci.* 12(4):2261. doi: [10.3390/app12042261](https://doi.org/10.3390/app12042261).
- Brewer MS, Vega JD. 1995. Detectable odor thresholds of selected lipid oxidation compounds in a meat model system. *J Food Sci.* 60(3):592–595. doi: [10.1111/j.1365-2621.1995.tb09834.x](https://doi.org/10.1111/j.1365-2621.1995.tb09834.x).
- Brodowska M, Guzek D, Kolota A, Glabska D, Gorska-Horczyzak E, Wojtasik-Kalinowska I, Wierzbicka A. 2016. Effect of diet on oxidation and profile of volatile compounds of pork after freezing storage. *J Food Nutr Res.* 55(1):40–47.

- Caruso M, Fabroni S, Emma R, Ballistreri G, Amenta M, Currenti W, Rinziivillo C, Rapisarda P. 2021. A new standardized phytoextract from red orange and lemon wastes (red orange and lemon extract) reduces basophil degranulation and activation. *Nat Prod Res.* 35(23):5354–5359. doi: [10.1080/14786419.2020.1761355](https://doi.org/10.1080/14786419.2020.1761355).
- Casaburi A, Piombino P, Nychas G-J, Villani F, Ercolini D. 2015. Bacterial populations and the volatilome associated to meat spoilage. *Food Microbiol.* 45(Pt A):83–102. doi: [10.1016/j.fm.2014.02.002](https://doi.org/10.1016/j.fm.2014.02.002).
- Damiano S, Iovane V, Squillacioti C, Mirabella N, Prisco F, Ariano A, Amenta M, Giordano A, Florio S, Ciarcia R. 2020. Red orange and lemon extract prevents the renal toxicity induced by ochratoxin A in rats. *J Cell Physiol.* 235(6): 5386–5393. doi: [10.1002/jcp.29425](https://doi.org/10.1002/jcp.29425).
- Damiano S, Longobardi C, Salzano A, D'Angelo L, Amenta M, Maggiolino A, De Palo P, Claps S, Rufrano D, Iannaccone F, et al. 2022. Red orange and lemon extract preserve from oxidative stress, DNA damage and inflammatory status in lambs. *Ital J Anim Sci.* 21(1):934–942. doi: [10.1080/1828051X.2022.2056527](https://doi.org/10.1080/1828051X.2022.2056527).
- Del Bianco S, Natalello A, Luciano G, Valenti B, Monahan F, Gkarane V, Rapisarda T, Carpino S, Edi P. 2020. Influence of dietary cardoon meal on volatile compounds and flavour in lamb meat. *Meat Sci.* 163:108086. doi: [10.1016/j.meatsci.2020.108086](https://doi.org/10.1016/j.meatsci.2020.108086).
- Domínguez R, Gómez M, Fonseca S, Lorenzo JM. 2014. Effect of different cooking methods on lipid oxidation and formation of volatile compounds in foal meat. *Meat Sci.* 97(2): 223–230. doi: [10.1016/j.meatsci.2014.01.023](https://doi.org/10.1016/j.meatsci.2014.01.023).
- Domínguez R, Pateiro M, Gagaoua M, Barba FJ, Zhang W, Lorenzo JM. 2019. A comprehensive review on lipid oxidation in meat and meat products. *Antioxidants.* 8(10):429. doi: [10.3390/antiox8100429](https://doi.org/10.3390/antiox8100429).
- Drumm TD, Spanier AM. 1991. Changes in the content of lipid autooxidation and sulfur-containing compounds in cooked beef during storage. *J Agric Food Chem.* 39(2): 336–343. doi: [10.1021/jf00002a023](https://doi.org/10.1021/jf00002a023).
- Echegaray N, Domínguez R, Cadavez VA, Bermúdez R, Purriños L, Gonzales-Barron U, Hoffman E, Lorenzo JM. 2021. Influence of the production system (intensive vs. extensive) at farm level on proximate composition and volatile compounds of Portuguese lamb meat. *Foods.* 10(7):1450. doi: [10.3390/foods10071450](https://doi.org/10.3390/foods10071450).
- Fabroni S, Ballistreri G, Amenta M, Romeo FV, Rapisarda P. 2016. Screening of the anthocyanin profile and in vitro pancreatic lipase inhibition by anthocyanin-containing extracts of fruits, vegetables, legumes and cereals. *J Sci Food Agric.* 96(14):4713–4723. doi: [10.1002/jsfa.7708](https://doi.org/10.1002/jsfa.7708).
- Ferrara M, Sgarro MF, Maggiolino A, Damiano S, Iannaccone F, Mulè G, De Palo P. 2021. Effect of red orange and lemon extract-enriched diet in suckling lambs' fecal microbiota. *Agriculture.* 11(7):572. doi: [10.3390/agriculture11070572](https://doi.org/10.3390/agriculture11070572).
- Gkarane V, Brunton NP, Harrison SM, Gravador RS, Allen P, Claffey NA, Diskin MG, Fahey AG, Farmer LJ, Moloney AP, et al. 2018. Volatile profile of grilled lamb as affected by castration and age at slaughter in two breeds. *J Food Sci.* 83(10):2466–2477. doi: [10.1111/1750-3841.14337](https://doi.org/10.1111/1750-3841.14337).
- Gonzatto MP, Santos JS. 2023. Introductory chapter: world citrus production and research. In: Mateus PG, Júlia SS, editors. *Citrus research—horticultural and human health aspects*. Rijeka: IntechOpen.
- Guo X, Wang Y, Lu S, Wang J, Fu H, Gu B, Lyu B, Wang Q. 2021. Monitoring quality changes in dry-cured mutton ham during processing. *J Food Process Preserv.* 45(4): e15349. doi: [10.1111/jfpp.15349](https://doi.org/10.1111/jfpp.15349).
- Guzmán JL, Delgado-Pertíñez M, Beriáin MJ, Pino R, Zarazaga LÁ, Horcada A. 2020. The use of concentrates rich in orange by-products in goat feed and its effects on physico-chemical, textural, fatty acids, volatile compounds and sensory characteristics of the meat of suckling kids. *Animals.* 10(5):766. doi: [10.3390/ani10050766](https://doi.org/10.3390/ani10050766).
- Ha M, McGilchrist P, Polkinghorne R, Huynh L, Galletly J, Kobayashi K, Nishimura T, Bonney S, Kelman KR, Warner RD. 2019. Effects of different ageing methods on colour, yield, oxidation and sensory qualities of Australian beef loins consumed in Australia and Japan. *Food Res Int.* 125: 108528. doi: [10.1016/j.foodres.2019.108528](https://doi.org/10.1016/j.foodres.2019.108528).
- Hadjipanayiotou M, Louca A. 1976. A note on the value of dried citrus pulp and grape marc as barley replacements in calf fattening diets. *Anim Sci.* 23(1):129–132. doi: [10.1017/S0003356100031184](https://doi.org/10.1017/S0003356100031184).
- Huang L, Xiong YL, Kong B, Huang X, Li J. 2013. Influence of storage temperature and duration on lipid and protein oxidation and flavour changes in frozen pork dumpling filler. *Meat Sci.* 95(2):295–301. doi: [10.1016/j.meatsci.2013.04.034](https://doi.org/10.1016/j.meatsci.2013.04.034).
- Inserra L, Priolo A, Biondi L, Lanza M, Bognanno M, Gravador R, Luciano G. 2014. Dietary citrus pulp reduces lipid oxidation in lamb meat. *Meat Sci.* 96(4):1489–1493. doi: [10.1016/j.meatsci.2013.12.014](https://doi.org/10.1016/j.meatsci.2013.12.014).
- Karabagias IK. 2018. Volatile profile of raw lamb meat stored at 4 ± 1 °C: the potential of specific aldehyde ratios as indicators of lamb meat quality. *Foods.* 7(3):40. doi: [10.3390/foods7030040](https://doi.org/10.3390/foods7030040).
- Khan MI, Jo C, Tariq MR. 2015. Meat flavor precursors and factors influencing flavor precursors—a systematic review. *Meat Sci.* 110:278–284. doi: [10.1016/j.meatsci.2015.08.002](https://doi.org/10.1016/j.meatsci.2015.08.002).
- Kosowska M, Majcher MA, Fortuna T. 2017. Volatile compounds in meat and meat products. *Food Sci Technol.* 37(1):1–7. doi: [10.1590/1678-457x.08416](https://doi.org/10.1590/1678-457x.08416).
- Li Q, Liu J, De Gobba C, Zhang L, Bredie WLP, Lametsch R. 2020. Production of taste enhancers from protein hydrolysates of porcine hemoglobin and meat using bacillus amyloliquefaciens γ -glutamyltranspeptidase. *J Agric Food Chem.* 68(42):11782–11789. doi: [10.1021/acs.jafc.0c04513](https://doi.org/10.1021/acs.jafc.0c04513).
- Lorenzo JM. 2014. Changes on physico-chemical, textural, lipolysis and volatile compounds during the manufacture of dry-cured foal “cecina”. *Meat Sci.* 96(1):256–263. doi: [10.1016/j.meatsci.2013.06.026](https://doi.org/10.1016/j.meatsci.2013.06.026).
- Ma Q, Hamid N, Bekhit A, Robertson J, Law T. 2012. Evaluation of pre-rigor injection of beef with proteases on cooked meat volatile profile after 1 day and 21 days post-mortem storage. *Meat Sci.* 92(4):430–439. doi: [10.1016/j.meatsci.2012.05.006](https://doi.org/10.1016/j.meatsci.2012.05.006).
- MacFie HJ, Bratchell N, Greenhoff K, Vallis LV. 1989. Designs to balance the effect of order of presentation and first-order carry-over effects in hall tests. *J Sens Stud.* 4(2):129–148. doi: [10.1111/j.1745-459X.1989.tb00463.x](https://doi.org/10.1111/j.1745-459X.1989.tb00463.x).
- Madruga MS, Elmore JS, Dodson AT, Mottram DS. 2009. Volatile flavour profile of goat meat extracted by three widely used techniques. *Food Chem.* 115(3):1081–1087. doi: [10.1016/j.foodchem.2008.12.065](https://doi.org/10.1016/j.foodchem.2008.12.065).
- Maggiolino A, Bragaglio A, Salzano A, Rufrano D, Claps S, Sepe L, Damiano S, Ciarcia R, Dinardo FR, Hopkins DL,

- et al. 2021. Dietary supplementation of suckling lambs with anthocyanins: effects on growth, carcass, oxidative and meat quality traits. *Anim Feed Sci Technol.* 276: 114925. doi: [10.1016/j.anifeedsci.2021.114925](https://doi.org/10.1016/j.anifeedsci.2021.114925).
- Maggiolino A, Lorenzo JM, Centoducati G, Domínguez R, Dinardo FR, Marino R, Malva A, Bragaglio A, De Palo P. 2020. How volatile compounds, oxidative profile and sensory evaluation can change with vacuum aging in donkey meat. *Animals.* 10(11):2126. doi: [10.3390/ani10112126](https://doi.org/10.3390/ani10112126).
- Maggiolino A, Lorenzo JM, Marino R, Della Malva A, Centoducati P, De Palo P. 2019. Foal meat volatile compounds: effect of vacuum ageing on semimembranosus muscle. *J Sci Food Agric.* 99(4):1660–1667. doi: [10.1002/jsfa.9350](https://doi.org/10.1002/jsfa.9350).
- Maggiolino A, Lorenzo JM, Salzano A, Faccia M, Blando F, Serrano MP, Latorre M, Quiñones J, De Palo P. 2020. Effects of aging and dietary supplementation with polyphenols from *Pinus taeda* hydrolysed lignin on quality parameters, fatty acid profile and oxidative stability of beef. *Anim Prod Sci.* 60(5):713–724. doi: [10.1071/AN19215](https://doi.org/10.1071/AN19215).
- Maggiolino A, Sgarro MF, Natrella G, Lorenzo J, Colucci A, Faccia M, De Palo P. 2021. Dry-aged beef steaks: effect of dietary supplementation with *Pinus taeda* hydrolyzed lignin on sensory profile, colorimetric and oxidative stability. *Foods.* 10(5):1080. doi: [10.3390/foods10051080](https://doi.org/10.3390/foods10051080).
- Miller G, Field R, Agboola H. 1986. Lipids in subcutaneous tissues and longissimus muscles of feedlot and grass-fed ewes. *J Food Qual.* 9(1):39–47. doi: [10.1111/j.1745-4557.1986.tb00853.x](https://doi.org/10.1111/j.1745-4557.1986.tb00853.x).
- Morán L, Giráldez FJ, Panseri S, Aldai N, Jordán MJ, Chiesa LM, Andrés S. 2013. Effect of dietary carnosic acid on the fatty acid profile and flavour stability of meat from fattening lambs. *Food Chem.* 138(4):2407–2414. doi: [10.1016/j.foodchem.2012.12.033](https://doi.org/10.1016/j.foodchem.2012.12.033).
- Natalello A, Menci R, Luciano G, Monahan F, Gravador RS, Valenti B, Pauselli M, Belvedere G, Scerra M, Priolo A. 2023. Effect of dietary pomegranate by-product on lamb flavour. *Meat Sci.* 198:109118. doi: [10.1016/j.meatsci.2023.109118](https://doi.org/10.1016/j.meatsci.2023.109118).
- Natrella G, Gambacorta G, De Palo P, Maggiolino A, Faccia M. 2020. Volatile organic compounds in milk and mozzarella: comparison between two different farming systems. *Int J Food Sci Technol.* 55(11):3403–3411. doi: [10.1111/ijfs.14671](https://doi.org/10.1111/ijfs.14671).
- Qwele K, Hugo A, Oyedemi S, Moyo B, Masika P, Muchenje V. 2013. Chemical composition, fatty acid content and antioxidant potential of meat from goats supplemented with *Moringa oleifera* leaves, sunflower cake and grass hay. *Meat Sci.* 93(3):455–462. doi: [10.1016/j.meatsci.2012.11.009](https://doi.org/10.1016/j.meatsci.2012.11.009).
- Ramírez MR, Estévez M, Morcuende D, Cava R. 2004. Effect of the type of frying culinary fat on volatile compounds isolated in fried pork loin chops by using SPME-GC-MS. *J Agric Food Chem.* 52(25):7637–7643. doi: [10.1021/jf049207s](https://doi.org/10.1021/jf049207s).
- Resconi VC, Escudero A, Campo MM. 2013. The development of aromas in ruminant meat. *Molecules.* 18(6):6748–6781. doi: [10.3390/molecules18066748](https://doi.org/10.3390/molecules18066748).
- Salzano A, Damiano S, D'Angelo L, Ballistreri G, Claps S, Rufrano D, Maggiolino A, Neglia G, De Palo P, Ciarcia R. 2021. Productive performance and meat characteristics of kids fed a red orange and lemon extract. *Animals.* 11(3): 809. doi: [10.3390/ani11030809](https://doi.org/10.3390/ani11030809).
- Sgarro MF, Maggiolino A, Pateiro M, Domínguez R, Iannaccone F, De Palo P, Lorenzo JM. 2022. Effects of anthocyanin supplementation and ageing time on the volatile organic compounds and sensory attributes of meat from goat kids. *Animals.* 12(2):139. doi: [10.3390/ani12020139](https://doi.org/10.3390/ani12020139).
- Shah MA, Bosco SJD, Mir SA. 2014. Plant extracts as natural antioxidants in meat and meat products. *Meat Sci.* 98(1): 21–33. doi: [10.1016/j.meatsci.2014.03.020](https://doi.org/10.1016/j.meatsci.2014.03.020).
- Sirtori F, Dimauro C, Bozzi R, Aquilani C, Franci O, Calamai L, Pezzati A, Pugliese C. 2020. Evolution of volatile compounds and physical, chemical and sensory characteristics of Toscano PDO ham from fresh to dry-cured product. *Eur Food Res Technol.* 246(3):409–424. doi: [10.1007/s00217-019-03410-0](https://doi.org/10.1007/s00217-019-03410-0).
- Soncin S, Chiesa L, Cantoni C, Biondi P. 2007. Preliminary study of the volatile fraction in the raw meat of pork, duck and goose. *J Food Compos Anal.* 20(5):436–439. doi: [10.1016/j.jfca.2006.09.001](https://doi.org/10.1016/j.jfca.2006.09.001).
- Tateo A, Maggiolino A, Domínguez R, Lorenzo JM, Dinardo FR, Ceci E, Marino R, Malva A, Bragaglio A, De Palo P. 2020. Volatile organic compounds, oxidative and sensory patterns of vacuum aged foal meat. *Animals.* 10(9):1495. doi: [10.3390/ani10091495](https://doi.org/10.3390/ani10091495).
- Tian X, Lu Q, Zhao S, Li J, Luo Q, Wang X, Zhang Y, Zheng N. 2021. Purple corn anthocyanin affects lipid mechanism, flavor compound profiles, and related gene expression of longissimus thoracis et lumborum muscle in goats. *Animals.* 11(8):2407. doi: [10.3390/ani11082407](https://doi.org/10.3390/ani11082407).
- Tsiplakou E, Pitino R, Manuelian CL, Simoni M, Mitsiopoulou C, De Marchi M, Righi F. 2021. Plant feed additives as natural alternatives to the use of synthetic antioxidant vitamins in livestock animal products yield, quality, and oxidative status: a review. *Antioxidants.* 10(5):780. doi: [10.3390/antiox10050780](https://doi.org/10.3390/antiox10050780).
- Vasta V, Aouadi D, Brogna DMR, Scerra M, Luciano G, Priolo A, Salem HB. 2013. Effect of the dietary supplementation of essential oils from rosemary and artemisia on muscle fatty acids and volatile compound profiles in Barbarine lambs. *Meat Sci.* 95(2):235–241. doi: [10.1016/j.meatsci.2012.12.021](https://doi.org/10.1016/j.meatsci.2012.12.021).
- Vasta V, Luciano G. 2011. The effects of dietary consumption of plants secondary compounds on small ruminants' products quality. *Small Rumin Res.* 101(1–3):150–159. doi: [10.1016/j.smallrumres.2011.09.035](https://doi.org/10.1016/j.smallrumres.2011.09.035).
- Vasta V, Ratel J, Engel E. 2007. Mass spectrometry analysis of volatile compounds in raw meat for the authentication of the feeding background of farm animals. *J Agric Food Chem.* 55(12):4630–4639. doi: [10.1021/jf063432n](https://doi.org/10.1021/jf063432n).
- Watanabe A, Kamada G, Imanari M, Shiba N, Yonai M, Muramoto T. 2015. Effect of aging on volatile compounds in cooked beef. *Meat Sci.* 107:12–19. doi: [10.1016/j.meatsci.2015.04.004](https://doi.org/10.1016/j.meatsci.2015.04.004).
- Wong E, Nixon LN, Johnson CB. 1975. Volatile medium chain fatty acids and mutton flavor. *J Agric Food Chem.* 23(3): 495–498. doi: [10.1021/jf60199a044](https://doi.org/10.1021/jf60199a044).
- Wood JD, Richardson RI, Nute GR, Fisher AV, Campo MM, Kasapidou E, Sheard PR, Enser M. 2004. Effects of fatty acids on meat quality: a review. *Meat Sci.* 66(1):21–32. doi: [10.1016/S0309-1740\(03\)00022-6](https://doi.org/10.1016/S0309-1740(03)00022-6).
- Zeng Z, Zhang S, Wang H, Piao X. 2015. Essential oil and aromatic plants as feed additives in non-ruminant nutrition: a review. *J Anim Sci Biotechnol.* 6(1):1–10.
- Zou Z, Xi W, Hu Y, Nie C, Zhou Z. 2016. Antioxidant activity of citrus fruits. *Food Chem.* 196:885–896. doi: [10.1016/j.foodchem.2015.09.072](https://doi.org/10.1016/j.foodchem.2015.09.072).