



Substituting monensin in lamb finisher diets with a Citral and Linalool blend on meat physicochemical properties, shelf-display stability and fatty acid composition

Zané Orffer^a, J.H.C. van Zyl^a, Farouk Semwogerere^{a,b}, Cletos Mapiye^a, Phillip E. Strydom^{a,*}

^a Department of Animal Sciences, Stellenbosch University, Stellenbosch 7606, South Africa

^b Animal Resources Research Program, Abi Zonal Agricultural and Development Institute (Abi ZARDI), National Agricultural Research Organization, PO Box 219, Arua, Uganda

ARTICLE INFO

Keywords:

Essential oils
Colour
Fatty acid
Shelf-life

ABSTRACT

Essential oils are aromatic volatile compounds used in ruminant diets to replace ionophores, specifically for their antimicrobial and antioxidative properties. This study investigated the effects of substituting monensin in lamb finisher diets with a blend of essential oils containing citral and linalool on meat physicochemical properties, shelf-display stability and fatty acid composition. Forty-eight Merino wether lambs (30.15 ± 2.43 kg) were randomly allocated to one of 3 treatment groups: (1) control (no supplement), (2) Monensin (20 ppm or 0.021 g/ lamb/ day), and (3) a blend of essential oil compounds containing citral and linalool (1 g/ lamb/ day) and slaughtered after 42 days in the feedlot. Post chilling (24 hours post-slaughter), the entire left LTL was collected for meat analyses. The addition of an essential oil compound and monensin both gave better colour stability results (higher redness and lower hue angle) over an extended shelf period than control samples. A tendency towards lower total fatty acid content, mono-unsaturated fatty acids, omega-3 fatty acids and conjugated linoleic acids was found for essential oil and monensin treatments, which was not expected. More research is required to determine the precise mechanism of action of the specific essential oils and establish optimal (probably higher) level of application in the diet.

1. Introduction

Public and academic concern fuelled by the emergence of antibiotic resistance in a variety of human pathogenic bacteria (Hummel et al., 1986; Manero et al., 2006; Parveen et al., 2006) and the potential presence of antibiotic residues in animal-derived foods (Ghimpeanu et al., 2022) have caused many countries, including Namibia and Botswana, to issue a ban on the use of routine antibiotics, such as ionophores (EC Regulation, 2003; Ministry of Agriculture and Forestry New Zealand, 2011; Australian Commission on safety and quality in health care, 2013; FDA, 2013; Laxminarayan et al., 2015; Selaedi et al., 2020; Mshana et al., 2021; Keyser et al., 2013). Even though anti-microbial growth promoters (AGPs) are still permitted in South Africa (Laxminarayan et al., 2015), consumer preference is gradually shifting towards more naturally produced meat and customers demand clarity of nutritional value and

* Corresponding author.

E-mail address: pestrydom@sun.ac.za (P.E. Strydom).

healthfulness of their foods' sources (Marandure et al., 2016). Consequently, research interest has shifted greatly to natural alternatives to antibiotics that enhance health, productivity and product quality via similar mechanisms to ionophores (Hughes and Heritage, 2004; Valero et al., 2014a; Valero et al., 2014b).

Essential oils (EO) are phytochemical substances composed of secondary plant metabolites with varying compositions and activities (Calsamiglia et al., 2007), including antimicrobial and antioxidant properties, depending on the specific composition of each essential oil (Benchaar et al., 2008). Citral is a monoterpene (terpenoid) aldehyde with demonstrated antimicrobial, antifungal, and antiparasitic properties that make it a natural preservative (Zeng et al., 2015) and linalool, a monoterpene, exhibits antioxidant and antimicrobial properties in various studies (Abdelaziz et al., 2019; Sojić et al., 2019).

Various blends of essential oils (BEO), in addition to pure essential oils, have been studied as industrial feed additives as they have the potential to influence metabolism and product quality (Hart et al., 2008; Prado et al., 2016; Valero et al., 2014b). Despite studies confirming the potential effects of essential oils on beef and lamb meat quality (Rivaroli et al., 2016) and improved shelf-life (Dorantes-Iturbide et al., 2022; Jayasena and Jo, 2013; Lucera et al., 2012), the effects of citral and linalool on lamb meat quality is less explored. This study investigated the effect of the inclusion of a commercial essential oil compound containing a blend of citral and linalool to substitute monensin in sheep feedlot diets on carcass characteristics and meat quality of feedlot lambs.

2. Materials and methods

2.1. Location, facilities, animals, experimental design, and diets

The feeding trial was conducted at Welgevallen Experimental Farm (33.9427° S, 18.8664° E; Stellenbosch University, South Africa) under the regulations of South African National Standards with ethical clearance from the Stellenbosch University ethics committee (reference number ACU-2022-24773). The study was approved under Section 20 of the Animal Diseases Act, 1984 (Act No 35 of 1984) by the South African Department of Agriculture, Land Reform and Rural Development.

Forty-eight Merino wethers (30.153 ± 2.43 kg) were sourced from a commercial farm. Upon arrival, animals were tagged, weighed, vaccinated for active immunisation against *Clostridium* strains for the prevention of pulpy kidney, malignant oedema, tetanus, and black quarter disease (Multivax® P Plus, MSD Animal Health, South Africa) and treated for internal and external parasites (Dectomax®, Zoetis ZA, South Africa). Sixteen lambs were randomly allocated to each of the 3 dietary treatments (n = 16). Diets were formulated to be iso-energetic and isonitrogenous and to meet nutrient requirements of feedlot lambs according to NRC (2007). The

Table 1
Physical and chemical composition of the three experimental diets.

Item ¹	Treatment ²		
	CON	MON	EOC
<i>Physical composition (g/kg)</i>			
Vitamin Mineral premix ³ with filler	17.00	-	-
Vitamin Mineral premix with Monensin	-	17.00	-
Vitamin Mineral premix with EOC	-	-	17.00
Commercial HPC ⁵	147.06	147.06	147.06
Maize	563.63	563.63	563.63
Oat hay	122.35	122.35	122.35
Wheat straw	49.02	49.02	49.02
Commercial molasses powder ⁶	19.61	19.61	19.61
Salt	9.80	9.80	9.80
Feed lime	9.80	9.80	9.80
Molasses syrup	78.43	78.43	78.43
<i>Chemical composition⁴ (g/kg DM)</i>			
Moisture (g/kg)	113.75	104.34	107.68
Ash (g/kg)	64.59	64.60	61.74
OM (g/kg)	935.41	935.40	938.26
CP (g/kg)	163.22	160.73	171.71
Ether Extract (g/kg)	29.50	28.91	26.41
NDF (g/kg)	196.77	199.76	183.57
ADF (g/kg)	104.45	97.55	90.48
GE (MJ/kg)	18.03	17.87	18.02
Starch (g/kg)	52.57	52.47	53.37

¹Item: HPC (High protein concentrate), DM (dry matter), OM (organic material), CP (crude protein), NDF (neutral detergent fibre), ADF (acid detergent fibre), GE (gross energy)

²Treatment: CON (control), MON (Monensin; 0.2 kg/ ton), EOC (essential oil compound containing citral and linalool; 0.944 kg/ ton)

³Vitamin Mineral premix (per kg): Ammonium chloride: 882.35 mg, Potassium chloride: 11.76 mg, Magnesium oxide: 20 mg, Zinc oxide: 3.3 mg, Manganese (II) oxide: 3.69 mg, Iron sulphate: 5.51 mg, Iodine (Potassium iodate): 0.1 mg, Cobalt sulphate: 0.27 mg, Sodium selenite: 0.26 mg, Vitamin A: 0.353 IU, Vitamin D3: 0.118 IU, Vitamin E: 0.2353 IU, Vitamin B1: 0.12 mg

⁴Values derived from proximate analyses of feed (AOAC, 2005)

⁵Commercial high protein concentrate (per kg): V18146, CP: 640 g, Calcium: 50 g, Phosphorous: 7 g

⁶Yara Kalori 3000 (per kg): CP: 90 g, Calcium: 45–70 g, Phosphorous: 2.5–4.5 g, Crude fibre: 7 g

dietary treatments were a control diet which was a commercial lamb finisher ration with no ionophore (CON), a diet containing Rumensin® (Elanco Animal Health, Centurion, RSA) at 20 ppm (0.021 g/ lamb/ day) added to the basal diet for the monensin (MON) treatment and a diet containing a commercial essential oil compound (EOC; Techna, Couëron, France) added at a rate of 1 g/ lamb/ day to the basal diet as recommended by the supplier. Diets were fed as total mixed ration (TMR) with feed additive included, and the entire TMR was ground and pelleted (Table 1).

Lambs were individually (1.8 m x 1.2 m) housed in a well-ventilated barn equipped with wooden slatted floors. For the duration of the trial fresh water was supplied *ad libitum* and pens were cleaned daily. An adaptation period of 14 days was allowed for animals to adapt to both diet and environment, whereafter data collection commenced and lambs were fed for 42 days. Thereafter, animals were transported for 80 km and slaughtered at a registered abattoir, Deli-Co (De La Fontaine Farm, Zonquadrift Road, Riebeeck Kasteel, Western Cape Province, South Africa).

2.2. Feed chemical analysis

Grab samples of each treatment were taken weekly, pooled and stored at 4°C for proximate analysis. Stored samples were milled through a 1 mm screen using a hammer mill (Scientec RSA Hammer mill Ser. Nr 372; Centrotec) as preparation for analyses. The dry matter (DM), organic matter, crude protein, and ether extract content were determined according to methods (934.01), (942.05), (935.11), and (920.39), respectively of AOAC (2005). Neutral detergent fibre (NDF) and acid detergent fibre (ADF) were determined with an ANKOM fibre analyser according to ANKOM procedures (ANKOM220 Fibre Analyzer, ANKOM Technology, Fairport, NY, USA) as described by Goering and Van Soest (1970).

2.3. Slaughter and meat sampling

The animals were in the lairage for 16 hours without feed but with *ad libitum* access to water before slaughter. Sheep were electrically stunned and slaughtered by exsanguination according to commercial standards. Carcasses were weighed immediately after dressing to determine hot carcass weight (HCW) and classed based on Act 119 of the Government Gazette of the Republic of South Africa (Government Gazette, 2006). The pH and temperature were determined at 1 hour and 24 h postmortem in the *longissimus thoracis* (LT) muscle between the 9th and 10th ribs with a hand-held digital meat pH meter with built-in Pt1000 temperature sensor for automatic temperature compensation (Crison pH 25, Crison Instruments, S.A). The pH meter was calibrated with pH 7.00 and 4.01 buffers at room temperature of 12 ± 2.0 °C for pH 1 h and 2.0 ± 2.0 °C for pH 24 h. Carcasses were chilled at ± 3 °C for 24 h.

The entire left *longissimus thoracis et lumborum* (LTL) muscle from each carcass was excised the day following slaughter and transported under refrigerated conditions to the meat laboratory at the Stellenbosch University campus. The LTL was sectioned into one 5 cm portion for proximate analyses, one 3 cm portion for fatty acid composition, and four 2.5 cm portions for shelf stability test (colour, drip loss, and oxidative stability) starting from the thoracic side in accordance with the procedure outlined in Baldi et al. (2019).

2.4. Meat proximate analyses

Samples that were used for proximate analyses were trimmed of any fat and homogenized in a knife mill (KnifeTec™ 1095, Höganäs, Sweden), vacuum packed, and stored at -20°C for chemical analysis. Moisture (method 950.46) and ash (method 942.05) analyses were performed in accordance with the AOAC (2005) guidelines. Crude fat was extracted using a chloroform/methanol (2:1 v/v) solvent and determined according to prescriptions of Lee et al. (1996). The Dumas combustion method 992.15 was used to determine the crude protein content of meat (AOAC, 2005). A 0.15 g defatted and finely ground meat sample was encapsulated in a Leco™ foil sheet and analyzed utilizing a LECO Nitrogen/Protein Analyzer (FP-528, Leco Corporation, USA). The Dumas technique was used to calculate total nitrogen (%) from both organic and inorganic fractions. To calculate meat protein, the total nitrogen (percent) was multiplied by 6.25 (100 g protein/16 g N).

2.5. Fatty acid composition

Total lipid content and fatty acid (FA) composition was done quantitatively. A 2:1 (v/v) mixture of methanol and chloroform was used to extract the lipids from 1 g of lyophilized LTL muscle (Folch, 1957). Ten mg of lipid extract dissolved in 1 mL of toluene containing 1 mg of cis10-heptadecenoic acid methyl ester (c10-17:1) was used as an internal standard (standard no. U-42 M, Nu-Chek Prep. Inc. Elysian, MN, USA). Cruz-Hernandez et al. (2004) described a two-step methylation process that involved first incubating 0.3 mL of sodium methoxide (0.5 M in methanol) in a water bath at 50 °C for 15 min, and then 1 mL of 5 % methanolic hydrochloric acid at 80 °C for 30 min. To clearly separate the phases, 1 mL of deionized water and 3 mL of hexane were added, well mixed, and centrifuged at 1000 g for 5 min after the samples had cooled to room temperature (~21 °C). To eliminate any water, the top organic phase containing Fatty Acid Methyl Esters (FAMES) was moved to a vial filled with sodium sulphate. Analyses of FAMES was performed according to the methods of Kramer et al., (2008) using a gas chromatography (GC, 6890 N, Agilent Technologies, Santa Clara, USA) equipped with a highly polar Rt-2560 capillary column (100 m, 0.25 mm ID, 0.20 µmol film thickness; Restek, USA) connected to a flame ionization detector (FID, Palo Alto, CA, USA). The temperature of the injector and detector was 250 °C, and the carrier gas was hydrogen with a flow rate of 1 mL/min. The machine was filled with one microliter of sample at a 5:1 split ratio. For a total run duration of 86 min, the oven temperature was set at 45 °C for 4 min, raised to 175 °C for 27 min at a rate of 13 °C/min for 1 minute, and

then increased to 215 °C for 35 min at a rate of 4 °C/min. The FAMES were identified by measuring retention durations in relation to a GC reference standard (standard no. 463) spiked with a mixture of four positional conjugated linoleic acid (CLA) isomers (standard no. UC-59 M). The GC reference standard mixture's CLA isomers were supplied by Nu-Chek-Prep Inc. (Elysian, MN, USA). Following that, FAMES were measured using internal standard-based computations and chromatographic peak area calculations, using the formula below and the findings of the FAME test were expressed as mg/100 g of meat:

$$\text{mg FAME} = \frac{\text{FAME peak area} \times \text{relative response factor} \times \text{mg internal standard}}{\text{internal standard peak area}}$$

2.6. Shelf- display study

Four loin slices of 2.5 cm thickness were trimmed of subcutaneous fat, and randomly assigned to black trays to evaluate the effect of different shelf storage display times (0, 2, 5, 8 days). Trays were covered with a 10 µm polyvinyl chloride (PVC) film (Versafilm, Crown National, Montague Gardens, Cape Town, South Africa, 585 g.cm, 2.h, 1.atm, 1 moisture vapour transfer rate and 180,000 and 25,000 cm³/ m².24 h, 1 permeability of carbon dioxide and oxygen, respectively) and displayed under a continuous, cool, white fluorescent illumination (Philips TL-D 58 W/33–640 1SL/25, Bielsko-Biala, Poland) at 4°C ± 2°C, simulating retail display conditions.

The loin samples used for meat colour analyses were also used for the determination of drip loss. Drip loss was measured after 2, 5 and 8 days on the shelf. Cuts were weighed at the start (day 0) and on days 2, 5, and 8 respectively. Drip loss was calculated using the equation of Honikel (1998). Colour was measured at four positions on the cross surface of the cut on the day of cutting (day 0) and subsequently after 2, 5 and 8 days respectively to determine true colour shelf-life stability. Measurements were taken on day 0 after allowing the muscle to bloom for 1 hour at 4°C ± 2°C and directly after opening of the cling film for subsequent measurements on days 2, 5 and 8. The CIE colour convention (Commission Internationale de l'Eclairage, 1976) was followed where the three fundamental outputs are L^* , a^* and b^* . Lightness (L^*) on a scale of 0 (all light absorbed) to 100 (all light reflected); redness (a^*) spans from + 60 (red) to – 60 (green) and yellowness (b^*) values spans from + 60 (yellow) to – 60 (blue). Saturation index, also known as Chroma (C^*) was calculated as $C^* = \sqrt{(a^*)^2 + (b^*)^2}$; and Hue angle (h^*), defined as $\tan^{-1} (b^*/a^*)$ was used to describe the 48 fundamental colours of a substance. A BYK Gardner Colour-Guide 45/0 (6807) Portable Colourimeter (BYK-Chemie GmbH, Abelstrasse 45, 46483 Wesel, Germany), set on D65 illuminance, 10° viewing angle, aperture of 8 mm, and calibrated on the CIELab colour space system (Commission Internationale de l'Eclairage, 1976) was used to measure colour parameters. For statistical analysis, the mean values of four measurements from different locations on the samples were used.

Thereafter, samples were homogenized at 4 ± 2 °C for ~15 s using a water-cooled knife mill (KnifeTec™ 1095, Höganäs, Sweden) and divided into two equal parts for analyses of lipid oxidation. These samples were vacuum-sealed and kept at –80 °C until analyzed. The level of lipid oxidation was determined using thiobarbituric acid reactive substances (TBARS) as described by Gatellier et al. (2005). Briefly, 1 g of lamb meat sample was combined with 20 mL of 150 mM potassium chloride buffer that included 0.1 mM BHT. The mixture was then homogenized at 3000 rpm for 20 seconds. A 500 µL homogenate aliquot was combined with 0.25 mL of 2.8 % (w/v) trichloroacetic acid (TCA) and 0.25 mL of a 1 % (w/v) thiobarbituric acid solution with 0.05 M NaOH. The mixture was vortexed and then incubated for one hour at 100 °C in a water bath. Following a cooling period to room temperature, samples were centrifuged at 2575 g for 30 min and 2 mL of 1-butanol was added. Three separate absorbance readings at 532 nm were taken using a spectrophotometer (SPECTROstar Nano, BMG, Ortenberg, Germany). The amount of 2-thiobarbituric acid reactive substances (TBARS) were expressed in mg malondialdehyde (MAD) per kg meat using a standard curve (0–20 µM; R² > 0.99) prepared from 1,1,3,3-tetramethoxypropane (TMP). Mean values of two independent determinations were used for statistical analysis.

Table 2

The effect (mean ± SEM) of feed additives in feedlot lamb diets on carcass composition, meat proximate composition and pH.

Item	Treatment ¹			P - value
	CON	MON	EOC	
Carcass attributes and growth performance				
Average daily gain (kg/ day)	0.331 ± 0.012	0.314 ± 0.0012	0.309 ± 0.130	0.44
Hot carcass weight (kg)	20.07 ± 0.41	20.34 ± 0.41	19.43 ± 0.43	0.30
Dressing percentage (%)	45.97 ^{ab} ± 0.39	46.77 ^a ± 0.39	45.42 ^b ± 0.41	0.05
Fat thickness (mm)	3.78 ± 0.31	3.80 ± 0.30	4.56 ± 0.30	0.13
pH and Temperature				
pH 60 min postmortem	6.32 ± 0.06	6.45 ± 0.06	6.39 ± 0.06	0.24
pH 24 h	5.66 ± 0.09	5.54 ± 0.09	5.53 ± 0.09	0.86
Temperature 60 min post-mortem (°C)	28.28 ± 0.59	28.65 ± 0.56	28.66 ± 0.59	0.90
Temperature 24 h (°C)	7.14 ± 0.30	7.51 ± 0.29	7.33 ± 0.30	0.71
Proximate Composition (% As is)				
Moisture	74.38 ± 0.23	74.80 ± 0.21	74.66 ± 0.23	0.63
Protein	20.53 ± 0.27	20.28 ± 0.25	20.05 ± 0.27	0.47
Ash	1.12 ± 0.07	1.15 ± 0.07	1.20 ± 0.07	0.33
Fat	3.97 ± 0.26	3.69 ± 0.25	4.05 ± 0.26	0.36

^{a, b} Means within rows with different superscripts differ ($P \leq 0.05$)

¹Treatment: CON (control), MON (Monensin; 20 ppm), EOC (essential oil compound containing citral and linalool; 1 g/ sheep/ day)

2.7. Statistical analyses

Two different analyses were conducted using STATISTICA (TIBCO Statistica® 14.0.1). Basic data management was done using Excel 2019 (Microsoft, Redmond, WA, USA). One way ANOVA with fixed effect feed additive (none/ monensin/ essential oil compound) was used to describe the differences across diet treatments for physicochemical properties and fatty acid profiles. Repeated measures analysis of variance (RMANOVA) with fixed effect feed additive (none, monensin/ essential oil compound) and time (days on display) was used to determine the effects of diet and display time as well as their interaction of shelf-life stability (colour parameters and TBARS). Post hoc Fisher's LSD multiple comparisons were used to determine significant differences between the levels of the

Table 3

The effect (mean $\pm$ SEM) of feed additives on fatty acid composition (mg/ 100 g tissue) of the meat.

Item ¹		Treatment ²			P- value
		CON	MON	EOC	
ΣTFA		2216.57 ± 176.35	1745.18 ± 167.30	1667.13 ± 176.35	0.08
ΣSFA		1000.48 ± 88.52	784.32 ± 83.97	738.96 ± 88.52	0.10
ΣMUFA		945.13 ± 80.01	739.69 ± 80.91	692.52 ± 85.28	0.08
ΣPUFA		207.21 ± 12.16	176.15 ± 11.53	192.56 ± 12.16	0.20
ΣCLA		61.65 ± 5.72	46.36 ± 5.43	43.70 ± 5.72	0.07
Σn-3		52.28 ± 3.83	40.74 ± 3.64	43.08 ± 3.83	0.09
Σn-6		154.13 ± 8.82	134.96 ± 8.37	148.90 ± 8.82	0.28
SFA	Saturated fatty acids				
12:0	Lauric acid	3.46 ± 0.43	2.62 ± 0.41	2.34 ± 0.43	0.12
13:0	Tridecyclic acid	5.41 ± 0.28	5.66 ± 0.27	5.13 ± 0.28	0.36
14:0	Myristic acid	57.52 ± 6.36	42.76 ± 6.03	39.06 ± 6.36	0.06
15:0	Pentadecyclic acid	15.15 ± 1.00	15.11 ± 0.95	13.41 ± 1.00	0.32
16:0	Palmitic acid	582.89 ± 55.54	453.04 ± 52.69	421.66 ± 55.54	0.09
17:0	Magaric acid	44.49 ^a ± 4.27	34.51 ^{ab} ± 4.06	31.20 ^b ± 4.27	0.04
18:0	Stearic acid	284.04 ± 28.66	221.71 ± 27.18	218.57 ± 28.66	0.14
19:0	Nonadecanoic acid	4.76 ^a ± 0.54	3.02 ^b ± 0.51	3.06 ^b ± 0.54	0.03
20:0	Arachidic acid	2.54 ± 0.44	1.87 ± 0.41	2.20 ± 0.44	0.55
22:0	Behenic acid	3.79 ± 0.43	3.49 ± 0.41	3.18 ± 0.43	0.62
23:0	Tricosanoic acid	1.06 ± 0.15	1.06 ± 0.14	0.73 ± 0.15	0.20
MUFA	Monounsaturated fatty acids				
C9-14:1	Myristoleic acid	20.47 ^a ± 1.55	15.43 ^b ± 1.47	15.23 ^b ± 1.55	0.01
c10-15:1	Pentadecenoic acid	7.46 ± 0.58	6.62 ± 0.55	7.26 ± 0.58	0.52
t9-16:1	Palmitelaidic acid	13.56 ^a ± 1.59	9.04 ^b ± 1.51	8.23 ^b ± 1.59	0.02
c9-16:1	Palmitoleic acid	51.38 ^a ± 4.92	39.45 ^{ab} ± 4.67	34.17 ^b ± 4.92	0.02
t9-18:1	Elaidic acid	13.37 ± 2.81	11.89 ± 2.66	4.42 ± 2.81	0.07
t10/ t11-18:1	Trans vaccenic acid	14.57 ± 3.67	13.63 ± 3.49	12.68 ± 3.67	0.94
c6-18:1	Petroselinic acid	14.89 ± 3.20	14.58 ± 3.04	10.62 ± 3.20	0.58
c9-18:1	Oleic acid	691.5 ± 57.11	592.70 ± 51.08	560.75 ± 53.84	0.24
c11-18:1	Cis- Vaccenic acid	32.58 ± 5.68	28.15 ± 5.39	30.66 ± 5.68	0.85
c7-19:1		5.54 ^a ± 0.45	4.25 ^b ± 0.42	4.04 ^b ± 0.45	0.05
c5-20:1	Eicosenoic acid	1.28 ± 0.20	1.08 ± 0.19	1.34 ± 0.20	0.61
c8-20:1	Eicosenoic acid	7.44 ± 1.00	5.04 ± 1.47	6.05 ± 1.00	0.22
c11-20:1	Eicosenoic acid	3.56 ± 0.31	2.86 ± 0.30	3.14 ± 0.31	0.29
PUFA ³	Poly unsaturated fatty acids				
18:2n-6	LA	140.67 ± 8.22	124.01 ± 7.79	136.63 ± 8.22	0.32
18:3n-3	ALA	7.44 ± 1.00	5.04 ± 1.47	6.05 ± 1.00	0.22
20:2n-6	ESA	1.65 ± 0.19	1.80 ± 0.18	1.85 ± 0.19	0.73
20:5n-3	DPA	0.80 ± 0.16	0.45 ± 0.15	0.58 ± 0.16	0.27
20:3n-3		8.99 ± 0.48	9.37 ± 0.46	8.86 ± 0.48	0.73
20:3n-6	D-GLA	0.28 ± 0.04	0.18 ± 0.03	0.17 ± 0.04	0.07
22:2n-6		6.38 ± 0.68	4.20 ± 0.65	5.60 ± 0.68	0.08
22:3n-3		0.62 ± 0.12	0.35 ± 0.12	0.34 ± 0.12	0.43
22:5n-3	DPA	24.44 ± 1.53	19.89 ± 1.46	21.21 ± 1.54	0.11
22:6n-3	DHA	8.78 ± 1.00	6.10 ± 0.95	6.61 ± 1.00	0.15
CLA	Conjugated linoleic acids				
t9, c11-18:2	Rumenic acid	23.93 ± 2.96	14.50 ± 2.81	13.66 ± 2.93	0.13
c11, t13-18:2		26.23 ± 3.20	24.76 ± 3.03	22.25 ± 3.20	0.68
t10, c12-18:2		2.71 ± 0.32	1.82 ± 0.30	2.15 ± 0.32	0.15

^{a, b} Means within rows with different superscripts differ ($P \leq 0.05$)

¹Item: Σ (Sigma, sum of), TFA (Total fatty acids); PUFA (Poly- unsaturated fatty acids), MUFA (mono- unsaturated fatty acids), SFA (saturated fatty acids), CLA (conjugated linoleic acids), n- 3 (Omega 3 fatty acids), n-6 (Omega 6 fatty acids)

²Treatment: CON (control), MON (Monensin; 20 ppm), EOC (essential oil compound containing citral and linalool; 1 g/ sheep/ day)

³PUFA: polyunsaturated fatty acids; LA: linoleic acid; ALA: alpha-linolenic acid; *GLA-AA: gamma-linolenic acid co-eluted with arachidonic acid; ESA; eicosapentaenoic acid; D-GLA; dihomo-gamma-linolenic acid; DPA: docosapentaenoic acid; DHA: docosahexaenoic acid; CLA: conjugated linoleic acid; t10/t11-18:1 – trans vaccenic acid co-eluted; c – cis; t – trans.

involved factors (feed additive and days on display). Significance was declared at $P \leq 0.05$ and tendencies at $P \leq 0.10$.

3. Results

3.1. Growth performance, carcass yield, and fatness

No differences were recorded for average daily gain, carcass weight or fatness across the three treatment groups (Table 2). Dressing percentage was higher for MON than for EOC ($P = 0.05$).

3.2. Meat physicochemical traits and fatty acid composition

The effects of dietary inclusion of an essential oil blend of Citral and Linalool or monensin on meat physicochemical attributes are displayed in Table 2. No significant effect of diet was recorded for pH and temperature measurements or proximate composition of loin muscle.

The meat fatty composition (mg FAME/ 100 g meat) as influenced by feed additive inclusion is displayed in Table 3. The CON group tended to have the highest total FA ($P = 0.08$), saturated FA (SFA; $P = 0.10$), monounsaturated FA (MUFA; $P = 0.08$), omega-3 FA ($P = 0.09$) and conjugated linoleic acid (CLA; $P = 0.07$) content compared to the other treatments. The trend for higher SFA in CON samples ($P = 0.10$) was accompanied by a lower C17 content ($P = 0.04$) in EOC samples and C19 content for both the MON and EOC groups ($P = 0.03$). C14 ($P = 0.06$) and C16 ($P = 0.09$) levels also showed higher trends for CON samples (Table 4).

For MUFAs, C14:1-*cis* 9 ($P = 0.01$), C16:1-*trans* 9 ($P = 0.02$) and C19:1-*cis* 7 ($P = 0.05$) were higher in the CON group compared to both other groups, and C16:1-*cis* 9 ($P = 0.02$) content of the CON group was superior to the EOC group. Only two PUFAs (C20:3n-6; $P = 0.07$ and C22:2n-6; $P = 0.08$) tended to be higher in the control group compared to MON and EOC). No difference between treatment groups for any conjugated linoleic acid (CLA) was observed. The C18:1*cis*-9, C16:0, and C18:0 were the most prevalent FA in all three treatment groups and collectively accounted for more than 70 % of all FA detected in the sample, with no discernible variation between groups.

3.3. Shelf- display study

Table 5 displays the effect of feed additive and time on shelf- life parameters. The collection of graphs in Figs. 1 to 7 demonstrates the interaction between feed treatment and ageing time (days) for drip loss ($P = 0.13$), lightness ($P = 0.02$), redness ($P = 0.04$), yellowness ($P = 0.01$), chroma ($P = 0.04$), hue- angle ($P = 0.01$) and lipid oxidation ($P = 0.995$).

Lightness (L^*) increased for all groups between day 0 and day 2, then remained stable between day 3 and 5 and declined significantly between day 5 and day 8. From day 0–5, no difference was observed among the treatment groups, but the EOC and MON groups recorded lower L^* values, therefore appeared darker, compared to the CON group by day 8 of display.

Values for redness (a^*) showed a consistent decline between day 0 and 8 for the CON treatment. In contrast, a^* values for EOC and MON remained stable between, day 0 and day 2, then declined significantly between day 2 and day 5 and remained stable again between day 5 and day 8. No differences in redness were recorded across the three treatments except on day 8 when CON recorded lower values than EOC and MON.

Yellowness increased for all groups between 0 and 2 days and then remained stable until 8 days. At day 0, CON recorded higher values for yellowness than EOC and MON, but no differences were recorded in subsequent days until day 8.

The chroma (saturation) of the CON group was higher compared to the MON and EOC groups on day 0. Thereafter chroma values remained stable for CON but increased significantly for MON and EOC. Between days 2 and day 5 all treatments showed a significant decline in chroma towards day 5 and then remained stable. No further differences were observed between the groups during shelf life between day 2 and day 8.

CON samples recorded higher values for hue angle at day 0 than MON samples. Between day 0 and day 2 hue angle values increased

Table 4

The effect (mean $\pm$ SEM) of feed additive on fatty acid ratios of the meat.

Item ¹	Treatment ²			P - value
	CON	MON	EOC	
Σ PUFA: Σ TFA	9.82 $\pm$ 0.78	10.57 $\pm$ 0.74	11.78 $\pm$ 0.78	0.22
Σ MUFA: Σ TFA	42.58 $\pm$ 0.92	42.12 $\pm$ 0.88	41.66 $\pm$ 0.92	0.78
Σ CLA: Σ TFA	2.76 $\pm$ 0.17	2.70 $\pm$ 0.16	2.60 $\pm$ 0.17	0.81
Σ SFA: Σ TFA	44.76 $\pm$ 1.06	44.69 $\pm$ 1.00	44.00 $\pm$ 1.06	0.85
Σ n-3: Σ TFA	2.47 $\pm$ 0.24	2.50 $\pm$ 0.23	2.62 $\pm$ 0.24	0.89
Σ n-6: Σ TFA	7.31 $\pm$ 0.56	8.04 $\pm$ 0.53	9.12 $\pm$ 0.56	0.09
Σ n-6: Σ n-3	3.03 $\pm$ 0.16	3.38 $\pm$ 0.15	3.49 $\pm$ 0.16	0.13

a, b Means within rows with different superscripts differ ($P \leq 0.05$)

¹Item: Σ (Sigma, sum of), TFA (Total fatty acids); PUFA (Poly- unsaturated fatty acids), MUFA (mono- unsaturated fatty acids), SFA (saturated fatty acids), CLA (conjugated linoleic acids), n- 3 (Omega 3 fatty acids), n- 6 (Omega 6 fatty acids)

²Treatment: CON (control), MON (Monensin; 20 ppm), EOC (essential oil compound containing citral and linalool; 1 g/ sheep/ day)

Table 5
Statistics showing the influence of feed additive on shelf- life attributes.

		Drip loss (%)	Lightness (L*)	Redness (a*)	Yellowness (b*)	Chroma (C*)	Hue Angle (h*)	TBARS (mg MDA/ kg meat)
Treatment	P- value	0.01	0.14	0.12	0.39	0.94	0.03	0.05
Days	P- value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Treatment x Days	P- value	0.13	0.02	0.04	0.01	0.04	0.010	0.995

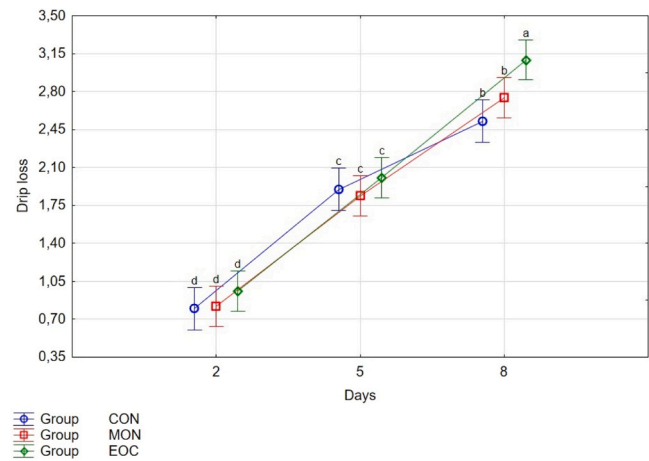


Fig. 1. Interaction between treatment and time of display for drip loss (mean $\pm$ SE; %) of the meat from each treatment group over the duration of 8 days ($P = 0.13$). Coordinates with different labels differ significantly ($P < 0.05$).

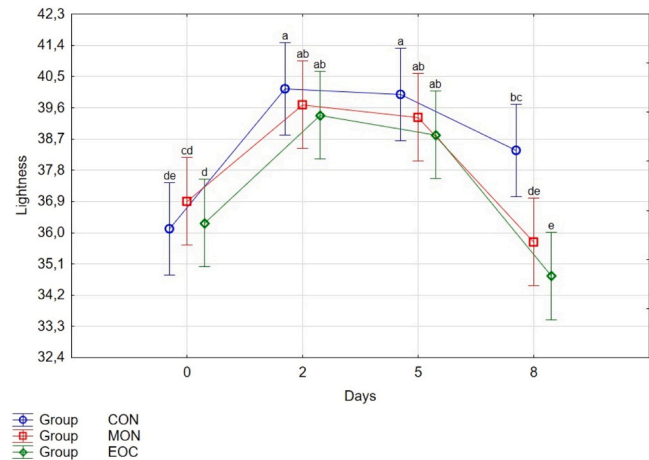


Fig. 2. Interaction between treatment and time of display for lightness (mean $\pm$ SEM) of the meat from each treatment group over the duration of 8 days ($P = 0.02$). Coordinates with different labels differ significantly ($P < 0.05$).

significantly for all treatments and remained stable between day 2 and 5. Between day 5 and day 8 hue angle increased significantly for CON samples, declined for MON samples and remained stable for EOC samples.

Despite no differences observed between groups of the meat from day 0 and day 8, all treatments had lipid oxidation values that increased between day 0 and day 8 with the EOC group having the lowest values on day 0 and day 8 and the CON group the highest. CON recorded a higher mean value than EOC on day 0.

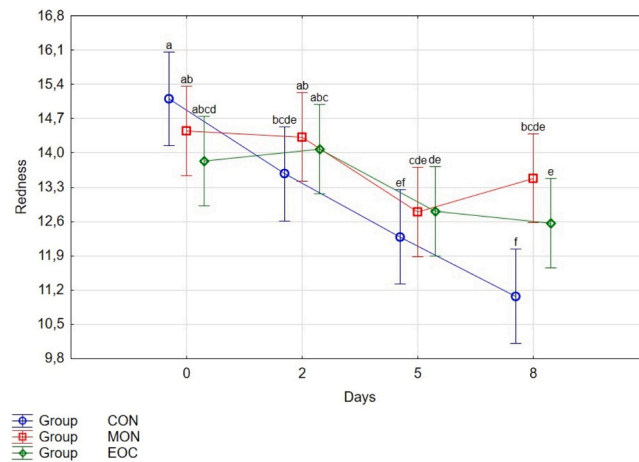


Fig. 3. Interaction between treatment and time of display for redness (mean $\pm$ SEM) of the meat from each treatment group over the duration of 8 days ($P = 0.04$). Coordinates with different labels differ significantly ($P < 0.05$).

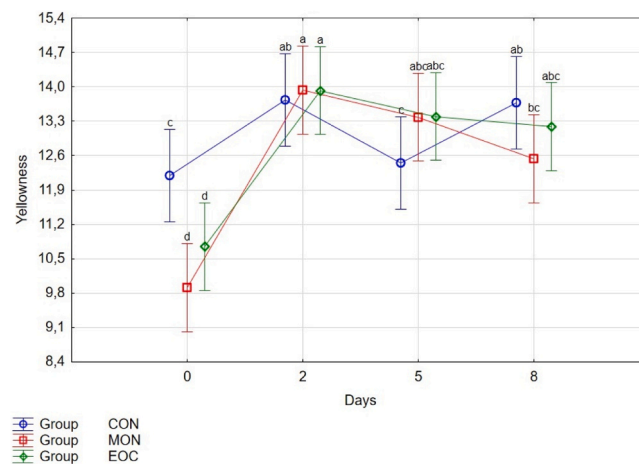


Fig. 4. Interaction between treatment and time of display for yellowness (mean $\pm$ SEM) of the meat from each treatment group over the duration of 8 days ($P = 0.01$). Coordinates with different labels differ significantly ($P < 0.05$).

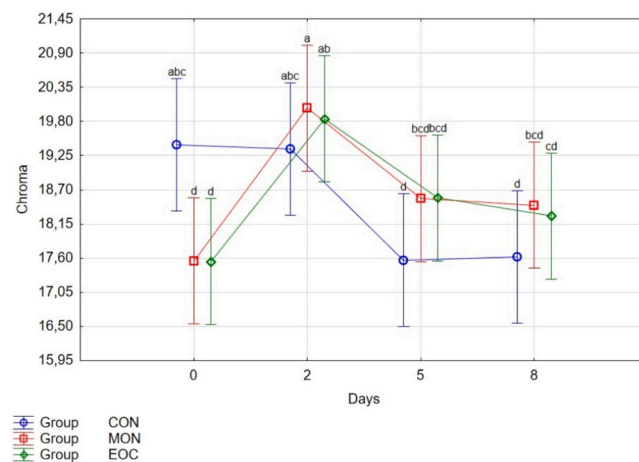


Fig. 5. Interaction between treatment and time of display for chroma (mean $\pm$ SEM) of the meat from each treatment group over the duration of 8 days ($P = 0.04$). Coordinates with different labels differ significantly ($P < 0.05$).

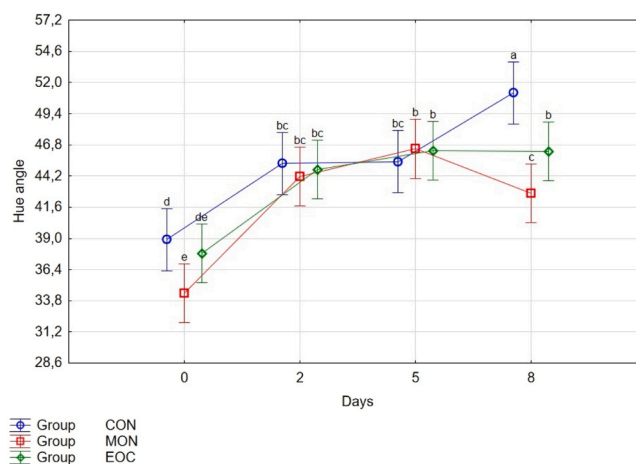


Fig. 6. Interaction between treatment and time of display for hue angle (mean $\pm$ SEM) of the meat from each treatment group over the duration of 8 days ($P = 0.01$). Coordinates with different labels differ significantly ($P = 0.01$).

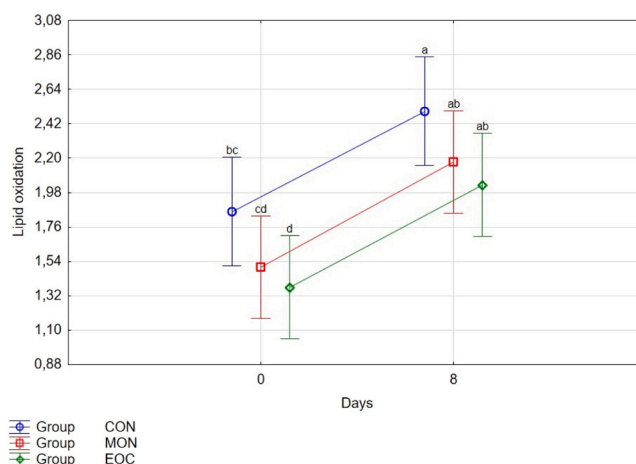


Fig. 7. Interaction between treatment and time of display for lipid oxidation (mean $\pm$ SEM) of the meat from each treatment group over the duration of 8 days ($P = 0.995$). Coordinates with different labels differ significantly ($P < 0.05$).

4. Discussion

4.1. Meat physicochemical properties

Initial pH decline is associated with the muscle's glycogen potential before slaughter and is influenced by several variables, including length of lairage, electrical stimulation, and rate of PM chilling (McGehehin et al., 2001). The pH and temperature values recorded at 1 h postmortem suggest a normal glycolysis pathway for non-electrically stimulated lambs (Warner, 2016; Holman et al., 2021). Despite the hypothesized shift in ruminal fermentation by EO (Benchaa and Greathead, 2011; Rodríguez-Prado et al., 2012; Foskolos et al., 2020) and MON (Benchaa et al., 2008, 2006) which could have influenced glycogen reserves of the lambs, ultimate pH was not affected by these dietary additions. The final pH of ~ 5.6 was within the accepted pH range of 5.4–5.8 for lamb meat (Warner, 2016; Holman et al., 2021). Numerous studies have reported similar meat pH values when ruminants were fed a finisher diet containing EO or BEO (De Oliveira Monteschio et al., 2017; Dorantes-Iturbide et al., 2022; Rivaroli et al., 2016).

The nutritional value (proximate composition) of meat is related to the presence of minerals, lipids, and proteins and, therefore, changes in dietary components which can possibly alter the composition of meat, in particular fat content (Toldrá, 2017). However, neither growth rate (not reported) nor carcass yield or fatness score were affected by treatment (Table 2); also, proximate composition of the LTL was unaffected. Since the basal formulated diet was identical for all three treatments and all animals had the same energy and protein availability, as well as the same intake, no differences in composition were expected. In accordance with the findings of the current study, previous studies on other EOs have indicated that the application of rosemary essential oil (Smeti et al., 2018), ferulago essential oil (Parvar et al., 2018), and a combination of dill, cinnamon, and eucalyptus essential oils (Ranucci et al., 2019) also did not

yield any discernible impact on the chemical composition of lamb meat.

4.2. Fatty acid composition

Fatty acids, in addition to their health benefits, have a key impact on meat flavour, and aroma, and henceforth, meat acceptance (Aranceta and Pérez-Rodrigo, 2012; Watkins et al., 2014). Several factors within a species affect meat FA composition, including breed, genotype, sex, slaughter weight, diet, fat depot, degree of fatness and muscle type, (Campo et al., 2016; Campo et al., 2013; Mapiye et al., 2012; Sinclair, 2007; Wood et al., 2008), with the most important being diet composition (Berthelot and Gruffat, 2018). Consequently, diet-based strategies have been examined for their potential to enrich sheep meat with beneficial FA for humans.

Since the chemical composition of the basal diets was identical (Table 1), changes in FA composition and ratios could only be due to the additives (MON and EOC). Some plant secondary metabolites, including terpenes such as citral and linalool, influence ruminal biohydrogenation (BH) by reducing rumen methanogenesis (Nanon et al., 2014; Simitzis et al., 2017). Due to rumen microbial biohydrogenation which subsequently decreases availability and absorption in the small intestine, the PUFA content of ruminant meat is different and significantly lower compared to that of monogastric animals whose FA profile is nearly identical to their diets (Fievez et al., 2007; Wood et al., 2004).

Even though the majority of branched chain fatty acids (BCFA) and odd-chained saturated fatty acids (OCSFA) in ruminant tissues are endogenously produced and incorporated by rumen bacteria, a small proportion is also reported to be diet-linked (Vlaeminck et al., 2006; Fievez et al., 2012). Phytochemicals have the potential to increase post ruminal supply, absorption and deposition of fatty acids through various mechanisms. The first is to decrease lipolysis by reacting with lipase enzymes (Frutos et al., 2020; Vahmani et al., 2020; Vasta et al., 2019). The second is the inhibition of certain microbes' capacity to degrade PUFA by binding to long-chain PUFA (Frutos et al., 2020; Mueller-Harvey et al., 2019), and the third is the suppression of ciliate protozoa, which are crucial for PUFA biohydrogenation (Khiaosa-Ard et al., 2009; Vasta et al., 2019).

Various studies have shown that blends of EO have no effect on meat FA composition (Chaves et al., 2008; Smeti et al., 2018; Nieto, 2013) while other studies have reported BEO and individual EO to both increase and decrease various FA in meat (Mohamed Khattab and Fathy Elgandy, 2024). Current study showed that EOC tended to lower the total FA as well as individual groups of FA (SFA, MUFA and PUFA). No effect of treatment was recorded for FA ratios (taking TFA out of the calculation), but omega-6 to TFA ratios tended to be higher for the EOC treatment compared to CON. It is therefore clear from literature and our results that some uncertainty regarding the effect of EO and different compounds thereof on FA composition in ruminant meat exists. This combined with uncertainty about the effect of inclusion level of EO on FA composition in meat warrants further investigation. It is also noteworthy that trends or significant differences in FA levels between EOC and CON normally coincided with MON values being closer to EOC rather than CON suggesting similar mechanisms involved.

4.3. Shelf- display study

According to the findings of Teixeira et al. (2005), drip loss of 1–3 % is observed in all muscle tissues following slaughter. Drip loss is expected during ageing because of alterations in muscle fibres produced by rigor mortis and modifications to myofibrillar structure (Huff-Lonergan and Lonergan, 2005), hence the increased drip loss observed for all treatment groups over the period of 8 days was expected and within normal limits. The potential effect (pro- or antioxidant) of essential oils to microbial cells and membranes varies depending on the active component and dosage. Bakkali et al. (2008) reported pro-oxidant effects of EO's at higher dosage rates, which can lead to increased water losses. EOC dosage in this study (1 g/ lamb/ day) is considered normal and therefore could not be considered as a possible explanation for the increased drip loss. A possible explanation could be the lower, but still within acceptable range final pH (5.53 ± 0.09) as pH and drip loss are inversely associated, according to Huff-Lonergan and Lonergan (2005) and Candek-Potokar et al. (2006).

Considering consumer acceptability, Khlij et al. (2010) found that the a^* (redness) and L^* (lightness) values for lamb should be equal to or exceed 9.5 and 34, respectively. In the current study the a^* and L^* values were above these thresholds although it should also be mentioned that the colour meter settings were different for the two studies and therefore direct comparisons may be precarious. Several studies have reported the addition of individual EOs or BEOs to have no effect on lamb meat lightness (Dorantes-Iturbide et al., 2022; Simitzis et al., 2008). In contrast, De Oliveira Monteschio et al. (2017) found that several blends of control samples recorded lower L^* between days 1 and 7 of ageing compared to EO samples and hypothesized that structural protein changes related to highly oxidising conditions, could possibly increase light dispersion, and be responsible for CON showing the highest value on day 7 (MacDougall, 1982), indicating that the addition of EO could have prevented oxidation.

For all groups, a numerical decrease was observed in redness during ageing. Simitzis et al. (2008) reported higher redness values for oregano EO supplemented group of lambs which was ascribed to indirect effects of phytochemical substances on meat colour, most likely by reducing haemoglobin oxidation and activating pathways that affect the distribution of pigment in tissues. De Oliveira Monteschio et al. (2017) also demonstrated the potential of EO to increase the protection and maintenance of redness in meat colour. According to Renner and Labas (1987), an elevated a^* can be linked to decreased mitochondrial respiratory activity of meat, which causes more oxygen to reach the sliced surface and produce a bright red colour via oxymyoglobin. Contrary to the findings of this study, Dorantes-Iturbide et al. (2022) reported no differences in a^* of meat when different EOCs were supplemented and explained it to be due to no differences in meat pH and fat content, which is believed to be correlated to meat redness (a^*) (Calnan et al., 2014). Some work on cattle reported monensin to have no effect on colour (Matos et al., 2024). It is noteworthy to report that in our study the response time on the shelf with regards to redness was the same (or slightly better) for MON and EOC.

It is possible that a^* values could affect b^* readings, as myoglobin oxidation causes a decrease in a^* values and reflects a lower haem concentration (Luciano et al., 2009). In literature, Simitzis et al. (2008), Dorantes-Iturbide et al. (2022) and Nieto et al. (2010) reported increased b^* when lambs were supplemented with various EO compared to a control due to antioxidant effects of EO. Whilst de Oliveira Monteschio et al. (2017) and Rivaroli et al. (2016) reported that the inclusion of EO in beef diets did not affect the b^* value of meat over a 7-day ageing period compared to a control with no supplementation. Parvar et al. (2018) and Smeti et al. (2018) concluded that the addition of EO to lamb diets had no effect on b^* . Apart from differences at day 0 where b^* values were lower for both MON and EOC, yellowness was not affected by treatment over time on display in our study.

The CON group's C^* , coinciding with the patterns of its a^* and b^* values, decreased from day 0 to day 8 (Fig. 5), possibly due to lower antioxidant activity (Uushona et al., 2023). The MON and EOC groups showed an increase and thereafter a plateau back to saturation values similar to day 0, indicating that the antioxidant activity in the meat of these groups only decreased at a later stage.

Once again coinciding with the a^* and b^* values in Figs. 3 and 4, the h^* of each group increased from days 0–8 despite still being within the range of 45 (light red) to 65 (moderate red) that was found acceptable by the consumer for lamb meat (Holman and Hopkins, 2021). A greater hue angle as observed in the CON group is indicative of colour moving away from the original red due to increased metmyoglobin (Sen et al., 2014) which can possibly be attributed to the lack of antioxidants in the diet compared to EOC and indicating possible antioxidant activity in the MON diet as well.

The pooled lipid oxidation can be brought into context with the observations of colour in Figs. 2 to 6, where the colour of the CON group was the least stable over the 8 days of shelf life for all attributes. Adding MON or EOC to the diet had a comparable impact against lipid oxidation of meat, and malonaldehyde production was slightly lower in these treatments compared to CON treatment. According to Falowo et al. (2014), one of the key non-microbial processes that contribute to meat quality degradation is lipid and protein oxidation. However, the animal breed, species, muscle type, and nutrition can all impact susceptibility to oxidation (Falowo et al., 2014; Min et al., 2008). The highly reactive byproducts of lipid and protein oxidation encourage the release of free radicals and haem ions, which oxidise deoxymyoglobin into oxymyoglobin and then to metmyoglobin, a more stable form of myoglobin, in the process. (Rhee et al., 1987). Various EOs and BEOs have demonstrated antioxidant effects (Garcia-Galicia et al., 2020; Rivaroli et al., 2016; Nieto et al., 2010; de Olivera Monteschio et al., 2017), while higher dosage rates of a blend of oregano, garlic, lemon, rosemary, thyme, eucalyptus and sweet orange exhibit pro-oxidative effects (Rivaroli et al., 2016).

5. Conclusions

The effects of the inclusion of an EOC consisting of citral and linalool on carcass characteristics and meat quality of Merino wether lambs in a feedlot are comparable to that of ionophores (monensin) and in certain cases (such as DP, fatty acid composition, meat colour and water holding capacity) different compared to a control. A degree of improved meat shelf life could be observed when the EOC was added to the diet compared to the control. Inclusion of the EOC in the diet generally reduced colour deterioration and lipid oxidation in the meat. The inconsistency of results from literature, in particular fatty acid results, warrants further investigation in the use and effect of dietary EO to optimize lamb meat quality. In this regard, higher dosages of EO may be considered.

CRediT authorship contribution statement

Strydom Phillip Evert: Writing – review & editing, Supervision, Methodology. **van Zyl JHC:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Orffer Zané:** Writing – original draft, Investigation, Data curation. **Mapiye Cletos:** Writing – review & editing, Methodology. **Semwogerere Farouk:** Writing – review & editing, Methodology.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. JHC van Zyl reports financial support and equipment, drugs, or supplies were provided by Techna (France) and AEI Animal Health. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- Abdelaziz, H.M., Freag, M.S., Elzoghby, A.O., 2019. Solid lipid nanoparticle-based drug delivery for lung cancer. In: Nanotechnology-based targeted drug delivery systems for lung cancer. In: Prashant Kesharwani. Academic Press, London, UK, pp. 95–121. <https://doi.org/10.1016/B978-0-12-815720-6.00005-8>.
- AOAC. 2005. Official methods of analysis. AOAC Arlington, VA.
- Aranceta, J., Pérez-Rodrigo, C., 2012. Recommended dietary reference intakes, nutritional goals and dietary guidelines for fat and fatty acids: a systematic review. Br. J. Nutr. 107 (S2), S8–S22. <https://doi.org/10.1017/S0007114512001444>.
- Australian Commission on safety and quality in health care. 2013. Australian One Health Antimicrobial Resistance Colloquium Background Paper. Available at: <http://www.safetyandquality.gov.au/sites/default/files/migrated/Briefing-paper-for-One-Health-AMRColloquium-participants-Final-Jul-2013.pdf>, accessed on 15/01/2025.
- Bakkali, F., Averbeck, S., Averbeck, D., 2008. Biological effects of essential oils – a review. Food Chem. Toxicol. 46, 446–475.
- Baldi, G., Soglia, F., Laghi, L., Tappi, S., Rocculi, P., Tavaniello, S., Prioriello, D., Mucci, R., Maiorano, G., Petracci, M., 2019. Comparison of quality traits among breast meat affected by current muscle abnormalities. Food Res. Int. 115, 369–376. <https://doi.org/10.1016/j.foodres.2018.11.020>.
- Benchaar, C., Calsamiglia, S., Chaves, A.V., Fraser, G.R., Colombatto, D., McAllister, T.A., Beauchemin, K.A., 2008. A review of plant-derived essential oils in ruminant nutrition and production. Anim. Feed Sci. Technol. 145 (1–4), 209–228. [dx.doi.org/10.1016/j.anifeedsci.2007.04.014](https://doi.org/10.1016/j.anifeedsci.2007.04.014).

- Benchaar, C., Duynisveld, J.L., Charmley, E., 2006. Effects of monensin and increasing dose levels of a mixture of essential oil compounds on intake, digestion and growth performance of beef cattle. *Can. J. Anim. Sci.* 86 (1), 91–96 doi/abs/10.4141/A05-027.
- Benchaar, C., Greathead, H., 2011. Essential oils and opportunities to mitigate enteric methane emissions from ruminants. *Anim. Feed Sci. Technol.* 166–167, 338–355. <https://doi.org/10.1016/j.anifeedsci.2011.04.024>.
- Berthelot, V., Gruffat, D., 2018. Fatty acid composition of muscle. In: Sauvant, D., Delaby, L., Nozière, P. (Eds.), *INRA Feeding System for Ruminants*. Wageningen Academic Publishers, Wageningen, NL, pp. 193–202. Available at: <https://hal.inrae.fr/hal-02928115/document>.
- Calnan, H.B., Jacob, R.H., Pethick, D.W., Gardner, G.E., 2014. Factors affecting the colour of lamb meat from the longissimus muscle during display: The influence of muscle weight and muscle oxidative capacity. *Meat Sci.* 96 (2), 1049–1057. <https://doi.org/10.1016/j.meatsci.2013.08.032>.
- Calsamiglia, S., Busquet, M., Cardozo, P.W., Castillejos, L., Ferret, A., 2007. Invited review: essential oils as modifiers of rumen microbial fermentation. *J. Dairy Sci.* 90, 2580–2595. <https://doi.org/10.3168/jds.2006-644>.
- Campo, M.M., Muela, E., Olleta, J.L., Moreno, L.A., Santaliestra-Pasías, A.M., Mesana, M.I., Sañudo, C., 2013. Influence of cooking method on the nutrient composition of Spanish light lamb. *J. Food Compos. Anal.* 31, 185–190 doi: 10.1016/j.jfca.2013.05.010.
- Campo, M.M., Muela, E., Resconi, V.C., Barahona, M., Sañudo, C., 2016. Influence of commercial cut on proximate composition and fatty acid profile of Rasa Aragonesa light lamb. *J. Food Compos. Anal.* 53, 7–12. <https://doi.org/10.1016/j.jfca.2016.08.001>.
- Čandek-Potokar, M., Prevolnik, M., Skrlep, M., 2006. Ability of near infrared spectroscopy to predict pork technological traits. *J. Infrared Spectrosc.* 14, 269–277. <https://doi.org/10.1255/jnirs.644>.
- Chaves, A.V., Stanford, K., Dugan, M.E.R., Gibson, L.L., McAllister, T.A., Van Herk, F., Benchaar, C., 2008. Effects of cinnamaldehyde, garlic and juniper berry essential oils on rumen fermentation, blood metabolites, growth performance, and carcass characteristics of growing lambs. *Livest. Sci.* 117, 215–224. <https://doi.org/10.1016/j.livsci.2007.12.013>.
- Commission International de l'Eclairage. 1976. *Colourimetry in CIE*, ed. 2nd ed. Vienna.
- Cruz-Hernandez, C., Deng, Z., Zhou, J., Hill, A., Yurawecz, M., Delmonte, P., Kramer, J., 2004. Methods for analysis of conjugated linoleic acids and trans-18:1 isomers in dairy fats by using a combination of gas chromatography, silver-ion thinlayer chromatography/gas chromatography, and silver-ion liquid chromatography. *J. AOAC Int.* 87, 545–562.
- De Oliveira Monteschio, J., de Souza, K.A., Vital, A.C.P., Guerrero, A., Valero, M.V., Kempinski, E.M.B.C., 2017. Clove and rosemary essential oils and encapsulated active principles (eugenol, thymol and vanillin blend) on meat quality of feedlot-finished heifers. *Meat Sci.* 130, 50–57. <https://doi.org/10.1016/j.meatsci.2017.04.002>.
- Dorantes-Iturbide, G., Orzuna-Orzuna, J.F., Lara-Bueno, A., Mendoza-Martínez, G.D., Miranda-Romero, L.A., Lee-Rangel, H.A., 2022. Essential oils as a dietary additive for small ruminants: a meta-analysis on performance, rumen parameters, serum metabolites, and product quality. *Vet. Sci.* 9, 475. <https://doi.org/10.3390/vetsci9090475>.
- EC Regulation, 2003. EC No 1831/2003 of the European Parliament and Council of 22 September 2003 on additives for use in animal nutrition. *Off. J. Eur. Community* L268, 29–43.
- Falowo, A.B., Fayemi, P.O., Muchenje, V., 2014. Natural antioxidants against lipid–protein oxidative deterioration in meat and meat products: a review. *Food Res. Int.* 64, 171–181. <https://doi.org/10.1016/j.foodres.2014.06.022>.
- FDA. 2013. Guidance for industry: New animal drugs and new animal drug combination products administered in or on medicated feed or drinking water of food-producing animals: Recommendations for Drug Sponsors for Voluntarily Aligning Product Use Conditions with GFI #209. Accessed at (<https://www.fda.gov/media/83488/download>) on 15/01/2025.
- Fievez, V., Colman, E., Castro-Montoya, J.M., Stefanov, I., Vlaeminck, B., 2012. Milk odd- and branched-chain fatty acids as biomarkers of rumen function— an update. *Anim. Feed Sci. Technol.* 172 (1–2), 51–65. <https://doi.org/10.1016/j.anifeedsci.2011.12.008>.
- Fievez, V., Vlaeminck, B., Jenkins, T., Enjalbert, F., Doreau, M., 2007. Assessing rumen biohydrogenation and its manipulation in vivo, in vitro and in situ. *Eur. J. Lipid Sci. Technol.* 109, 740–756. <https://doi.org/10.1002/ejlt.200700033>.
- Folch, J., Lees, M., Sloane Stanley, G.H., 1957. A simple method for the isolation and purification of total lipides from animal tissues. *J. Biol. Chem.* 497–537. [https://doi.org/10.1016/S0021-9258\(18\)64849-5](https://doi.org/10.1016/S0021-9258(18)64849-5).
- Foskolos, A., Ferret, A., Siurana, A., Castillejos, L., Calsamiglia, S., 2020. Effects of capsicum and propyl-propane thiosulfonate on rumen fermentation, digestion, and milk production and composition in dairy cows. *Animals* 10, 859. <https://doi.org/10.3390/ani10050859>.
- Frutos, P., Hervás, G., Natalello, A., Luciano, G., Fondevila, M., Priolo, A., Toral, P.G., 2020. Ability of tannins to modulate ruminal lipid metabolism and milk and meat fatty acid profiles. *Anim. Feed Sci. Technol.* 269, 114623. <https://doi.org/10.1016/j.anifeedsci.2020.114623>.
- García-Galicia, I.A., Jose, A., Arras-Acosta, J.A., Huerta-Jimenez, M., Rentería-Monterrubio, A.L., Loya-Olguin, J.L., Carrillo-Lopez, L.M., Tirado-Gallegos, J.M., Alarcon-Rojas, A.D., 2020. Natural oregano essential oil may replace antibiotics in lamb diets: effects on meat quality. *Antibiotics* 9 (5), 248. <https://doi.org/10.3390/antibiotics9050248>.
- Gatellier, P., Mercier, Y., Juin, H., Renner, M., 2005. Effect of finishing mode (pasture- or mixed-diet) on lipid composition, colour stability and lipid oxidation in meat from Charolais cattle. *Meat Sci.* 69, 175–186. <https://doi.org/10.1016/j.meatsci.2004.06.022>.
- Ghimpeanu, O.M., Pogurschi, E.N., Popa, D.C., Dragomir, N., Drăgătoiu, T., Mihai, O.D., Petcu, C.D., 2022. Antibiotic use in livestock and residues in food-A public health threat: a review. *Foods* 11 (10), 1430. <https://doi.org/10.3390/foods11101430>.
- Goering, H.K., & Van Soest, P.J. 1970. Forage fibre analyses (Apparatus, reagents, procedures and some application). In: USDA Agricultural Handbook No. 379, Washington, DC, USA, pp. 1–20. (<http://naldc.nal.usda.gov/download/CAT87209099/PDF>). Accessed on 15/01/2025.
- Government Gazette 2006. Government Notice No. R. 863 of 1 September 2006. Agricultural product standards Act 119 of 1990. Regulations regarding the classification and marketing of meat in the Republic of South Africa. Accessed at (<https://www.rmaa.co.za/wp-content/uploads/2016/02/Act-119-of-1990-Meat-Classification-R-863-2006.pdf>) on 15/01/2025.
- Hart, K.J., Yáñez-Ruiz, D.R., Duval, S.M., McEwan, N.R., Newbold, C.J., 2008. Plant extracts to manipulate rumen fermentation. *Anim. Feed Sci. Technol.* 147, 8–35. <https://doi.org/10.1016/j.anifeedsci.2007.09.007>.
- Holman, B.W.B., Hayes, R.C., Newell, M.T., Refshauge, G., McGrath, S.R., Folwer, S.M., Shanley, A.R., Hopkins, D.L., 2021. The quality and mineral composition of the longissimus lumborum and semimembranosus muscles from lambs fed perennial or annual wheat forage with or without lucerne. *Meat Sci.* 180, 108564. <https://doi.org/10.1016/j.meatsci.2021.108564>.
- Holman, B.W.B., Hopkins, D.L., 2021. The use of conventional laboratory-based methods to predict consumer acceptance of beef and sheep meat: a review. *Meat Sci.* 181, 108586. <https://doi.org/10.1016/J.MEATSCI.2021.108586>.
- Honikel, K.O., 1998. Reference methods for the assessment of physical characteristics of meat. *Meat Sci.* 49, 447–457. [https://doi.org/10.1016/S0309-1740\(98\)00034-5](https://doi.org/10.1016/S0309-1740(98)00034-5).
- Huff-Loneragan, E., Lonergan, S.M., 2005. Mechanisms of water-holding capacity of meat: the role of postmortem biochemical and structural changes. *Meat Sci.* 71 (1), 194–204. <https://doi.org/10.1016/j.meatsci.2005.04.022>.
- Hughes, P., & Heritage, J. 2004. Antibiotic Growth-promoters in Food Animals. FAO, Available at: (https://www.adiveter.com/ftp_public/articulo1138.pdf).
- Hummel, R., Tschäpe, H., Witte, W., 1986. Ecologic studies of the nourseothricin resistance of coliform bacteria of intestinal flora in humans and animals. *Arch. Exp. Vet. Med* 40, 670–675. PMID: 3028298.
- Jayasena, D.D., Jo, C., 2013. Essential oils as potential antimicrobial agents in meat and meat products: a review. *Trends Food Sci. Technol.* 34 (2), 96–108. <https://doi.org/10.1016/j.tifs.2013.09.002>.
- Keyser, J., Malope, P., Neven, D., & van Engelen, A. 2013. Botswana agrifood value chain Africa: Beef value chain study. Food and Agriculture Organization of the United Nations. ISBN 978-92-5-107446-6. Accessed at (<https://www.fao.org/4/i3158e/i3158e.pdf>).
- Khiaosa-Ard, R., Bryner, S.F., Scheeder, M.R.L., Wettstein, H.-R., Leiber, F., Kreuzer, M., Soliva, C.R., 2009. Evidence for the inhibition of the terminal step of ruminal α -linolenic acid biohydrogenation by condensed tannins. *J. Dairy Sci.* 92, 177–188. <https://doi.org/10.3168/jds.2008-1117>.

- Khilji, S., Van de Ven, R., Lamb, T.A., Lanza, M., Hopkins, D.L., 2010. Relationship between consumer ranking of lamb colour and objective measures of colour. *Meat Sci.* 85, 224–229. <https://doi.org/10.1016/j.meatsci.2010.01.002>.
- Kramer, J.K.G., Hernandez, M., Cruz-Hernandez, C., Kraft, J., Dugan, M.E.R., 2008. Combining results of two GC separations partly achieves determination of all cis and trans 16:1, 18:1, 18:2 and 18:3 except CLA isomers of milk fat as demonstrated using ag-ion SPE fractionation. *Lipids* 43, 259–273.
- Laxminarayan, R.T., van Boeckel, T., Teillant, A., 2015. The economic costs of withdrawing antimicrobial growth promoters from the livestock sector. *OECD Food, Agriculture and Fisheries Papers*, No. 78. OECD Publishing. <https://doi.org/10.1787/5js64kst5wvl-en>.
- Lee, C.M., Trevino, B., Chaiyawat, M., 1996. A simple and rapid solvent extraction method for determining total lipids in fish tissue. *J. AOAC Int* 79, 487–492. doi.org/10.1093/jaoac/79.2.487.
- Lucera, A., Costa, C., Conte, A., Del Nobile, M.A., 2012. Food applications of natural antimicrobial compounds. *Front. Microbiol.* 3, 1–13. <https://doi.org/10.3389/fmicb.2012.00287>.
- Luciano, G., Monahan, F.J., Vasta, V., Biondi, L., Lanza, M., Priolo, A., 2009. Dietary tannins improve lamb meat colour stability. *Meat Sci.* 81, 120–125. <https://doi.org/10.1016/j.meatsci.2008.07.006>.
- MacDougall, D.B., 1982. Changes in the colour and opacity of meat. *Food Chem.* 9, 75–88. [https://doi.org/10.1016/0308-8146\(82\)90070-X](https://doi.org/10.1016/0308-8146(82)90070-X).
- Manero, A., Vilanova, X., Cerda-Cuellar, M., Blanch, A.R., 2006. Vancomycin- and erythromycin-resistant enterococci in a pig farm and its environment. *Environ. Microbiol.* 8, 667–674. <https://doi.org/10.1111/j.1462-2920.2005.00945.x>.
- Mapiye, C., Dugan, M.E.R., Juárez, M., Basarab, J.A., Baron, V.S., Turner, T., 2012. Influence of α -tocopherol supplementation on trans-18:1 and conjugated linoleic acid profiles in beef from steers fed a barley-based diet. *Animal* 6 (11), 1888–1896. <https://doi.org/10.1017/S1751731112000730>.
- Marandure, T., Mapiye, C., Makombe, G., Nengovhela, B., Strydom, P., Muchenje, V., Dzama, K., 2016. Beef traders' and consumers' perceptions on the development of a natural pasture-fed beef brand by smallholder cattle producers in South Africa. *Afr. J. Range Forage Sci.* 33, 207–214. <https://doi.org/10.2989/10220119.2016.1235616>.
- Matos, A.M., Duarte, V., Carvalho, V.M., Prado, R.M., Do, Cardoso, M.A.P., Vital, A.C.P., Silva, L.F.C.E., Monteschio, J.O., Guerrero, A., Prado, I.N. Do, 2024. Effects of monensin only, monensin and virginiamycin combination, or monensin and a blend of organic trace minerals and yeast on meat quality of crossbred bulls finished in feedlot individual pens and fed with high-grain diets. *Food Sci. Technol.* 44. doi.org/10.5327/fst.00108.
- McGeehin, B., Sheridan, J.J., Butler, F., 2001. Factors affecting the pH decline in lamb after slaughter. *Meat Sci.* 58, 79–84.
- Min, B., Nam, K.C., Cordray, J., Ahn, D.U., 2008. Endogenous factors affecting oxidative stability of beef loin, pork loin, and chicken breast and thigh meats. *J. Food Sci.* 73 (6), C439–C446. <https://doi.org/10.1111/j.1750-3841.2008.00805.x>.
- Ministry of Agriculture and Forestry New Zealand. 2011. Antibiotic resistance: Review and update on New Zealand Regulatory Control of Antimicrobial Agricultural Compounds with Regard to Antimicrobial Resistance. (www.mpi.govt.nz/dmsdocument/26383/direct), Accessed on 15/01/2025.
- Mohamed Khattab, I., Fathy Elgandy, M., 2024. Essential oils in animal diets to improve the fatty acids composition of meat and milk quality in ruminant. *Intech Open*. <https://doi.org/10.5772/intechopen.114045>.
- Mshana, S.E., Sindato, C., Matee, M.I., Mboera, L.E.G., 2021. Antimicrobial use and resistance in agriculture and food production systems in Africa: a systematic review. *Antibiotics* 10. <https://doi.org/10.3390/antibiotics10080976>.
- Mueller-Harvey, I., Bee, G., Dohme-Meier, F., Hoste, H., Karonen, M., Kolliker, R., Waghorn, G.C., 2019. Benefits of condensed tannins in forage legumes fed to ruminants: importance of structure, concentration, and diet composition. *Crop Sci.* 59 (3), 861–885. <https://doi.org/10.2135/cropsci2017.06.0369>.
- Nanon, A., Sukombat, W., Yang, W.Z., 2014. Effects of essential oils supplementation on in vitro and in situ feed digestion in beef cattle. *Anim. Feed Sci. Technol.* 196, 50–59. <https://doi.org/10.1016/j.anifeeds.2014.07.006>.
- Nieto, G., Díaz, P., Barón, S., Garrido, M.D., Nieto, G., 2010. Effect on lamb meat quality of including thyme (*Thymuszygisspp.gracilis*) leaves in ewes' diet. *Meat Sci.* 85, 82–88. <https://doi.org/10.1016/j.meatsci.2009.12.009>.
- Nieto, G., Jongberg, S., Andersen, M.L., Skibsted, L.H., 2013. Thiol oxidation and protein cross-link formation during chill storage of pork patties added essential oil of oregano, rosemary, or garlic. *Meat Sci.* 95, 177–184. <https://doi.org/10.1016/j.meatsci.2013.05.016>.
- NRC, 2007. National Research Council. Nutrient requirements of small ruminants: Sheep, goats, cervids, and new world camelids. National Academy of Sciences, New York, USA.
- Parvar, R., Ghoorch, T., Kashfi, H., Parvar, K., 2018. Effect of *Ferulago angulata* (Chavil) essential oil supplementation on lamb growth performance and meat quality characteristics. *Small Rumin. Res.* 167, 48–54. <https://doi.org/10.1016/j.smallrumres.2018.07.026>.
- Parveen, S., Lukaski, J., Scott, T.M., Tamplin, M.L., Portier, K.M., Sheperd, S., Braun, K., Farrah, S.R., 2006. Geographical variation in antibiotic resistance profiles of *E. coli* isolated from swine poultry beef and dairy cattle farm water retention ponds in Florida. *J. Appl. Microbiol.* 100 (1), 50–57. <https://doi.org/10.1111/j.1365-2672.2005.02773.x>.
- Prado, I.N., Cruz, O.T.B., Valero, M.V., Zawadzki, F., Eiras, C.E., Rivaroli, D.C., Visentainer, J.V., 2016. Effects of glycerin and essential oils (*Anacardium occidentale* and *Ricinus communis*) on the meat quality of crossbred bulls finished in a feedlot. *Anim. Sci. Prod.* 56, 2105–2114. <https://doi.org/10.1071/AN14661>.
- Ranucci, D., Branciar, R., Cobellis, G., Acuti, G., Miraglia, D., Olivieri, O., Roila, R., Trabalza-Marinucci, M., 2019. Dietary essential oil mix improves oxidative stability and hygienic characteristic of lamb meat. *Small Rumin. Res.* 175, 104–109. <https://doi.org/10.1016/j.smallrumres.2019.04.012>.
- Renerre, M., Labas, R., 1987. Biochemical factors influencing metmyoglobin formation in beef muscles. *Meat Sci.* 19 (2), 151–165. [https://doi.org/10.1016/0309-1740\(87\)90020-9](https://doi.org/10.1016/0309-1740(87)90020-9).
- Rivaroli, D.C., Guerrero, A., Velandia Valero, M., Zawadzki, F., Eiras, C.E., Campo, M.D.M., Prado, I., 2016. Effect of essential oils on meat and fat qualities of crossbred young bulls finished in feedlots. *Meat Sci.* 121, 278–284. <https://doi.org/10.1016/j.meatsci.2016.06.017>.
- Rodríguez-Prado, M., Ferret, A., Zwieten, J., Gonzalez, L., Bravo, D., Calsamiglia, S., 2012. Effects of dietary addition of capsicum extract on intake, water consumption, and rumen fermentation of fattening heifers fed a high-concentrate diet. *J. Anim. Sci.* 90, 1879–1884. <https://doi.org/10.2527/jas.2010.3191>.
- Selaledi, L.A., Hassan, Z.M., Manyelo, T.G., Mabelebe, M., 2020. The current status of the alternative use to antibiotics in poultry production: an African perspective. *Antibiotics* 9, 594. <https://doi.org/10.3390/antibiotics9090594>.
- Sen, A.R., Naveena, B.M., Muthukumar, M., Vaithyanathan, S., 2014. Colour, myoglobin denaturation and storage stability of raw and cooked mutton chops at different end point cooking temperature. *J. Food Sci. Technol.* 51 (5), 970–975. <https://doi.org/10.1007/s13197-011-0557-z>.
- Simitzis, P.E., 2017. Enrichment of animal diets with essential oils—a great perspective on improving animal performance and quality characteristics of the derived products. *Medicines* 4, 35. <https://doi.org/10.3390/medicines4020035>.
- Simitzis, P.E., Deligeorgis, S.G., Bizelis, J.A., Dardamani, A., Theodosiou, I., Fegeros, K., 2008. Effect of dietary oregano oil supplementation on lamb meat characteristics. *Meat Sci.* 79, 217–223. <https://doi.org/10.1016/j.meatsci.2007.09.005>.
- Sinclair, L.A., 2007. Nutritional manipulation of the fatty acid composition of sheep meat: a review. *J. Agric. Sci.* 145 (5), 419–434. <https://doi.org/10.1017/S0021859607007186>.
- Smeti, S., Hajji, H., Mekki, I., Mahouachi, M., Atti, N., 2018. Effects of dose and administration form of rosemary essential oils on meat quality and fatty acid profile of lamb. *Small Rumin. Res.* 158, 62–68. <https://doi.org/10.1016/j.smallrumres.2017.10.007>.
- Šojić, B., Pavlič, B., Ikončić, P., Tomović, V., Ikončić, B., Zeković, Z., Kocić-Tanackov, S., Jokanović, M., Škaljac, S., Ivić, M., 2019. Coriander essential oil as natural food additive improves quality and safety of cooked pork sausages with different nitrite levels. *Meat Sci.* 157, 107879. <https://doi.org/10.1016/j.meatsci.2019.107879>.
- Teixera, A., Batista, S., Delfa, R., Cadavex, V., 2005. Lamb meat quality of two breeds with protected origin designation. Influence of breed, sex and live weight. *Meat Sci.* 71, 530–536. <https://doi.org/10.1016/j.gsd.2017.06.008>.
- Toldrá, F., 2017. *Lawrie's Meat Science*, 8th ed. Woodhead Publishing Limited, Cambridge, UK, p. 713.
- Uushona, T., Chikwanha, O.C., Katiyatiya, C.L.F., Strydom, P.E., Mapiye, C., 2023. Fatty acid and oxidative shelf-life profiles of meat from lambs fed finisher diets containing *Acacia mearnsii* leaf-meal. *Meat Sci.* 201, 109190. <https://doi.org/10.1016/j.meatsci.2023.109190>.
- Vahmani, P., Ponnampalam, E.N., Kraft, J., Mapiye, C., Bermingham, E.N., Watkins, P.J., Dugan, M.E.R., 2020. Bioactivity and health effects of ruminant meat lipids. *Invit. Rev. Meat Sci.* 165, 108114. [10.1016/J.MEATSCI.2020.108114](https://doi.org/10.1016/J.MEATSCI.2020.108114).

- Valero, M.V., Prado, R.M.D., Zawadzki, F., Eiras, C.E., Madrona, G.S., Prado, I.N.D., 2014a. Propolis and essential oils additives in the diets improved animal performance and feed efficiency of bulls finished in feedlot. *Acta Sci. Anim. Sci.* 36, 419–426. <https://doi.org/10.4025/actascianimsci.v36i4.23856>.
- Valero, M.V., Torrecilhas, J.A., Zawadzki, F., Bonafe, E.G., Madrona, G.S., Prado, R.M.D., Prado, I.N.D., 2014b. Propolis or cashew and castor oils effects on composition of Longissimus muscle of crossbred bulls finished in feedlot. *Chil. J. Agric. Res.* 74, 445–451. <https://doi.org/10.4067/S0718-58392014000400011>.
- Vasta, V., Daghighi, M., Cappucci, A., Buccioni, A., Serra, A., Viti, C., Mele, M., 2019. Invited review: Plant polyphenols and rumen microbiota responsible for fatty acid biohydrogenation, fiber digestion, and methane emission: experimental evidence and methodological approaches. *J. Dairy Sci.* 102 (5), 3781–3804. <https://doi.org/10.3168/jds.2018-14985>.
- Vlaeminck, B., Fievez, V., Cabrita, A.R.J., Fonseca, A.J.M., Dewhurst, R.J., 2006. Factors affecting odd- and branched-chain fatty acids in milk: a review. *Anim. Feed Sci. Technol.* 131 (3), 389–417. <https://doi.org/10.1016/j.anifeedsci.2006.06.017>.
- Warner, R. 2016, Meat: Conversion of muscle into meat. Editor(s): Benjamin Caballero, Paul M. Finglas, Fidel Toldrá, In: Encyclopedia of Food and Health, Academic Press, pp 677–684, ISBN 9780123849533, <https://doi.org/10.1016/B978-0-12-384947-2.00452-9>.
- Watkins, P.J., Kearney, G., Rose, G., Allen, D., Ball, A.J., Pethick, D.W., Warner, R.D., 2014. Effect of branched-chain fatty acids, 3-methylindole and 4-methylphenol on consumer sensory scores of grilled lamb meat. *Meat Sci.* 96, 1088–1094. <https://doi.org/10.1016/j.meatsci.2012.08.011>.
- Wood, J.D., Enser, M., Fisher, A.V., Nute, G.R., Sheard, P.R., Richardson, R.I., Whittington, F.M., 2008. Fat deposition, fatty acid composition and meat quality: a review. *Meat Sci.* 78 (4), 343–358. <https://doi.org/10.1016/j.meatsci.2007.07.019>.
- Wood, J.D., Richardson, R.I., Nute, G.R., Fisher, A.V., Campo, M.M., Kasapidou, E., Enser, M., 2004. Effects of fatty acids on meat quality: a review. *Meat Sci.* 66 (1), 21–32. [https://doi.org/10.1016/S0309-1740\(03\)00022-6](https://doi.org/10.1016/S0309-1740(03)00022-6).
- Zeng, S., Kapur, A., Patankar, M.S., Xiong, M.P., 2015. Formulation, characterization, and antitumor properties of trans- and cis-citral in the 4t1 breast cancer xenograft mouse model. *Pharm. Res.* 32 (8), 2548–2558. <https://doi.org/10.1007/s11095-015-1643-0>.