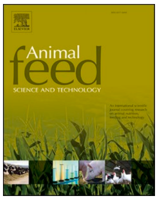
Animal Feed Science and Technology 332 (2026) 116609

Contents lists available at ScienceDirect

Animal Feed Science and Technology

journal homepage: www.elsevier.com/locate/anifeedsci



Impact of dietary phytochemicals on production and quality of ruminant meat and milk: A comprehensive systematic review

Cletos Mapiye [a,*], Farouk Semwogerere [a,b], Lobke Steyn [a], Hasitha Priyashantha [c], Antonio Natalello [d], Jeannne Marais [e], Olugbenga P. Soladoye [f], Alessandro Priolo [d], Eric N. Ponnampalam [g,*]

[a] *Department of Animal Sciences, Faculty of AgriSciences, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa*
[b] *Animal Resources Research Program, Abi Zonal Agricultural and Development Institute (Abi ZARDI), National Agricultural Research Organization, P.O. Box 219, Arua, Uganda*
[c] *Department of Animal Science, Faculty of Agriculture, University of Ruhuna, Mapalana, Kamburupitiya 81100, Sri Lanka*
[d] *Department of Agriculture, Food and Environment (Di3A), University of Catania, Via Santa Sofia 100, Catania 95123, Italy*
[e] *Department of Food Science, Faculty of AgriSciences, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa*
[f] *Agriculture and Agri-Food Canada, Government of Canada, Lacombe Research and Development Centre, 6000 C&E Trail, Lacombe, Alberta T4L 1W1, Canada*
[g] *School of Agriculture, Food and Ecosystems Sciences, The University of Melbourne, Parkville, Victoria 3010, Australia*

ARTICLE INFO

Keywords:
Biopreservatives
Growth enhancers
Essential oils
Meat
Milk
Polyphenols

ABSTRACT

The role of phytochemicals such as polyphenols, essential oils, saponins and organosulfur compounds in ruminant production systems has evolved from their riddance as anti-nutritional factors in the past to current exploration as potential natural antimethanogens, anthelmintics, stress alleviators, growth enhancers, and biopreservatives. This shift stems from the desire to improve animal health, production and product quality while reducing greenhouse gas emissions and reliance on antibiotics and synthetic additives. The impact, mechanism of action and transfer efficiency of dietary phytochemicals for ruminant production and product preservation have, however, been reported to be uncertain primarily due to a lack of optimized application conditions. The current review provides a comprehensive update on the impacts of dietary phytochemicals for ruminant production and product quality enhancement and suggests directions for future research, innovation and adoption. A Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) approach was conducted in Scopus, Web of Science and Google Scholar databases to identify and select peer-reviewed journal articles published between 2010 and 2025. The comprehensive systematic review used data from 174 *in vivo* studies. The results show no impact, insufficient investigation into the mechanisms and transfer efficiency of dietary phytochemicals for ruminant production and product quality. Nonetheless, there are indications that essential oils and polyphenols hold potential to enhance ruminant production, oxidative stability and health value of edible products. A portfolio of future directions, including optimizing application conditions, customizing diet formulations, educating value-chain actors, enacting harmonized regulations and polices, fostering transdisciplinary collaboration and establishing institutions to coordinate research and innovation, was proposed to fully unlock the value of dietary essential oils and polyphenols in ruminant production systems.

---

* Corresponding authors.
E-mail addresses: cmapiye@sun.ac.za (C. Mapiye), eponnampalam@unimelb.edu.au (E.N. Ponnampalam).

https://doi.org/10.1016/j.anifeedsci.2025.116609
Received 24 September 2025; Received in revised form 26 November 2025; Accepted 14 December 2025

1. Introduction

Phytochemicals represent a diverse group of naturally occurring, non-nutritive, bioactive secondary metabolites found in plants, including forages, trees, shrubs, vegetables, herbs and spices (Khajali and Rafiei, 2024; Tedeschi et al., 2021). They are synthesized by plants as part of the defence, signalling and adaptive mechanisms, serving ecological functions such as protection against herbivores and pathogens, attraction of pollinators and tolerance to environmental stresses (Divekar et al., 2022). Phytochemicals were once considered anti-nutritional factors in ruminant feed but are now suggested to have potential benefits in animal production and product quality. Specifically, essential oils (Andri et al., 2020; Dorantes-Iturbide et al., 2022; Wells, 2024), polyphenols (Al Rharad et al., 2025; Bešlo et al., 2022; Orzuna-Orzuna et al., 2023), organosulfur compounds (Ding et al., 2023; Iommelli et al., 2025) and saponins (Kholif, 2023; Ramdani et al., 2023) are being explored for their roles as natural rumen modifiers, antimethanogens, anthelmintics, reproductive enhancers, growth promoters, stress alleviators and biopreservatives.

The evolution in the role of phytochemicals has been largely driven by increasing antimicrobial resistance (Enshaie et al., 2025; Wang et al., 2024), climate change (FAO, 2023; Soltan and Patra, 2024), growing consumer demand for safer natural and sustainable healthy foods (Wang et al., 2024; Warner, 2024) and the call for transition towards a circular economy in food systems (Rizwan et al., 2025; Stempfle et al., 2024).

Globally, meat and milk from domesticated ruminants (e.g., cattle, buffalo, goats and sheep) account for about 16 % of the total protein intake and 8 % of total energy intake (Mottet et al., 2017). Moreover, they are excellent sources of other essential nutrients, including minerals, vitamins and bioactive compounds. Ruminants, with their specialized digestive system and gut microbiome, are uniquely adapted to valorize fibrous and phytochemical-rich feedstuffs into edible products like meat and milk for human consumption (Cuchillo-Hilario et al., 2024; Kholif, 2023). However, it is challenging to isolate and describe the specific effects of an individual phytochemical compound or a group of phytochemical compounds on animal production and product quality, as phytochemicals cover a wide range of compounds from many diverse subclasses. While *in vitro* studies offer advantages in terms of control, time, cost and mechanism elucidation, *in vivo* animal studies are more accurate for evaluating the effects of extracts or feedstuffs rich in phytochemicals due to their ability to model realistic biological systems and identify potential toxicity and pharmacological effects (Formato et al., 2022; Naumann et al., 2017; Tedeschi et al., 2021). Even under controlled *in vivo* studies, the effects of dietary phytochemical extracts (DPEs) on feed intake, animal performance and quality of ruminant meat and milk have been quite unpredictable. This is because the effects of DPEs can be either positive, negative, neutral or transient, depending on specific application conditions, including phytochemical type, dietary inclusion level and form, rumen microbial adaptation and animal factors such as species, age and weight (Martins et al., 2023; Ponnampalam et al., 2024; Serra et al., 2021).

Recent studies generally suggest that moderate levels of DPEs improve ruminant performance and the quality of meat and milk (Costa et al., 2021; dos Santos et al., 2024; Hassan et al., 2020) by modulating rumen microbiome and enhancing carbohydrate, protein and lipid metabolism (Kholif and Olafadehan, 2021; Singh et al., 2024; Vasta et al., 2019). Specifically, DPEs and/or their metabolites may accumulate in muscle or milk, consequently improving physicochemical quality, lipid and protein oxidative stability, microbial safety and sensory attributes (El-Essawy et al., 2021; Soldado et al., 2024; Tian et al., 2025). These positive effects could be explained by the biopreservative (i.e., antioxidant and antimicrobial) activities exerted by a broad spectrum of phytochemicals, including essential oils, polyphenols, organosulfur compounds and saponins (Serra et al., 2021; Vasta et al., 2019).

Despite the wealth of information, the impact of DPEs on production and quality of ruminant meat and milk remains uncertain. Additionally, there is a noticeable gap in research on the transfer of individual compounds from DPE subclasses into meat or milk. Specifically, there is a lack of studies that simultaneously quantify individual phytochemical compounds or their subgroups in ruminant animal feeds, tissues and products, which is crucial for gaining valuable insights into their bioavailability, bioefficacy and underlying mechanisms of action. Further elucidation of these lesser-known aspects of individual phytochemical compounds is crucial for developing feasible and reliable strategies to enhance ruminant production and product quality. Thus, the objective of the current comprehensive systematic review was to present the recent updates on the impact of DPEs on production and quality of meat and milk, and propose future directions for research, innovation and adoption. It was hypothesized that DPEs can enhance ruminant production and product quality and achieving this potential requires a holistic approach involving appropriate research, innovation and adoption strategies.

2. Review methodology

Research questions were generated with a Population, Intervention, Comparison, and Outcome (PICO) strategy (Nishikawa-Pacher, 2022). The population was ruminants (cattle, goats, and sheep), the intervention was dietary supplementation with pure or crude phytochemical extracts (essential oils, polyphenols, saponins and organosulfur compounds), the comparison was with diets with no extract supplements, and the outcomes were meat or milk production, physicochemical quality, shelf-life stability, fatty acids and sensory quality of the diet treatment means. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach (Page et al., 2021) was used to search scientific articles in electronic databases, including Web of Science, Scopus and Google Scholar, between March and August 2025. The search only included articles published between 2010 and 2025. A broad Boolean search string ("Dietary phytochemicals" OR "polyphenol" OR "tannin" OR "saponin" OR "essential oil" OR "organosulfur compounds" OR "extract") AND ("ruminant" OR "dairy" OR "meat" OR "lamb" OR "milk yield" OR "goat" OR "sheep" OR "cow" OR "milk") was used and followed by various combinations of keywords such as ("plant extracts" OR "cattle" OR "meats" OR "bovine" OR "dietary supplements" OR "milk" OR "fatty acids" OR "dietary supplement" OR "bioactive compounds" OR "sheep" OR "lipid Oxidation" OR "essential oils" OR "oxidation" OR "growth performance" OR "shelf life" OR "lactation" OR "meat quality" OR "body weight" OR "colour" OR "antioxidant capacity" OR "flavonoid" OR "goat" OR "ruminant" OR "tannins" OR "sensory analysis" OR "body weight gain" OR "goats" OR "beef" OR "oxidative stability" OR "dry matter intake"). The gathered literature was managed using Mendeley and screened for relevance to the topic, as shown in Fig. 1. The inclusion procedure considered only research articles (excluding reviews, books, and chapters) on DPEs fed to ruminants with results on meat or milk production, physicochemical quality, shelf-life stability, fatty acids, and sensory quality. An extra 110 scientific articles were gathered from Scopus and Google Scholar, between March and August 2025 based on relevance irrespective of time of publication to explain production aspects, availability and mechanisms around DPE use in ruminants and derived food products.

3. Dietary sources of phytochemicals for ruminant production and quality of edible products

The main categories of phytochemicals identified from crude or pure extracts were essential oils, polyphenols (flavonoids and tannins), saponins and organosulfur compounds (Tables 1 – 7). Black wattle (*Acacia mearnsii*;19 citations), chilli pepper (*Capsicum oleoresin*; 16 citations), oregano (*Origanum vulgare*; 15 citations), chestnut (*Castanea sativa*; 14 citations), quebracho (*Schinopsis lorenzii*; 13 citations), and rosemary (*Rosmarinus officinalis*; 12 citations) were the most researched sources of phytochemicals for meat and milk production (Supplementary Table 1 and 2). *Acacia mearnsii* and *Schinopsis spp* have high contents of condensed tannins (CTs), while *Castanea spp* are rich in hydrolysable tannins (HTs), *Capsicum spp* contains capsaicin, *Origanum spp* is an excellent source of carvacrol, and *R. officinalis* is known for containing 1,8 cineole. The essential oil category was dominated by capsaicin, a polyphenolic amide and carvacrol, a monoterpenoid phenol, while CTs and HTs were the main polyphenols. This aligns with literature, which shows that polyphenols, specifically tannins, and essential oils are the main phytochemical compounds studied under dietary nutraceutical supplements for ruminant meat and milk production (Biondi et al., 2019; Vasta and Luciano, 2011). Extracts from *Acacia*, *Schinopsis, Capsicum*, *Origanum*, *Castanea* and *Rosmarinus* species are commercially available on the local markets in most medium-high income countries (Brunetto et al., 2024; Soldado et al., 2024; Valenti et al., 2019). The popularity of these sources could be related to their adaptability to diverse environments, wide geographical distribution and high polyphenolic contents, which require less complex extraction protocols and affordable solvents (Valenti et al., 2019; Vasta et al., 2013; Vasta and Luciano, 2011).

Notably, there is a lack of literature on the use of phytochemical extracts from indigenous plants in low-income countries, especially in Africa, despite the fact that numerous plants or plant parts are continuously used in ruminant production as nutraceutical supplements (Mapiye et al., 2025). This may be ascribed to the lack of simple, accessible and affordable solvents and equipment for phytochemical extract recovery, especially for resource-limited, small-scale ruminant producers who are the majority in Africa. It is also important to note that a number of studies investigating the impact of phytochemicals on ruminant production and product quality often use broader subclass names rather than specifying the scientific names for the individual compounds (Ponnampalam et al., 2025). This level of detail is critical for clarity, accuracy, reproducibility, reliable comparisons and understanding of individual phytochemical effects.

The effects of crude or pure DPEs on ruminant meat or milk production and quality have been assessed among domesticated meat- and milk-producing ruminants (Tables 1 – 7). For meat production, lamb (73 citations) was the most studied animal, followed by beef cattle (29 citations) and chevon goats (9 citations). The increased focus of studies on lamb compared to beef could be primarily driven by the lower production costs associated with the former species and the growing demand for its meat due to relatively low intramuscular fat (Lisitsyn et al., 2017; Mandolesi et al., 2020; Ponnampalam et al., 2024). For milk production, cow (59 citations) studies were dominant, followed by ewes (8 citations) and does (5 citations). The concentration of research on cows may be attributable to the large quantities of milk produced compared to ewes and does. In meat production studies, the duration of feeding varied with the animal species. Lambs were fed for 12–161 days, goats for 56–121 days and cattle for 30–390 days. This largely reflects the different growth rates and market targets for each ruminant species. In studies that focused on milk production, the duration of feeding also varied across species, with cattle feeding periods ranging from 9 to 169 days, ewes from 28 to 43 days, and does from 22 to 70 days. This indicates differences in their physiological needs related to lactation periods, reproduction cycles, gestation lengths and milk production requirements for the offspring.

3.1. *Feed intake, growth and carcass attributes of meat-producing ruminants*

Most of the studies that examined the influence of DPEs on meat production attributes reported neutral outcomes on dry matter intake (DMI; 53 of 71 citations), average daily gain (ADG; 45 of 72), feed efficiency (37 of 52), slaughter weight (52 of 72) and dressing percentage (i.e., carcass yield; 39 of 49; Table 1). A smaller proportion found either positive or negative outcomes (Table 1). The lack of differences reported for these production attributes could be attributed to lower DPEs inclusion levels for most studies. However, extracts containing carvacrol (Wu et al., 2020), cinnamaldehyde (Ornaghi et al., 2017), D-limonene (Dias Junior et al., 2024), eugenol (Ornaghi et al., 2017) and allicin (Tang et al., 2024; Yuan et al., 2025) positively impacted at least three animal production parameters. Essential oils (i.e., carvacrol, cinnamaldehyde, D-limonene and eugenol) may have improved animal production through enhancing the palatability of feed and increasing digestion of fibre and protein by rumen microbes (Dorantes-Iturbide et al., 2022; Li et al., 2025; Patra and Yu, 2012). Allicin, an organosulfur compound, could improve productive performance of ruminants through its ability to positively impact rumen microbiota, potentially leading to enhanced fermentation and digestion (Ding et al., 2023; Yuan et al., 2025; Zhang et al., 2025).

García-Salas et al. (2022) found an increase in animal performance when feeding lower doses of CTs (1.75 and 3.5 g/kg DM) from *A. mearnsi,* while higher doses (5 g/kg DM) decreased performance. Low doses of CTs have been reported to enhance rumen

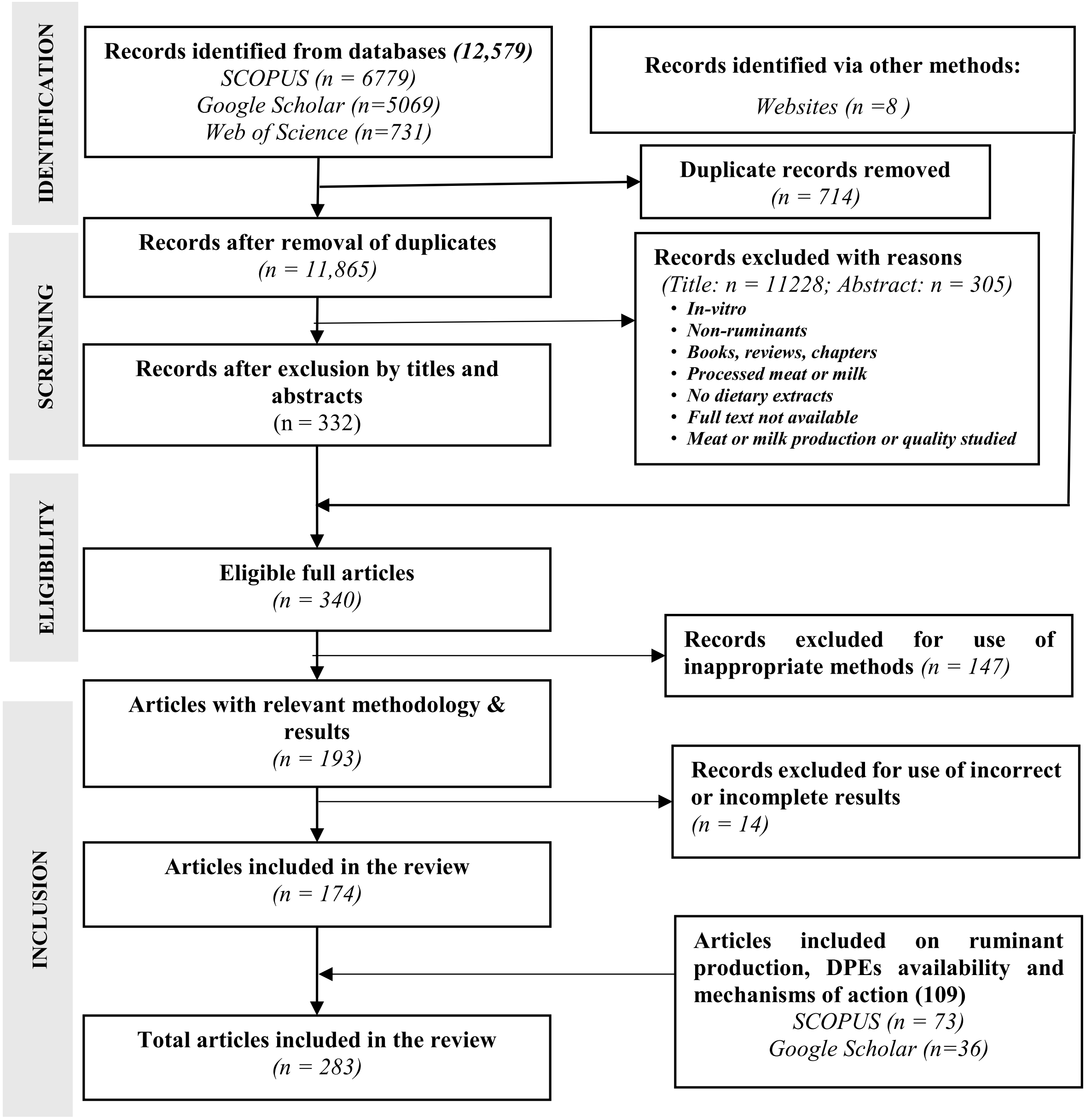


Fig. 1. PRISMA Flow diagram.

fermentation and protein bypass, ultimately leading to improved animal performance (Besharati et al., 2022; Orzuna-Orzuna et al., 2023). However, studies feeding diets containing high doses of CTs extracts (> 40 g/kg) from sources like *A. mearnsii* (Costa et al., 2021; dos Santos et al., 2024; Pimentel et al., 2021), *S. lorentzii* (dos Santos et al., 2022a) and *Corymbia citriodora* (Eucalyptus, Hassan et al., 2020) reported adverse impacts on productive performance of ruminants. This can be accredited to the astringent and nutrient-binding properties of CTs, which respectively reduce palatability and nutrient digestibility (Gao et al., 2024; Jacondino et al., 2022; Ma et al., 2024). Notably, the effects CTs extracts from *A. mearnsii* (Costa et al., 2021; dos Santos et al., 2024), were dose-dependent, reaching an optimum performance at 30–40 g/kg DM. In a recent meta-analysis, Ahmed et al. (2025) suggested 15 g/kg DM as the optimal inclusion level for tannin extracts from *A. mearnsii*, *S. lorentzii* and *C. sativa* in sheep and cattle for sustained animal performance. Previous reviews set the upper limits for polyphenols, including tannins between 40 and 50 g/kg DM beyond which nutrient digestion and animal performance is impaired (Al Rharad et al., 2025; Besharati et al., 2022; Orzuna-Orzuna et al., 2023). In this context, further research is recommended to establish optimal levels for specific phytochemical compounds within a subclass (e.g., allicin, carvacrol or quercetin) for each ruminant species.

Table 1

Effects of dietary phytochemical extracts on ruminant meat production and citation summary of directions of effects for each parameter.

Phytochemical [Source]	Animal (age, mo)	Feeding period (days)	Dose	Dry matter intake	Average daily gain	Slaughter weight	Feed efficiency	Carcass weight	Carcass yield	Economic viability	Reference
1,8 cineole* [Rosemary (*Rosmarinus officinalis*)]	Lamb (4)	70	0.25 or 0.5 g/kg	↔	↔	↔	↔	↔	↔	–	Güney et al. (2021)
	Lamb	100	0.6 g/kg, 0.3 or 0.6 ml/d	↔	↔	↔	–	–	–	–	Smeti et al. (2018)
Carvacrol* [Oregano (*Lippia graveolens*)]	Lamb (3)	60	0.2 or 0.4 g/kg	↔	↔	↔	↔	↔	↔	–	Muñoz-cuautle and Herrera-haro (2022)
Carvacrol* [Oregano (*Oregano onites L.*)]	Lamb (2)	56	0.3 g/kg	↔	↔	↔	–	↔	↔	–	Ünlü et al. (2022)
Carvacrol* [Oregano (*Origanum vulgare ssp. hirtum*)]	Bull (2)	240	0.026 g/kg	↑	↑	↑	↔	–	–	–	Wu et al. (2020)
Cinnamaldehyde* [Cinnamon]	Bull (10)	187	3.5 or 7 g/d	↑	↑	↑	↔	↑	↔	–	Ornaghi et al. (2017)
	Lamb (1.5)	35	0.4 ml/d	↔	↔	↔	–	↔	↔	–	Simitzis et al. (2014)
Cinnamaldehyde & carvacrol (2:1)* [Cinnamon and oregano]	Lamb (3)	60	0.03, 0.06 or 0.12 g/kg	↔	↑	↑	–	–	–	–	Ma et al. (2023)
D-limonene* [Arnica montana]	Lamb (3)	90	0.45, 0.9, or 1.35 g/kg	↔	↑	↑	↑	↑	↔	–	Dias Junior et al. (2023)
D-limonene* [Orange (*Citrus sinensis*)]	Lamb (3)	84	0.1, 0.5 or 1 g/kg	↑	↑	↑	↑	↑	↔	–	Dias Junior et al. (2024)
Eugenol* [Clove (*Syzygium aromaticum*)]	Goat (6–8)	121	2.5 g/kg	↔	↔	↔	–	↔	↔	–	Mandal et al. (2014)
	Bull (10)	187	3.5 or 7 g/d	↑	↑	↑	↔	↑	↔	–	Ornaghi et al. (2017)
Mixture* [Thyme, rosemary, and orange essential oil + Cinnamomum and Quillaja saponaria extract]	Steers (5)	120	0.2 g/kg	↔	↔	↔	↔	–	↔	–	Wandscheer et al. (2024)
Mixture* [Oregano, rosemary, lemon, garlic, eucalyptus, thyme & sweet orange]	Heifer (12)	90	3.5 or 7 g/d	–	–	↔	–	↔	↔	–	Guerrero et al., (2018)
	Steers (12)	120		–	–	↔	–	↔	↔	–	
Mixture* [Thymol, eugenol, vanillin, guaiacol, and limonene]	Steers	98	1 g/d	↔	↔	↔	–	↔	↔	–	Wang et al. (2020a); (2020b)
Mixture* (Oregano, castor bean, and cashew oils)	Bulls (22)	94	4 g/d	↔	↑	↑	↔	↑	↔	-	Fugita et al. (2018)
Unspecified* [Rum-A-fresh: 1.3 % essential oils + 0.75 % cobalt]	Goats	90	0.052 or 0.091	–	↑	↑	↑	↑	↑$^{0.091\ g/kg}$	-	Lei et al. (2018)
Unspecified* [myrtle, *Myrtus communis* L.]	Goats (3)	67	30 or 60 g/kg	↔	↓$^{30g/kg}$	↔	–	↔	↔	–	Smeti et al. (2021)

(*continued on next page*)

Table 1 (*continued*)

Phytochemical [Source]	**Animal (age, mo)**	**Feeding period (days)**	**Dose**	**Dry matter intake**	**Average daily gain**	**Slaughter weight**	**Feed efficiency**	**Carcass weight**	**Carcass yield**	**Economic viability**	**Reference**
Unspecified*	Steer (7)	167	1g/d	↔	↔	↔	↔	↔	↔	–	Pukrop et al. (2019)
Saponin* [*Acacia concinna* pods]	Goat (6–8)	121	5 g/kg	↔	↔	↔	–	↔	↔	–	Mandal et al. (2014)
Sesquiterpenes* [Copaiba (*Copaifera* spp.)]	Lamb (8)	90	0.5, 1 or 1.5 g/kg	↔	↑	↔	↔	↔	–	–	Moura et al. (2017)
Anthocyanind[†] [Corn]	Goat	74	0.5 or 1g/d	↔	↔	↔	↔	–	–	–	Tian et al. (2022)
Quercetin[†] [Chinese scholar tree (*Sophora japonica* L.)]	Lamb	42	2 g/kg	↔	↔	↔	–	↔	–	–	Andrés et al. (2013)
Capsaicin[′] [Hot pepper (*Capsicum annuum* L.)]	Lamb (2)	56	0.3 g/kg	↔	↔	↔	–	↔	↔	–	Ünlü et al. (2022)
Chlorogenic acid[′] [*Eucommia ulmoides* Oliver]	Lamb (2)	49	5 or 10 g/kg	↔	↔	–	↔	–	–	–	Liu et al. (2018a)
Condensed & hydrolyzable tannin[′] [Quebracho & chestnut (1:1)]	Lamb (6)	70	2, 4, or 6 g/kg	↔	↔	↔	–	↔	–	–	Rojas-Román et al. (2017)
Condensed tannin[′] [*Acacia mearnsii*]	Lamb (2)	89	2.5 g/kg	↔	↔	↔	↔	↔	↑	–	Brunetto et al. (2024)
	Lamb (4)	85	20, 40, 60, or 80 g/kg	$\downarrow^{>60g/kg}$	$\downarrow^{>60g/kg}$	$\downarrow^{>60g/kg}$	–	$\downarrow^{>40g/kg}$	$\downarrow^{>40g/kg}$	–	Costa et al. (2021)
	Bull (16)	99	10, 30 or 50 g/kg	$\downarrow^{50g/kg}$	$\downarrow^{50g/kg}$	$\downarrow^{50g/kg}$	↔	↔	↑	–	dos Santos et al. (2024)
	Lambs (3)	70	1.75, 3.5 or 5.25 g/kg	$\uparrow^{1.75,\ 3.5\ g/kg}$	$\uparrow^{1.75,\ 3.5\ g/kg}$	$\uparrow^{1.75,\ 3.5\ g/kg}$	$\uparrow^{1.75g/kg}$	$\uparrow^{3.5\ g/kg}$	$\uparrow^{3.5,\ 5.25\ g/kg}$	–	García-Salas et al. (2022)
	Lamb (5)	62	40 g/kg	↔	↔	↔	↔	↓	–	–	Jacondino et al. (2022)
	Lamb (2)	75	40 g/kg	↔	↔	↔	↔	↔	↔	–	Biondi et al. (2019); (Valenti et al., 2021, 2019)
	Bull (20)	110	0.8, 1.6, or 3.2 g/kg	↔	↔	↔	↔	↔	↔	–	Silva et al. (2024)
	Goats (4)	84	16, 32 or 48 g/kg	$\downarrow^{\geq 48g/kg}$	↔	$\downarrow^{\geq 48g/kg}$	–	$\downarrow^{\geq 48g/kg}$	–	–	Pimentel et al. (2021)
Condensed tannin[′] [gambier (*Uncaria gambir*)]	Lamb (2)	75	40 g/kg	↔	↔	↔	↔	↔	↔	–	Valenti et al. (2021)
Condensed tannin[′] [Quebracho (*Schinopsis lorenzii*)]	Lamb (4)	49	10, 30 or 60 g/kg	$\downarrow^{\geq 30g/kg}$	$\downarrow^{60g/kg}$	$\downarrow^{>\geq 30g/kg}$	$\uparrow^{60g/kg}$	$\downarrow^{\geq 30g/kg}$	↔	–	dos Santos et al. (2022a)
	Lamb (90)	70	20 or 40 g/kg	↑	↑	↔	↔	–	–	–	Kamel et al. (2018)
	Bullock	40	3 g/kg	↑	↔	↔	↔	↔	–	–	Ortiz-López et al. (2024)
Condensed tannin[′] [Eucalyptus (*Corymbia citriodora*)]	Calf (4–5)	105	10 or 20 ml/d	↓	↓	↓	↑	–	–	–	Hassan et al. (2020)
Condensed tannin[′] [Grape seed (*Vitis vinifera* L)]	Lamb	42	25 g/kg	↔	↔	↔	–	↔	↑	–	Jerónimo et al. (2010)

(*continued on next page*)

Table 1 (*continued*)

Phytochemical [Source]	Animal (age, mo)	Feeding period (days)	Dose	Dry matter intake	Average daily gain	Slaughter weight	Feed efficiency	Carcass weight	Carcass yield	Economic viability	Reference
Condensed tannin′ [Rockrose (*Cistus ladanifer* L.)]	Lamb	42	250 g/kg	↔	↔	↔	–	↔	↑	–	Jerónimo et al. (2010)
	Lamb (3)	35	15 g/kg	↔	↔	↔	↔	↔	↔	↔	Dentinho et al. (2020)
	Lamb	42	20.5 or 41 g/kg	↔	↔	↔	$\downarrow^{20.5g/kg}\uparrow^{41g/kg}$	$\downarrow^{41g/kg}$	↔	–	Guerreiro et al. (2020); Soldado et al. (2024)
Condensed tannin′ [Unspecified]	Steer	328	1.5 g/kg	↔	↔	↔	↔	↔	↔	–	Carvalho et al. (2024)
	Lamb	28	30, 40 or 50 g/kg	↔	↔	↔	–	–	–	–	Ngámbi et al. (2022)
Hydrolysable tannin′ [Tara (*Caesalpinia spinosa*)]	Lamb (2)	75	40 g/kg	↔	↔	↔	↔	↔	↔	–	Biondi et al. (2019), Valenti et al. (2019), (2021)
Hydrolysable tannin′ [Yerba mate (*Ilex paraguariensis*)]	Lamb (3)	53	10, 20 or 40g/kg	–	–	↔	–	–	–	–	Pena-Bermudez et al. (2022)
	Steer (21)	94	5, 10 or 15g/kg	↔	↔	–	↔	↔	↔	–	de Zawadzki et al. (2017)
Hydrolysable tannin′ [Chestnut (*Castanea sativa*)]	Lamb (3–4)	70	2 or 4 g/kg	↑	↑	↔	↔	–	–	–	Gao et al. (2024)
	Lamb (4)	60	10 or 30 g/kg	↔	↔	↔	↔	–	–	–	Liu et al. (2011)
	Bull	210	1 or 1.5 g/kg	↔	↔	↔	↔	↔	↔	–	Mergeduš et al. (2022)
	Lamb (4)	56	5 or 10 g/kg	↔	↑	↔	↑	↔	↔	–	Liu et al. (2016)
	Lamb (2)	75	40 g/kg	↓	↓	↓	↓	↓	↓	–	Valenti et al. (2019), (2021)
	Lamb (3)	90	3 or 6 g/kg	↔	$\uparrow^{3g/kg}\downarrow^{6g/kg}$	$\uparrow^{3g/kg}\downarrow^{6g/kg}$	↔	↔	↔	-	Wang et al. (2023)
Hydrolysable tannin′ [Pomegranate (*Punica granatum* L)]	Lamb	86	15, 30 or 45 ml/kg	↔	↑	↔	↔	–	–	–	Rajabi et al. (2017)
Unspecified	Lamb (2)	70	3 or 6 g/d	–	–	$\uparrow^{3g/d}$	–	$\uparrow^{3g/d}$	↔	–	Ma et al. (2024)
Proanthocyanidins′ [Grape, olive, & pomegranate]	Lamb (4–5)	85	3 g/kg	↔	↔	↔	↔	–	–	–	Poli et al. (2021)
Ferulic acid′ [Corn or unspecified]	Heifer	30	0.25 or 0.5 g/kg	↔	↑	↑	↔	↑	$\downarrow^{0.25g/kg}$	–	Peña-Torres et al. (2021)
	Lamb (4)	40	0.25 g/kg	↔	↔	↔	↔	↔	↔	–	Valadez-García et al. (2021)
	Lambs (4)	34	0.3 g/kg	↔	↔	↔	↔	↔	↔	–	Macías-Cruz et al. (2014)
	Lamb (3)	30	0.08, 0.4 or 2 g/kg	↔	$\uparrow^{0.08g/kg}$	↔	$\uparrow^{0.08g/kg}$	–	–	–	Wang et al. (2019)
Rosmarinic acid′ [*Leucaena leucocephala*]	Lamb (3–4)	63	30 ml/	↑	↑	–	–	–	–	–	Salem et al. (2011)
Salicin′ [*Salix babylonica*]				↔	↑	–	–	–	–	–	
Hydroxytyrosol′ [Olive mill extract]	Goat (2)	78	0.0032 g/d	↔	↔	↔	–	↔	↔	–	Cimmino et al. (2018)

(*continued on next page*)

Table 1 (*continued*)

Phytochemical [Source]	Animal (age, mo)	Feeding period (days)	Dose	Dry matter intake	Average daily gain	Slaughter weight	Feed efficiency	Carcass weight	Carcass yield	Economic viability	Reference
Tannic acidʹ [unspecified]	Steer	154	30 or 60 g /d	↔	↔	↔	↔	↔	↔	–	Tabke et al. (2017)
Unspecifiedʹ [*Pinus taeda* hydrolysed lignin]	Bulls (6.5)	120	35 g/d at 1–90 days 70 g/d at 91–120 days	–	↔	↔	–	↔	–	–	Maggiolino et al. (2020)
Terpenesʹ [*Ferulago angulata*]	Lamb (45)	104	0.25, 0.5, 0.75 g/kg	↓	↔	↔	–	↔	↔	–	Parvar et al. (2018)
Unspecifiedʹ [Radiata pine bark]	Lamb (4)	35	10 or 20 g/kg	↔	↔	↔	↔	↔	↔	–	Vera et al. (2023)
Unspecifiedˠ [Wild onion (*Allium mongolicum*)]	Lamb (5)	60	2.8 or 3.4 g/d	↔	↔	↔	↔	–	-	–	Ding et al. (2021)
	Lamb (3)	60	2.8 or 3.4 g/d	↓	↔	↔	$\uparrow^{2.8g/d}$	↔	↔	–	Liu and Ao (2021)
	Lamb (3)	90	30 g/d	↔	↔	↔	–	↔	–	↓	Zhang et al. (2023)
	Lamb (3)	60	2.8 or 3.4 g/d	↔	↑	↔	↓	↔	↔	–	Yaxing et al. (2021)
Saponin [Red feathers (*Echium amoenum*)]	Lamb (6)	97	0.3, 1.5 or 3 ml/kg	↔	↔	↔	↔	–	–	–	Soroor et al. (2013)
Saponin [Alfalfa (*Medicago sativa L.*)]	Lamb (3–4)	90	0.5, 1, 2, or 4 g/kg	↔	↔	↑	↔	–	–	–	Liu et al. (2018b)
Allicinˠ [Garlic (*Allium sativum*)]	Goat (3–4)	75	0.5, 0.75 or 1g/kg	$\uparrow^{0.75g/kg}$	↑	$\uparrow^{0.75g/kg}$	↓	$\uparrow^{0.5,\ 0.75g/kg}$	$\downarrow^{0.75g/kg}$	↑	Yuan et al. (2025)
	Goats (3)	56	0.75 g/d	↔	↑	↑	↑	–	–	–	Tang et al. (2024)
Citations summary of directions of effects	Neutral (↔) effects			53	45	52	37	40	39	1	
	Negative (↓) effects			8	7	7	4	6	4	1	
	Positive (↑) effects			10	22	15	11	10	6	1	
Total number of citations				71	74	74	52	56	49	3	

*: Essential oil; †: flavonoid; ʹ: polyphenol; ˠ: organosulfur; mo: months; ↔: no significant effect; ↑: significant increase; ↓: significant decrease; –: not reported.

Table 2
Effects of dietary phytochemical extracts on ruminant meat quality attributes and citation summary of directions of effects for each parameter.

Phytochemical [Source]	Animal (age, mo)	Feeding (days)	Dose	pH	Water holding capacity	Drip loss	Cooking loss	Shear force	L*	a*	b*	Moisture content	Ash	Crude protein	Intramuscular fat	Antioxidant activity	Myoglobin oxidation	Lipid oxidation	Protein oxidation	Microbial growth	Reference
1,8 cineole* [Rosemary (*Rosmarinus officinalis*)]	Lamb (3)	95	0.4 g/kg	–	–	–	–	–	↔	↔	↔	–	–	–	–	$\uparrow^{\mathrm{FRAP}}$	–	↔	–	–	Aouadi et al. (2014); Vasta et al. (2013)
	Lamb	100	0.6g/kg, 0.3 or 0.6 ml/d	↔	–	–	↔	↔	↔	↔	↔	↔	↔	↔	↔	–	–	↔	–	–	Smeti et al. (2018)
		60	0.6g/kg	↔	–	–	↔	–	↔	↔	↔	↔	↔	↔	↔	–	–	↔	–	–	Smeti et al., (2013)
	Lamb (4)	70	0.25 or 0.5 g/kg	↔	↔	–	↔	↔	↔	↔	↓	↔	↔	↔	↔	–	–	↔	–	–	Güney et al. (2021)
Carnosic acid and carnosol‡ [Rosemary leaves (*Rosmarinus officinalis*)]	Lamb	80	0.0002 or 0.0004 g/kg	↔	–	–	–	–	↔	↔	↔	–	–	–	–	–	–	↓	↔	↔	Ortuño et al. (2014)
	Lamb	50	0.6 g/kg	↔	–	–	–	–	↔	↔	–	↔	–	↔	↔	–	–	↔	–	↓	Ortuño et al. (2015)
1,8 cineole* [laurel leaf (*Laurus nobilis* L.)]	Lamb (5-6)	90	0.5 ml/d	↔	↔	–	↔	–	–	–	–	↔	↔	↔	↔	–	–	↓	–	–	Al-Obaidi et al. (2021)
Camphor* [Artemisia (*Artemisia herba alba*)]	Lamb (3)	95	0.4 g/kg	–	–	–	–	–	↔	↔	↔	–	–	–	–	$\uparrow^{\mathrm{FRAP}}$	–	↔	–	–	Aouadi et al. (2014); Vasta et al. (2013)
Carvacrol* [Oregano]	Steer (12)	390	0.13 or 0.26 g/d	↓	–	↑	↑	–	↔	↔	↔	–	–	–	–	$\uparrow^{\mathrm{EA}}$	–	–	–	–	He et al. (2023)
Carvacrol* [Oregano (*Lippia graveolens*)]	Lamb (3)	60	0.2 or 0.4 g/kg	↔	–	–	–	–	–	–	–	↔	↔	↔	↔	$\uparrow^{\mathrm{FRAP}}$	–	↓	–	–	Muñoz-cuautle & Herrera-haro (2022)
Carvacrol* [Oregano (*Lippia S. berlandieri*)]	Lamb	70	0.2, 0.3 or 0.4 g/kg	–	–	–	–	–	↑	↑	↑	–	–	–	–	–	–	↔	–	–	Garcia-galicia et al. (2020)
Carvacrol* [Oregano (*Oregano onites L.*)]	Lamb (2)	56	0.3 g/kg	–	–	↔	↔	–	↔	↔	↔	↔	–	↔	↑	–	–	↔	–	–	Ünlü et al. (2022)
Cinnamaldehyde* [Cinnamon (*Cinnamonum zeylanicum*)]	Bull (10)	187	0.45 or 0.88 g/kg	↔	–	–	↔	↔	↓	↔	↔	↔	↔	↔	↔	–	–	↔	–	–	Torrecilhas et al. (2021)
	Lamb (1.5)	35	0.4 ml/d	↔	↔	–	↔	↔	↔	↔	↔	–	–	–	↔	–	–	↔	–	↔	Simitzis et al. (2014)
Eugenol* [Clove *(Eugenia caryophyllus)*]	Goat (6-8)	121	2.5 g/kg	–	–	–	–	–	–	–	–	↔	↔	↔	↔	–	–	–	–	–	Mandal et al. (2014)
	Lamb (5-6)	90	0.5 ml/d	↔	↔	–	↔	–	–	–	–	↔	↔	↔	↔	–	–	↓	–	–	Al-Obaidi et al. (2021)
	Bull (10)	187	0.45 or 0.88 g/kg	↔	–	–	↔	↔	↔	↔	↔	↔	↔	↔	↔	–	–	↔	–	–	Torrecilhas et al. (2021)
Mixture* [Clove leaf (*Eugenia aromatica*) + castor oil (*Ricinus communis*) + cashew oil (*Anacardium occidentale*) + commercial blend (vanillin, eugenol, & thymol)]	Bull (16)	62	1.5, 3, 4.5 or 6 g/d	↓	–	↔	↔	↔	↔	↔	↔	–	–	–	–	–	–	↔	–	–	Ornaghi et al. (2020)
Mixture* [Rosemary; Eugenol, thymol & vanillin blend; Clove]	Heifer	73	4 g/d	↔	–	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	$\uparrow^{\mathrm{ABTS,\ DPPH,\ FRAP}}$	–	↔	–	–	de Oliveira Monteschio et al. (2017); Monteschio et al. (2019)
Mixture* [Thyme, rosemary, & orange essential oil + Cinnamomum &	Steers (5)	120	0.2 g/kg	–	–	–	–	–	–	–	–	–	–	↔	↑	$\downarrow^{\mathrm{ROS}}$	–	↓	–	–	Wandscheer et al. (2024)

(continued on next page)

Table 2 (*continued*)

Quillaja saponaria extract]																					
Mixture* [Thymol, eugenol, vanillin, guaiacol, and limonene]	Steers	98	1g/d	↔	−	−	↔	↔	↑	↔	↔	↓	−	−	↑	−	−	↔	−	−	Wang et al. (2020a; 2020b)
Mixture* [Oregano, rosemary, lemon, garlic, eucalyptus, thyme & sweet orange]	Heifer (12)	90	3.5 or 7 g/d	↔	−	−	↔	↔	↔	$\uparrow^{\text{3.5g/d}}$	↔	↔	↔	↔	↔	$\uparrow^{\text{DPPH}}$	−	↔	−	−	Rivaroli et al. (2016, 2020)
Mixture* [Clove, cashew and castor oils + eugenol, thymol and vanillin	Steers (20)	80	1.5, 3, 4.5 or 6 g/d	↔	−	↔	−	↑	↔	↔	↔	−	−	−	↔	$\uparrow^{\text{TPC, DPPH, FRAP}}$	−	↑	−	−	(Ornaghi et al., 2020)
Mixture* (oregano oils, castor bean, cashew)	Bulls (22)	94	4 g/d	−	−	−	↔	↑	−	−	−	−	−	↑	−	−	−	↔	−	−	Fugita et al. (2018)
Mixture* [thymol, carvacrol, eucalyptol and cinnamaldehyde]	Lamb (3)	56	0.15 g/kg	↑	↔	−	−	↓	−	−	−	−	−	↔	↔	−	−	−	−	−	Ortiz-Heredia et al. (2023)
Unspecified* [Rum-A-fresh: 1.3% essential oils + 0.75% cobalt]	Goats	90	0.052 or 0.091	↔	↔	↔	↔	−	↔	↔	↔	−	−	−	−	−	−	−	−	−	Lei et al. (2018)
Unspecified* [myrtle, *Myrtus communis* L.]	Goats (3)	67	30 or 60 g/kg	↔	−	−	↔	−	↔	↔	↔	↔	↔	↔	↔	$\uparrow^{\text{TPC}}$ $\leftrightarrow^{\alpha\text{-T, }\gamma\text{-T, ABTS}}$	−	↓	−	−	Smeti et al. (2021)
Unspecified*	Steer (7)	167	1g/d	↔	−	−	↔	↔	−	−	−	−	−	−	−	−	−	↔	−	−	Pukrop et al. (2019)
Ketones* Sage leaves *(Salvia officinalis L.)*	Lamb (5-6)	90	0.5 ml/d	↔	↔	−	↔	−	−	−	−	↔	↔	↔	↔	−	−	↓	−	−	Al-Obaidi et al. (2021)
Saponin* [*Acacia concinna* pods]	Goat (6-8)	121	5 g/kg	−	−	−	−	−	−	−	−	↔	↔	↔	↔	−	−	−	−	−	Mandal et al. (2014)
Sesquiterpenes* [Copaiba (*Copaifera* spp.)]	Lamb (8)	90	0.5, 1 or 1.5 g/kg	↔	↔	−	$\uparrow^{\text{1.5g/kg}}$	↔	↔	↔	↔	↔	↔	↔	↔	−	−	−	−	−	Moura et al. (2017)
Anthocyanind† [Corn]	Goat	74	0.5 or 1g/d	↔	−	↔	↔	↓	−	−	−	−	−	−	−	$\uparrow^{\text{DPPH}}$	−	↔	−	−	Tian et al. (2022)
Quercetin† [Chinese scholar tree (*Sophora japonica* L.)]	Lamb	42	2 g/kg	↔	−	−	−	−	↔	↔	↔	↔	↔	↔	↔	−	−	↔	−	↓	Andrés et al. (2013)
Capsaicin‡ [Hot pepper (*Capsicum annuum* L.)]	Lamb (2)	56	0.3 g/kg	↔	−	↔	↔	↔	−	↔	↔	↔	−	↔	↔	−	−	↔	−	−	Ünlü et al. (2022)
Condensed & hydrolyzable tannin‡ [Quebracho & chestnut (1:1)]	Lamb (6)	70	2, 4, or 6 g/kg	↔	↔	↔	↔	↑	↑	↔	↔	−	−	−	−	−	−	−	−	−	Castro-Pérez et al. (2021)
Condensed tannin‡ [*Acacia mearnsii*]	Lamb (2)	89	2.5 g/kg	↔	↔	−	−	−	↔	↔	↔	↔	↔	↔	↑	−	−	↓	−	−	Brunetto et al. (2024)
	Lamb (4)	85	20, 40, 60, or 80 g/kg	↔	↔	−	↔	↔	↑	↓	↔	↔	↔	↔	↔	−	−	−	−	−	Costa et al. (2021)
	Bull (16)	99	10, 30 or 50 g/kg	↔	↓	−	↑	↓	↔	↔	↔	↔	↔	↔	↔	−	−	↓	−	−	dos Santos et al. (2024)
	Lambs (3)	70	1.75, 3.5 or 5.25 g/kg	$\uparrow^{\text{5.25g/kg}}$	−	−	−	−	−	−	−	↔	$\downarrow^{\text{5.25g/kg}}$	$\uparrow^{\text{3.5g/kg}}$	↔	−	−	−	−	−	García-Salas et al. (2022)
	Lamb (5)	62	40 g/kg	↔	−	−	−	↔	↔	↔	↔	↔	↔	↔	↔	−	↔	↔	−	−	Jacondino et al. (2022)
	Lamb (3)	133	20 g/kg	−	−	−	−	−	↔	↔	↔	↔	−	−	−	−	−	−	−	−	Venter et al. (2024)
	Bull (20)	110	0.8, 1.6, or 3.2 g/kg	↔	−	−	↔	↔	↔	↔	↔	↔	↓	↔	↔	−	−	−	−	−	Silva et al. (2024)
	Goats (4)	84	16, 32 or 48 g/kg	↔	↔	−	↔	↔	↔	↔	↔	↔	↔	↔	↔	−	−	−	−	−	Pimentel et al. (2021)

(*continued on next page*)

Table 2 (*continued*)

	Lamb (2)	75	40 g/kg	↔	–	–	–	–	↔	↔	↔	–	–	–	–	$\leftrightarrow^{\alpha\text{-T},\ \gamma\text{-T}}$	↓	↔	–	↔	Biondi et al. (2019), Valenti et al. (2019, 2021)
Condensed tannin‡ [Quebracho (*Schinopsis lorenzii*)]	Lamb (4)	49	10, 30 or 60 g/kg	↔	–	–	↔	↓	↔	↔	↑	↔	↔	↔	↔	–	↔	↔	↔	–	dos Santos et al. (2022a)
	Lamb (90)	70	20 or 40 g/kg	–	–	–	–	–	–	–	–	–	–	↔	↔	–	–	–	–	–	Kamel et al. (2018)
	Bullock	40	3 g/kg	↔	–	–	–	–	↔	↔	↔	↔	↔	↔	↔	–	–	↔	–	–	Ortiz-López et al. (2024)
Condensed tannin‡ [Quebracho (*Aspidosperma quebracho*)]	Lamb (2)	12	0.08 g/kg	–	–	–	–	–	–	–	–	–	–	–	–	–	–	↔	–	–	Brogna et al. (2014)
Condensed tannin‡ [Grape seed (*Vitis vinifera* L)]	Lamb	42	25 g/kg	–	–	–	–	–	↔	↔	↔	–	–	–	–	–	–	↔	–	–	Jerónimo et al. (2012)
Condensed tannin‡ [Rockrose (*Cistus ladanifer* L.)]	Lamb (3)	35	15 g/kg	↔	–	–	↔	↔	–	–	–	↔	–	↔	↔	–	–	–	–	–	Dentinho et al. (2020)
	Lamb	42	20.5 or 41 g /kg	↔	–	–	↑	↔	$\uparrow^{41\text{g/kg}}$	↔	↔	–	–	–	–	$\leftrightarrow^{\text{TPC},\ \alpha\text{-T TEAC, FRAP}}$	–	↔	–	–	Guerreiro et al. (2020); Soldado et al. (2024)
Condensed tannin‡ [Unspecified]	Lamb	28	30, 40 or 50 g/kg	↔	–	–	–	–	↔	↔	↔	–	–	–	–	$\uparrow^{\text{DPPH}}$	–	–	–	–	Ngámbi et al. (2022)
Unspecified* [Cashew (*Anacardium occidentale* L.) and castor (*Ricinus communis* L.)]	Bulls (20)	55	3 g/d	↔	–	–	–	↔	↔	↔	↔	↔	↔	↔	↔	–	–	↔	–	–	Valero et al. (2014)
Unspecified‡ [*Pinus taeda* hydrolysed lignin]	Bulls (6.5)	120	35 g/d at 1–90 days 70 g/d at 91–120 days	↔	–	–	↔	↔	↔	↔	↔	↔	↔	↔	↔	–	–	↔	↔	–	Maggiolino et al. (2020)
Chrysin * [Unspecified]	Bulls (20)	55	3 g/d	↔	–	–	–	↔	↔	↔	↔	↔	↔	↔	↔	–	–	↔	–	–	Valero et al. (2014)
Hydrolysable tannin‡ [Tara (*Caesalpinia spinosa*)]	Lamb (2)	75	40 g/kg	↔	–	–	–	–	↔	↔	↔	–	–	–	–	$\leftrightarrow^{\alpha\text{-T}}$ $\uparrow^{\gamma\text{-T}}$	↔	↔	–	↔	Biondi et al. (2019), Valenti et al. (2019, 2021)
Hydrolysable tannin‡ [Yerba mate (*Ilex paraguariensis*)]	Lamb (3)	53	10, 20 or 40g/kg	↔	–	–	–	–	↔	↔	$\uparrow^{40\text{g/kg}}$	–	–	–	–	$\leftrightarrow^{\text{EA}}$	–	↔	↔	–	Pena-Bermudez et al. (2020, 2022)
Hydrolysable tannin‡ [Chestnut (*Castanea sativa*)]	Bull	210	1 or 1.5 g/kg	↔	–	↓	↔	↔	↔	↔	↔	↔	↔	↔	↔	–	–	–	–	–	Mergeduš et al. (2022)
	Lamb (4)	56	5 or 10 g/kg	↔	–	–	↔	↔	↑	↔	↑	–	–	–	–	–	–	↓	–	–	Liu et al. (2016)
	Lamb (2)	75	40 g/kg	↔	–	–	–	–	↔	↔	↔	–	–	–	–	$\leftrightarrow^{\alpha\text{-T},\ \gamma\text{-T}}$	↓	↔	–	–	Valenti et al. (2019, 2021)
	Lamb (3)	90	3 or 6 g/kg	↔	$\uparrow^{6\text{g/kg}}$	↔	↔	↓	↔	↔	↔	–	–	–	↔	$\uparrow^{\text{TOC}}$	–	–	↓	–	Wang et al. (2023)
Hydrolysable tannin‡ [Unspecified]	Lamb (2)	70	3 or 6 g/d	–	–	↔	↔	↓	–	–	–	–	–	–	↑	–	–	–	–	–	Ma et al. (2024)
Proanthocyanidins‡ [Grape, olive, & pomegranate]	Lamb (4-5)	85	3g/kg	–	–	–	–	–	–	–	–	–	–	–	–	–	–	↔	–	–	Poli et al. (2021)
Ferulic acid‡ [Corn]	Steer (24)	30 or 60	0.006 g/kg BW	↔	↔	–	↔	↔	↔	↔	↔	↔	–	–	↔	–	–	$\uparrow^{60\text{d}}$	–	–	González-Ríos et al. (2016)
	Heifer	30	0.25 or 0.5 g/kg	↔	–	↔	↔	↔	↔	↔	↔	↔	–	–	↔	–	–	–	–	–	Peña-Torres et al. (2021)
	Lamb (4)	40	0.25 g/kg	↔	–	–	–	↔	↔	↔	↔	–	–	–	–	–	–	–	–	–	Valadez-García et al. (2021)
Flavanols‡ [Red wine extract]	Lamb	40	0.9 g/kg	↔	–	–	–	–	–	–	–	–	–	–	–	$\leftrightarrow^{\alpha\text{-T, TPC}}$	↔	↔	↑	–	Muíño et al. (2014)
Hydroxytyrosol‡ [Olive mill extract]	Goat (2)	78	0.0032 g/d	↔	–	–	–	↔	↔	↔	↔	↔	↔	↔	↔	–	↔	–	–	–	Cimmino et al. (2018)
Tannic acid‡ [unspecified]	Steer	154	30 or 60 g /d	↔	–	–	–	–	↔	↔	↔	–	–	–	–	–	$\uparrow^{60\text{g/kg}}$	↔	–	–	Tabke et al. (2017)

(*continued on next page*)

Table 2 (*continued*)

Terpenes⸙ [*Ferulago angulata*]	Lamb (45)	104	0.25, 0.5, 0.75 g/kg	↔	–	–	↔	↔	↔	↔	↔	↔	↔	↔	↔	–	–	↓	–	–	Parvar et al. (2018)
Unspecified⸙ Moringa leaf (*Moringa oleifera*)	Lamb (4)	161	0.05 g/kg	–	–	–	–	–	–	–	–	–	–	–	↔	–	–	–	–	–	Webb et al. (2022)
Unspecifiedɣ [Wild onion (*Allium mongolicum*)]	Lamb (3)	75	2.8 g/d	↔	↔	–	↓	↓	↔	↔	↔	↔	↔	↔	↑	–	–	–	–	–	Zhao et al. (2023)
	Lamb (5)	60	2.8 or 3.4 g/d	↔	–	↓	↔	↔	↔	↔	↔	–	–	–	–	–	–	↔	–	–	Ding et al. (2021)
	Lamb (3)	60	2.8 or 3.4 g/d	↔	↑$^{3.4g/d}$	–	↓	–	–	–	–	–	–	–	↑	–	–	–	–	–	Yaxing et al. (2021)
	Lamb (6)	75	0.011, 0.022, or 0.033 g/kg	↔	–	↑	↑	↑	↔	–	–	–	↔	↔	↔	↑	–	–	–	–	Liu et al. (2019)
Saponin⸙ [Soap bark tree bark (*Quillaja saponaria*)]	Lamb (2)	12	0.015 g/kg	–	–	–	–	–	–	–	–	–	–	–	–	–	–	↔	–	–	Brogna et al. (2014)
Citation summary of directions of effects	Neutral (↔) effects			56	14	11	35	29	47	51	48	39	31	39	42	7	5	38	4	4	
	Negative (↓) effects			2	1	2	2	7	1	1	1	1	2	0	0	1	2	11	1	2	
	Positive (↑) effects			2	2	2	5	4	6	2	4	0	0	2	8	13	1	2	1	0	
	Total number of citations			60	17	15	42	40	54	54	53	40	33	41	50	21	8	51	6	6	

*: Essential oil; †: flavonoid; ⁄: polyphenol; ɣ: organosulfur; mo: months; ABTS: 2,2′-azinobis(3-ethylbenzothiazoline-6-sulfonic acid; DPPH: 2,2-diphenyl-1-picrylhydrazyl assay; EA: Enzyme assays; FRAP: Ferric reducing antioxidant power assay; ROS: Reactive oxygen species; TOC: Total antioxidant capacity; TPC: Total phenolic content; TEAC: Trolox equivalent antioxidant capacity; α-T: α-tocopherol; γ-T: γ-Tocopherol; ↔: no significant effect; ↑: significant increase; ↓: significant decrease; (–): not reported.

Apart from source, type and dose of DPEs, the variation in animals' responses to DPEs seems to be further influenced by time on feed (Table 1). Most studies reporting an increase in production performance fed DPEs for more than 60 days to small ruminants and 120 days to cattle. This could be a potential indicator of slow adaptation of ruminants to DPEs and/ or assimilation of DPEs into meat. Hence, further research on DPEs for ruminant meat production should consider longer feeding periods. While research indicates low contents of essential oils and organosulfur compounds and moderate contents of CTs can potentially benefit ruminants, there is a notable scarcity of economic impact studies. This lack of economic data makes it difficult to assess the true value of DPEs in ruminant production, hindering efforts to develop sustainable applications.

3.2. *Meat quality attributes*

3.2.1. *Meat ultimate pH*

Meat ultimate pH (pH_u) strongly affects fundamental quality characteristics such as water retention, colour, tenderness, flavour and shelf life. At 24 h postmortem, optimum pH_u values for meat are generally considered to be between 5.5 and 5.7 (Matarneh et al., 2023). Although the rate of pH decline during the conversion of muscle to meat is also a key factor, there is a notable lack of data in the literature on pH trend during the first 24 h postmortem in studies evaluating the effects of DPEs on ruminant meat. For this reason, only pH_u will be discussed in the present review. As evident from Table 2, the majority of the identified DPEs studies (56 of 60citations) had no effect on pH_u values of meat from ruminants. Only a few studies demonstrated an impact of DPEs on meat pH_u. Specifically, García-Salas et al. (2022) observed a higher pH_u in meat from lambs supplemented with 5.25 g/kg of CTs from *A. mearnsii* extract, but no effect was found with lower doses. Similarly, a blend of essential oils (i.e., thymol, carvacrol, eucalyptol and cinnamaldehyde) administered at a dose of 0.15 g/kg to lambs' diet increased meat pH_u (Ortiz-Heredia et al., 2023). However, He et al. (2023) reported a decline in pH_u when steers were fed 0.13 or 0.26 g/day of oregano essential oil. Furthermore, Ornaghi et al. (2020) observed a decrease in meat pH_u when supplementing young bulls with a mixture containing clove leaves, castor oil, cashew oil, vanillin, eugenol and thymol at the doses of 3 and 6 g/day, while no changes occurred with lower doses of 1.5 and 4.5 g/day. Of importance, the increase in pH_u was only noted in lambs (2 citations) while a decline was observed in cattle (2 citations). Where minor inconsistent effects were found, the pH_u values often remained within the range considered optimal. However, further investigation into effects of DPEs on pH_u among different species is important to fully understand these inconsistencies. Based on the gathered studies, it is evident that DPEs have neutral effects on meat pH_u.

3.2.2. *Meat water holding capacity, drip and cooking loss*

The ability of meat to retain water is a key property that affects many quality parameters such as appearance, juiciness, tenderness and flavour (Warner, 2024). This ability to maintain water during portioning, mincing, storage, processing and cooking is known as water-holding capacity (WHC) and it is inversely related to drip and cooking losses (Warner, 2024). Based on Table 2, it appears that DPEs exert no discernible effects on the WHC (14 of 17), drip loss (DL; 11 of 15), and cooking loss (CL; 35 of 42) of meat. For example, dos Santos et al. (2024) reported lower values of WHC in the beef from Nellore bulls fed 10, 30 and 50 g/kg DM of *A. mearnsii* extracts rich in CTs. In contrast, Wang et al. (2023) observed a higher WHC when lambs were supplemented with 6 g/kg DM of *C. sativa* tannin

Table 3

Effects of dietary phytochemical extracts on ruminant meat shelf-life and ageing quality and citation summary of directions of effects for each parameter.

Phytochemical [Source]	Animal (age, mo)	Feeding period (days)	Dose	Antioxidant activity	Oxidation			Microbial growth	L*	a*	b*	Ageing (SF)	Reference
					Myoglobin	Lipid	Protein						
1,8 cineole* [Rosemary (*Rosmarinus officinalis*)]	Lamb (4)	70	0.25 or 0.5 g/kg	–	–	↔	–	–	↔	↔	↔	–	Güney et al. (2021)
	Lamb	100	0.6g/kg, 0.3 or 0.6 ml/d	–	–	↔	–	–	–	–	–	–	Smeti et al. (2018)
		60	0.6g/kg	–	–	↔	–	–	↔	↔	↔	–	Smeti et al., (2013)
	Lamb (3)	95	0.4 g/kg	–	–	↔	–	–	↔	↔	↔	–	Aouadi et al. (2014); Vasta et al. (2013)
Carnosic acid and carnosol′ [Rosemary (*Rosmarinus officinalis*)]	Lamb	80	0.2 or 0.4 mg/kg	–	–	↓	↓	↔	↓	↑	↓	–	Ortuño et al. (2014)
	Lamb	50	0.6 g/kg	–	–	↓	↓	↔	↓	↔	–	–	Ortuño et al. (2015)
	Lamb (1.5)	42	0.6 or 1.2 g/kg	–	–	↓$^{1.2g/kg}$	↔	–	–	–	–	↔	Morán et al. (2012)
1,8 cineole* [laurel leaf (*Laurus nobilis* L.)]	Lamb (5–6)	90	0.5 ml/d	–	–	↔	–	–	–	–	–	–	Al-Obaidi et al. (2021)
Camphor* [Artemisia (*Artemisia herba alba*)]	Lamb (3)	95	0.4 g/kg	–	–	↔	–	–	↔	↔	↔	–	Aouadi et al. (2014); Vasta et al. (2013)
Carvacrol* [Oregano (*Lippia S. berlandieri*)]	Lamb	70	0.2, 0.3 or 0.4 g/kg	–	–	↔	–	–	↔	↔	↔	–	Garcia-galicia et al. (2020)
Carvacrol* [Oregano (*Oregano onites L.*)]	Lamb (2)	56	0.3 g/kg	–	–	↔	–	–	–	–	–	–	Ünlü et al. (2022)
Cinnamaldehyde* [Cinnamon (*Cinnamonum zeylanicum*)]	Bull (10)	187	0.45 or 0.88 g/kg	–	–	↔	–	–	↔	↔	↔	↔	Torrecilhas et al. (2021)
	Lamb (1.5)	35	0.4 ml/d	–	–	↔	–	↔	–	–	–	–	Simitzis et al. (2014)
Eugenol* [Clove *(Eugenia caryophyllus)*]	Bull (10)	187	0.45 or 0.88 g/kg	–	–	↔	–	–	↔	↔	↔	↔	Torrecilhas et al. (2021)
	Lamb (5–6)	90	0.5 ml/d	–	–	↔	–	–	–	–	–	–	Al-Obaidi et al. (2021)
Mixture* [Clove leaf (*Eugenia aromatica*) + castor oil (*Ricinus communis*) + cashew oil (*Anacardium occidentale*) + commercial blend (vanillin, eugenol, & thymol)]	Bull (16)	62	1.5, 3, 4.5 or 6 g/d	–	–	↔	–	–	↔	↔	↔	↔	Ornaghi et al. (2020)
Mixture* [Thymol, eugenol, vanillin, guaiacol, and limonene]	Steers	98	1g/d	–	–	–	–	–	–	–	–	↔	Wang et al. (2020b)
Mixture* [Rosemary; Eugenol, thymol & vanillin blend; Clove]	Heifer	73	4 g/d	–	–	↔	–	–	↔	↔	↔	↔	de Oliveira Monteschio et al. (2017)
Mixture* [Oregano, rosemary, lemon, garlic, eucalyptus, thyme & sweet orange]	Heifer (12)	90	3.5 or 7 g/d	↑^{DPPH}	–	↔	–	–	↔	↔	↔	↔	Rivaroli et al. (2016), (2020)
Mixture* [Clove, cashew and castor oils + eugenol, thymol and vanillin	Steers (20)	80	1.5, 3, 4.5 or 6 g/d	↔$^{TPC,\ ABTS\ DPPH,\ FRAP}$	–	↔	–	–	–	↔	↔	↔	Mottin et al. (2022)

(*continued on next page*)

Table 3 (*continued*)

Phytochemical [Source]	Animal (age, mo)	Feeding period (days)	Dose	Antioxidant activity	Oxidation			Microbial growth	L*	a*	b*	Ageing (SF)	Reference
					Myoglobin	Lipid	Protein						
Unspecified* [myrtle, *Myrtus communis* L.]	Goats (3)	67	30 or 60 g/kg	–	–	↓	–	–	↔	↔	↓	–	Smeti et al. (2021)
Unspecified*	Steer (7)	167	1g/d	–	–	↔	–	–	–	–	–	–	Pukrop et al. (2019)
Ketones* Sage leaves *(Salvia officinalis L.)*	Lamb (5–6)	90	0.5 ml/d	–	–	↔	–	–	–	–	–	–	Al-Obaidi et al. (2021)
Quercetin[†] [Chinese scholar tree (*Sophora japonica* L.)]	Lamb	42	2 g/kg	–	–	–	–	↔	↔	↔	↔	–	Andrés et al. (2013)
Capsaicin[🌿] [Hot pepper (*Capsicum annuum* L.)]	Lamb (2)	56	0.3 g/kg	–	–	↔	–	–	–	–	–	–	Ünlü et al. (2022)
Condensed tannin[🌿] [*Acacia mearnsii*]	Lamb (5)	62	40 g/kg	–	–	↔	–	–	↔	↔	↔	–	Jacondino et al. (2022b)
	Lamb (3)	133	20 g/kg	–	–	–	–	–	↔	↔	↔	–	Venter et al. (2024)
	Lamb (2)	75	40 g/kg	–	–	↔	–	↓	↔	↔	↔	–	Biondi et al. (2019)
Hydrolysable tannin[🌿] [Chestnut (*Castanea sativa*)]	Lamb (3)	90	3 or 6 g/kg	–	–	–	↓	–	–	–	–	–	Wang et al. (2023)
	Lamb (4)	56	5 or 10 g/kg	–	–	↔	–	–	–	–	–	–	Liu et al. (2016)
Condensed tannin[🌿] [Quebracho (*Schinopsis lorenzii*)]	Lamb (4)	49	10, 30 or 60 g/kg	–	–	↔	↔	–	↔	↔	↓	↔	dos Santos et al. (2022b)
	Bullocks	40	3 g/kg	–	–	↔	–	–	↔	↔	↔	–	Ortiz-López et al. (2024)
Condensed tannin[🌿] [Quebracho (*Aspidosperma quebracho*)]	Lamb (2)	12	80 mg/kg	–	–	↓	–	–	–	–	–	–	Brogna et al. (2014)
Condensed tannin[🌿] [Grape seed (*Vitis vinifera* L)]	Lamb	42	25 g/kg	–	–	↔	–	–	↔	↔	↔	–	Jerónimo et al. (2012)
Condensed tannin[🌿] [Rockrose (*Cistus ladanifer* L.)]	Lamb	42	20.5 or 41 g /kg	-	–	↔	–	–	↔	↔	↔	–	Soldado et al. (2024)
Unspecified[🌿] [*Pinus taeda* hydrolysed lignin]	Bulls (6.5)	120	35 g/d at 1–90 days 70 g/d at 91–120 days	-	–	$\downarrow^{8, 11d}$	$\downarrow^{8d}$	–	↔	↔	↓	↔	Maggiolino et al. (2020)
Hydrolysable tannin[🌿] [Tara (*Caesalpinia spinosa*)]	Lamb (2)	75	40 g/kg	–	↔	↔	–	↓	↔	↔	↔	–	Biondi et al. (2019)
Hydrolysable tannin[🌿] [Yerba mate (*Ilex paraguariensis*)]	Lamb (3)	53	10, 20 or 40g/kg	–	↔	↔	↔	–	↔	↔	↔	–	Pena-Bermudez et al., (2020)
Ferulic acid[🌿] [Corn]	Steer (24)	30 or 60	6 mg/kg BW	–	–	↓	–	–	↔	↔	↔	–	González-Ríos et al. (2016)
Flavanols[🌿] [Red wine extract]	Lamb	40	900 mg/kg	–	–	↔	↔	–	–	–	–	–	Muíño et al. (2014)
Tannic acid[🌿] [unspecified]	Steer	154	30 or 60 g /d	–	↔	↔	–	–	↔	↔	↔	–	Tabke et al. (2017)
Terpenes[🌿] [*Ferulago angulata*]	Lamb (45)	104	0.25, 0.5, 0.75 g/kg	–	–	↔	–	–	–	–	–	–	Parvar et al. (2018)

(*continued on next page*)

Table 3 (*continued*)

Phytochemical [Source]	Animal (age, mo)	Feeding period (days)	Dose	Antioxidant activity	Oxidation			Microbial growth	L*	a*	b*	Ageing (SF)	Reference
					Myoglobin	Lipid	Protein						
Saponin🌿 [Soap bark tree bark (*Quillaja saponaria*)]	Lamb (2)	12	15 mg/kg	–	–	↓	–	–	–	–	–	–	Brogna et al. (2014)
Citation summary of direction of effects	Neutral (↔) effects			1	3	31	4	4	24	26	22	10	
	Negative (↓) effects			0	0	8	4	2	2	0	4	0	
	Positive (↑) effects			1	0	0	0	0	0	1	0	0	
Total number of studies				2	3	39	8	6	26	27	26	10	

mo: months; SF: shear force; ↔: no significant interaction; ↑: significant increase; ↓: significant decrease; –: not reported.
ABTS: 2,2′-azinobis(3-ethylbenzothiazoline-6-sulfonic acid; DPPH: 2,2-diphenyl-1-picrylhydrazyl assay; FRAP: Ferric reducing antioxidant power assay; TPC: Total phenolic content.

Table 4
Effects of dietary phytochemical extracts on muscle (*longissimus thoracics*) fatty acid profile of ruminants and citation summary of directions of effects for each parameter.

Phytochemical [Source]	Animal (age, mo)	Feeding (days)	Dose	Saturated fatty acids				18:1			CLA		*n*3			*n*6		Reference
				12:0	14:0	16:0	18:0	t10	t11	c9	c9, t11	t10, c12	18:3	20:5	22:6	18:2	20:4	
1,8 cineole* [Rosemary (*Rosmarinus officinalis*)]	Lamb (3)	95	0.4 g/kg	↔	↔	↔	↔	–	↔	↔	↔	–	↔	↔	↔	↔	↔	Vasta et al. (2013)
	Lamb (4)	70	0.25 or 0.5 g/kg	↔	↔	↔	↔	–	↔	↔	↑	–	↔	↔	–	↔	↑	Güney et al. (2021)
Carnosic acid and carnosol🌿 [Rosemary (*Rosmarinus officinalis*)]	Lamb	100	0.6g/kg, 0.3 or 0.6 ml/d	↔	↔	↔	↔	–	↔	↔	↔	–	↔	↑	↔	↑	↑	Smeti et al. (2018)
	Lamb (1.5)	42	0.6 or 1.2 g/kg	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	Morán et al. (2013)
Camphor* [Artemisia (*Artemisia herba alba*)]	Lamb (3)	95	0.4 g/kg	↔	↔	↔	↔	–	↑	↔	↑	–	↑	↔	↔	↔	↔	Vasta et al. (2013)
Carvacrol* [Oregano]	Steer (12)	390	0.13 or 0.26 g/d	↔	↔	↓	↓	–	–	↔	↑	–	↔	↔	↔	↑	↔	He et al. (2023)
Carvacrol* [Oregano (*Lippia S. berlandieri*)]	Lamb	70	0.2, 0.3 or 0.4 g/kg	↔	↔	↔	↔	–	↔	↔	–	–	↔	↔	↔	↔	↔	Garcia-galicia et al. (2020)
Carvacrol* [Oregano (*Oregano onites L.*)]	Lamb (2)	56	0.3 g/kg	↔	↔	↔	↔	–	–	↔	–	–	↔	–	–	↔	–	Ünlü et al. (2022)
Cinnamaldehyde & carvacrol (2:1)* [Cinnamon & oregano]	Lamb (3)	60	0.03, 0.06 or 0.12 g/kg	–	↓	↔	↔	–	–	↔	–	–	↔	↑	–	↑	–	Ma et al. (2023)
D-limonene* [Arnica montana]	Lamb (3)	90	0.45, 0.9, or 1.35 g/kg	↔	↔	↔	↓	–	↓	↔	↔	↔	↑	↔	↓	↑	–	Dias Junior et al. (2023)
D-limonene* [Orange (*Citrus sinensis*)]	Lamb (3)	84	0.1, 0.5, or 1 g/kg	↔	↔	↔	↔	–	↔	↔	↔	↔	↔	↔	↔	↔	–	Dias Junior et al. (2024)
Eugenol* [Clove *(Syzygium aromaticum)*]	Goat (6–8)	121	2.5 g/kg	↔	↔	↔	↓	–	↔	↔	↔	↔	↔	↔	↔	↑	–	Mandal et al. (2014)
Mixture* [Rosemary; Eugenol, thymol & vanillin blend; Clove]	Heifer	73	4 g/d	↔	↔	↔	↔	↔	↔	↔	↔	–	↔	↔	↔	↔	↔	Monteschio et al. (2019)
Mixture* [Thyme, rosemary, & orange essential oil + Cinnamomum & Quillaja saponaria extract]	Steers (5)	120	0.2 g/kg	–	↓	↓	↔	–	–	↑	–	–	↔	–	–	↑	↔	Wandscheer et al. (2024)
Mixture* [Thymol, eugenol, vanillin, guaiacol, and limonene]	Steers	98	1g/d	–	↔	↔	↔	–	–	↔	–	–	↑	↔	–	↔	↔	Wang et al. (2020a)

(*continued on next page*)

Table 4 (*continued*)

Phytochemical [Source]	Animal (age, mo)	Feeding (days)	Dose	Saturated fatty acids				18:1			CLA		*n*3			*n*6		Reference
				12:0	14:0	16:0	18:0	t10	t11	c9	c9, t11	t10, c12	18:3	20:5	22:6	18:2	20:4	
Mixture* [Oregano, rosemary, lemon, garlic, eucalyptus, thyme & sweet orange]	Heifer (12)	90	3.5 or 7 g/d	↔	↔	↔	↔	–	–	↔	↔	–	↔	↔	↔	↔	↔	Rivaroli et al. (2020)
Mixture* [thymol, carvacrol, eucalyptol and cinnamaldehyde]	Lamb (3)	56	0.15 g/kg	–	↔	↔	↔	↔	↔	↔	–	–	↔	↔	↔	↔	↔	Ortiz-Heredia et al. (2023)
Mixture* (oregano oils, castor bean, cashew)	Bulls (22)	94	4 g/d	↔	↔	↑	↔	–	–	↓	–	–	↔	↔	↔	↔	↔	Fugita et al. (2018)
Unspecified* [myrtle, *Myrtus communis* L.]	Goats (3)	67	30 or 60 g/kg	↔	↔	↔	↔	↔	↔	↔	↔	–	↔	↔	↔	↔	↔	Smeti et al. (2021)
Saponin* [*Acacia concinna* pods]	Goat (6–8)	121	5 g/kg	↔	↔	↔	↔	–	↔	↔	↔	↔	↔	↔	↔	↔	↔	Mandal et al. (2014)
Anthocyanins† [Corn]	Goat	74	0.5 or 1g/d	↓$^{0.5g/d}$	↔	↓$^{0.5g/d}$	↔	–	–	↔	–	–	↔	–	↑$^{0.5g/d}$	↔	↑	Tian et al. (2022)
Capsaicin′ [Hot pepper (*Capsicum annuum* L.)]	Lamb (2)	56	0.3 g/kg	↔	↔	↔	↔	–	–	↔	↔	–	↔	–	–	↔	–	Ünlü et al. (2022)
Condensed tannin′ [*Acacia mearnsii*]	Lamb (2)	89	2.5 g/kg	↔	↔	↔	↓	–	–	↑	–	–	↔	↔	↔	↓	↑	Brunetto et al. (2024)
	Lamb (4)	85	20, 40, 60, or 80 g/kg	↑	↔	↔	↔	–	–	↓	↔	–	↑	↑	↓$^{>40g/kg}$	↑	↑	Costa et al. (2021)
	Lamb (2)	75	40 g/kg	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	Valenti et al. (2021)
	Bull (16)	99	10, 30 or 50 g/kg	↔	↑$^{10, 30 g/kg}$	↔	↔	–	↑	↑$^{10, 30 g/kg}$	↑	–	↔	↑	↑	↑	↑	dos Santos et al. (2024)
	Lamb (5)	62	40 g/kg	↔	↔	↔	↔	–	–	↔	–	–	↔	↔	–	↔	↔	Jacondino et al. (2022)
	Lamb (3)	133	20 g/kg	↔	↔	↔	↔	–	–	↔	–	–	↔	–	↔	↔	↔	Venter et al. (2024)
	Goats (4)	84	16, 32 or 48 g/kg	↔	↔	↔	↔	–	–	↓	↔	–	↑	↔	↔	↑	↔	Pimentel et al. (2021)
Condensed tannin′ [gambier (*Uncaria gambir*)]	Lamb (2)	75	40 g/kg	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	Valenti et al. (2021)
Condensed tannin′ [Quebracho (*Schinopsis lorenzii*)]	Lamb (90)	70	20 or 40 g/kg	↔	↔	↔	↓	–	–	↔	↑	–	↔	–	–	↔	–	Kamel et al. (2018)
Condensed tannin′ [Quebracho	Lamb (2)	12	0.08 g/kg	↔	↑	↔	↔	–	↔	↔	↔	↔	↔	↔	↔	↔	↔	Brogna et al. (2014)

(*continued on next page*)

Table 4 (*continued*)

Phytochemical [Source]	Animal (age, mo)	Feeding (days)	Dose	Saturated fatty acids				18:1			CLA		*n*3			*n*6		Reference
				12:0	14:0	16:0	18:0	t10	t11	c9	c9, t11	t10, c12	18:3	20:5	22:6	18:2	20:4	
(*Aspidosperma quebracho*)]																		
Condensed tannin′ [Grape seed (*Vitis vinifera* L)]	Lamb	42	25 g/kg	–	↔	↔	↔	–	↔	↔	↔	–	↔	↔	↑	↔	↑	Jerónimo et al. (2012)
Condensed tannin′ [Rockrose (*Cistus ladanifer* L.)]	Lamb (2)	42	20.5 or 41 g /kg	↔	↔	↔	↔	↔	↑$^{20.5/kg}$	↔	↔	–	↔	↔	↔	↔	↔	Guerreiro et al. (2020)
Unspecified* [Cashew (*Anacardium occidentale* L.) and castor (*Ricinus communis* L.)]	Bulls (20)	55	3 g/d	↔	↔	↔	↔	–	↔	↔	–	–	↔	↔	↔	↔		Valero et al. (2014)
Chrysin* [Unspecified]	Bulls (20)	55	3 g/d	↔	↔	↔	↔	–	↔	↔	–	–	↔	↔	↔	↔		Valero et al. (2014)
Unspecified′ [*Pinus taeda* hydrolysed lignin]	Bulls (6.5)	120	35 g/d at 1–90 days 70 g/d at 91–120 days	↔	↑	↑	↓	–	↓	↓	–	–	↓	–	↓	↓	↓	Maggiolino et al. (2020)
Hydrolysable tannin′ [Tara (*Caesalpinia spinosa*)]	Lamb (2)	75	40 g/kg	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	Valenti et al. (2021)
Hydrolysable tannin′ [Yerba mate (*Ilex paraguariensis*)]	Lamb (3)	53	10, 20 or 40g/kg	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	Pena-Bermudez et al. (2022)
Hydrolysable tannin′ [Chestnut (*Castanea sativa*)]	Lamb (3–4)	70	2 or 4 g/kg	–	↔	↓	↔	–	↔	↔	↔	↔	↔	↑	↔	↔	↔	Gao et al. (2024)
	Lamb (2)	75	40 g/kg	↔	↔	↔	↔	↓	↔	↔	↔	↔	↔	↔	↔	↔	↔	Valenti et al. (2021)
	Lamb (3)	90	30 or 60 g/kg	↔	↔	↔	↔	–	–	↔	–	–	↔	↔	↔	↔	↔	Wang et al. (2023)
Unspecified′ [*Terminalia chebula*]	Goat (5–6)	90	1.06 or 3.18g/kgBW	↔	↔	↓$^{3.18g/kgBW}$	↓$^{3.18g/kgBW}$	–	↔	↔	↑	↔	↔	↔	↔	↔	↔	Rana et al. (2012)
Ferulic acid′ [Corn]	Steer (24)	30 or 60	0.006 g/kg BW	↔	↔	↔	↔	–	–	↔	–	–	↔	–	–	↑	–	González-Ríos et al. (2016)
Flavanols′ [Red wine extract]	Lamb	40	0.9 g/kg	–	–	–	↔	–	–	↔	–	–	↔	↔	↑	↔	–	Muíño et al. (2014)
Hydroxytyrosol′ [Olive mill extract]	Goat (2)	78	0.0032 g/d	↔	↓	↓	↔	–	–	↑	↔	–	–	–	↔	↔	↔	Cimmino et al. (2018)
Terpenes′ [*Ferulago angulata*]	Lamb (45)	104	0.25, 0.5, 0.75 g/kg	↔	↔	↔	↔	–	–	↔	–	–	↔	↔	↑	↔	↔	Parvar et al. (2018)
Unspecified′ Moringa leaf (*Moringa oleifera*)	Lamb (4)	161	0.05 g/kg	↔	↔	↔	↔	–	–	↔	–	–	↔	–	–	↔	–	Webb et al. (2022)
Saponin [tea saponins]	Lamb	60	3 g/d	–	↓	↔	↔	–	↑	↔	↔	↔	↔	↔	↔	↔	↔	Mao et al. (2012)

(*continued on next page*)

Table 4 (*continued*)

Phytochemical [Source]	**Animal (age, mo)**	**Feeding (days)**	**Dose**	**Saturated fatty acids**				**18:1**			**CLA**		***n*3**			***n*6**		**Reference**
				12:0	**14:0**	**16:0**	**18:0**	**t10**	**t11**	**c9**	**c9, t11**	**t10, c12**	**18:3**	**20:5**	**22:6**	**18:2**	**20:4**	
Unspecifiedɣ [Wild onion (*Allium mongolicum*)]	Lamb (3)	75	2.8 g/d	↔	↔	↔	↓	–	–	↑$^{2.8g/d}$	–	–	↔	↔	↑	↔	–	Zhao et al. (2023)
	Lamb (3)	60	2.8 or 3.4 g/d	↔	↑	↓	↓	↑$^{2.8g/d}$	↑$^{2.8g/d}$	↔	–	–	↔	↔	↔	↔	↔	Yaxing et al. (2021)
	Lamb (6)	75	0.011, 0.022, or 0.033 g/kg	↔	↔	↔	↓	–	–	↔	–	–	↔	↔	↑	↔	↔	Liu et al. (2019)
Unspecifiedʹ [Neem leaf (*Azadirachta indica*)]	Lamb (4)	161	0.05 g/kg	↔	↔	↔	↔	–	–	↔	–	–	↔	–	–	↔	–	Webb et al. (2022)
Saponinʹ [Soap bark tree bark (*Quillaja saponaria*)]	Lamb (2)	12	0.015 g/kg	↔	↔	↔	↔	–	↔	↔	↔	↔	↔	↔	↔	↔	↔	Brogna et al. (2014)
Citation summary of directions of effects	Neutral (↔) effects			44	45	44	44	9	23	45	25	15	47	38	33	42	32	
	Negative (↓) effects			1	4	7	10	1	2	4	0	0	1	0	3	2	1	
	Positive (↑) effects			1	4	2	0	1	5	5	6	0	5	5	7	10	7	
Total number of studies				46	53	53	54	11	30	54	31	15	53	43	43	54	40	

*: Essential oil; †: flavonoid; ʹ: polyphenol; ɣ: organosulfur; m: months; CLA: Conjugated linoleic acid; ↔: no significant effect; ↑: significant increase; ↓: significant decrease; –: not reported.

Table 5
Effects of dietary phytochemical extracts on meat volatile compounds, sensory and consumer perception profiles in ruminants and citation summary of directions of effects for each parameter.

Phytochemical [Source]	Animal (age, m)	Feeding (days)	Dose	Volatile compounds				Sensory profile				Reference
				Alcohols	Aldehydes	Furans	Organic acids	Juiciness	Tenderness	Flavour	Acceptability	
								Descriptive sensory analysis				
1,8 cineole* [Rosemary (*Rosmarinus officinalis*)]	Lamb (4)	70	250 or 500 mg/kg	–	–	–	–	↔	↔	↔	↔	Güney et al. (2021)
	Lamb (3)	95	400 mg/kg	↔	↔	↔	↔	–	–	–	–	Aouadi et al. (2014); Vasta et al. (2013)
	Lamb	100	0.6g/kg, 0.3 or 0.6 ml/d	–	–	–	–	↔	↔	↑	↑	Smeti et al. (2018)
		60	0.6g/kg	–	–	–	–	↔	↔	↔	↔	Smeti et al., (2013)
Carnosic acid and carnosolʹ [Rosemary (*Rosmarinus officinalis*)]	Lamb	80	0.2 or 0.4 mg/kg	↓	↓	↓	↓	–	–	↔	–	Ortuño et al. (2014)
	Lamb (1.5)	42	0.6 or 1.2 g/kg	↓$^{0.6g/kg}$	↔		↓$^{0.6g/kg}$	–	–	–	–	Morán et al. (2013)
Camphor* [Artemisia (*Artemisia herba alba*)]	Lamb (3)	95	0.4 g/kg	↔	↔	↔	↔	–	–	–	–	Aouadi et al. (2014); Vasta et al. (2013)
Carvacrol* [Oregano (*Oregano onites L.*)]	Lamb (2)	56	0.3 g/kg	–	–	–	–	↔	↔	↔	↔	Ünlü et al. (2022)
Mixture* [Thymol, eugenol, vanillin, guaiacol, and limonene]	Steers	98	1g/d	–	–	–	–	↑	↑	↔	–	Wang et al. (2020b)
Capsaicinʹ [Hot pepper (*Capsicum annuum* L.)]	Lamb (2)	56	0.3 g/kg	–	–	–	–	↔	↔	↔	↔	Ünlü et al. (2022)
Condensed tanninʹ [Quebracho (*Aspidosperma quebracho*)]	Lamb (2)	12	0.08 mg/kg	↔	↔	↔	↔	–	–	–	–	Brogna et al. (2014)
Condensed tanninʹ [Rockrose (*Cistus ladanifer* L.)]	Lamb (3)	35	15 g/kg	–	–	–	–	↔	↔	↔	↔	Dentinho et al. (2020)
	Lamb	42	20.5 or 41 g /kg	–	–	–	–	↓$^{20.5g/kg}$	↔	↔	↑	Guerreiro et al. (2020)
Condensed tanninʹ [Unspecified]	Lamb	28	30, 40 or 50 g/kg	–	–	–	–	↔	↔	↔	↔	Ngámbi et al. (2022)
Ferulic acidʹ [Corn]	Steer (24)	30 or 60	0.006 g/kg BW	–	–	–	–	↔	↔	↔	↔	González-Ríos et al. (2016)
	Heifer	30	0.25 or 0.5 g/kg	–	–	–	–	↔	↔	↔	↔	Peña-Torres et al. (2021)
Flavanolsʹ [Red wine extract]	Lamb	40	0.9 g/kg	–	–	–	–	↔	↔	↔	↔	Muíño et al. (2014)
Saponinʹ [Soap bark tree bark (*Quillaja saponaria*)]	Lamb (2)	12	0.015 g/kg	↔	↔	↔	↔	–	–	–	–	Brogna et al. (2014)
								Consumer sensory analysis				

(*continued on next page*)

Table 5 (*continued*)

Phytochemical [Source]	**Animal (age, m)**	**Feeding (days)**	**Dose**	**Volatile compounds**				**Sensory profile**				**Reference**
				Alcohols	**Aldehydes**	**Furans**	**Organic acids**	**Juiciness**	**Tenderness**	**Flavour**	**Acceptability**	
Mixture* [Oregano, rosemary, lemon, garlic, eucalyptus, thyme & sweet orange]	Heifer (12)	90	3.5 or 7 g/d	–	–	–	–	–	↑$^{3.5g/d}$	–	↔	Guerrero et al. (2018)
	Steers (12)	120		–	–	–	–	–	↔	–	↔	
Rosemary*	Heifer (24)	73	4 g/d	–	–	–	–	–	↔	↔	↔	de Oliveira Monteschio et al. (2020)
Mixture* [Eugenol, thymol, and vanillin]				–	–	–	–	–	↔	↔	↔	
Mixture* [Eugenol, thymol, and vanillin] + Clove				–	–	–	–	–	↔	↑	↔	
Mixture* [Eugenol, thymol, and vanillin] + Rosemary + clove				–	–	–	–	–	↑	↑	↔	
Cinnamaldehyde* [Cinnamon (*Cinnamonum zeylanicum*)]	Bull (10)	187	0.45 or 0.88 g/kg	–	–	–	–	↔	↔	↔	↔	Torrecilhas et al. (2021)
Eugenol* [Clove *(Eugenia caryophyllus)*]				–	–	–	–	↔	↔	↔	↔	
Mixture* [Clove leaf (*Eugenia aromatica*) + castor oil (*Ricinus communis*) + cashew oil (*Anacardium occidentale*) + commercial blend (vanillin, eugenol, & thymol)]	Bull (16)	62	1.5, 3, 4.5 or 6 g/d	–	–	–	–	↔	↔	↔	↔	Ornaghi et al. (2020)
Quercetin† [Chinese scholar tree (*Sophora japonica* L.)]	Lamb	42	2 g/kg	–	↔	–	–	–	↓	–	↓	Andrés et al. (2014)
Hydrolysable tannin′ [Yerba mate (*Ilex paraguariensis*)]	Lamb (3)	53	10, 20 or 40g/kg	–	–	–	–	↔	↔	↔	↔	Pena-Bermudez et al. (2022)
Condensed tannin′ [*Acacia mearnsii*]	Lamb (4)	85	20, 40, 60, or 80 g/kg	–	–	–	–	–	↓	↔	↔	Costa et al. (2021)
	Goats (4)	84	16, 32 or 48 g/kg	–	–	–	–	↔	↑	↑	↑	Pimentel et al. (2021)
Citation summary of directions of effects	Neutral (↔) effects			4	6	4	4	10 (5)	11 (8)	12 (3)	9 (11)	
	Negative (↓) effects			2	1	1	2	1 (0)	0 (2)	0 (0)	0 (1)	
	Positive (↑) effects			0	0	0	0	1 (0)	1 (3)	1 (3)	2 (1)	
Total number of citations				6	7	5	6	12 (5)	12 (13)	13 (6)	11 (13)	

*Essential oil; †: flavonoid; ′: polyphenol; ¥: organosulfur; mo: months; ↔: no significant effect; ↑: significant increase; ↓: significant decrease; –: not reported; The sensory total values are present as descriptive sensory analysis (consumer sensory analysis)

Table 6
Effects of dietary phytochemical extracts on ruminant milk production and citation summary of directions of effects for each parameter.

Phytochemical [Source]	Animal	Feeding (days)	Dose	Dry matter intake	Yield							Feed efficiency	Content			Somatic cell count	Reference
					Milk	3.5 % FCM^{1}	Fat	Protein	Lactose	Total solids	Solid not fat		Fat	Protein	Lactose		
Anethole* [Anise (*Pimpinella anisum*)]	Goat	22	2 ml/d	↔	↔	↔	↑	↔	↔	–	–	↔	↑	↔	↔	–	El-Essawy et al. (2021)
Eugenol* [Clove (*Syzygium aromaticum*)]				↔	↔	↔	↑	↔	↔	–	–	–	↑	↔	↔	–	
Thymol* [Thyme (*Thymus vulgaris*)]				↔	↔	↔	↑	↔	↔	–	–	–	↑	↔	↔	–	
Carvacrol* [Oregano (*Origanum vulgare*)]	Cow	58	0.56 g/kg	↔	↔	↔	–	–	–	↔	↔	↔	↓	↓	↔	–	Kolling et al. (2018)
		28	0.07 g/kg	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	Oh et al. (2019)
		28	0.05 g/kg	↔	↔	–	↔	↔	↔	–	–	↔	↔	↔	↔	–	Benchaar (2020)
		42	10 g/d	↔	↔	↔	–	–	–	↔	–	↔	↔	↔	↔	↓	Vizzotto et al. (2021)
Carvacrol* [Unspecified]	Cow	28	0.05 g/kg	↔	↔	–	↔	↔	↔	–	–	↔	↔	↔	↔	–	Benchaar (2020)
Eugenol* [Unspecified]	Cow	28	0.025, 0.05 or 0.075 g/kg	↔	↔	↔	↔	↔	↔	–	–	–	↔	↔	↔	↔	Benchaar et al. (2015)
Thymol, guaiacol, eugenol, vanillin, salicylaldehyde and limonene* [Unspecified]	Cow	21	1 g/d	↔	↔	↔	↔	↔	↔	–	–	–	–	–	–	–	Vendramini et al. (2016)
Catechin🪶 [Green tea (*Camellia sinensis* L.)]	Cow	42	5 g/d	↔	↔	↔	–	–	–	↔	–	↔	↔	↔	↔	–	Vizzotto et al. (2021)
		58	0.28 g/kg	↔	↔	↔	–	–	–	↔	↔	↔	↔	↑	↔	–	Kolling et al. (2018)
D-limonene* [Orange (*Citrus sinensis*)]	Cow	28	4 g/d	↔	↔	–	↔	↔	↔	–	–	–	↔	↔	↔	↓	Havlin and Robinson (2015)
Citral* [Lemongrass (*Cymbopogon citratus*)]	Cow	35	0.08, 0.16 or 0.24 m/kg BW	↔	↔	↔	↓	↔	↔	–	–	↔	↔	↔	↔	–	Canaes et al. (2017)
Cumin seed* [*Cuminum cyminum*)	Goat	32	12.7 or 25.3 g/DMI	↔	↑$^{12.7g/DMI}$	–	↔	↔	↑$^{12.7g/DMI}$	–	↑$^{12.7g/DMI}$	–	↔	↔	↔	–	Miri et al. (2013)
[*Aloe vera*]🪶	Goat	100	20 or 40 g/DM	↔	↑	–	↑	↑	↑	–	↑	–	↔	↔	↔	–	Banakar et al. (2023), (2021)
Hesperidin [Citrus peel extract]	Cow	42	4 g/d	–	↑	–	↔	↑	↑	–	–	–	–	–	–	–	Ju et al. (2024)
Cinnamaldehyde, eugenol, capsicum oleoresin* [Unspecified]	Cow	42	1 g/d	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	Martins et al. (2023)
Eugenol, geranyl acetate, linalool* [Coriander & others]	Cow	56	1 g/d	↔	↔	↔	↔	↔	↔	–	–	↔	↔	↔	↔	–	Elcoso et al. (2019)
		28		↔	↔		↔	↔	↔	–	–	–	↑	↔	↔	↔	Santos et al. (2010)
Cresols, Thymol, Limonene, Vanillin, guaiacol, eugenol, salicylates* [Unspecified]	Cow	105	1.2 g/d	↔	↔	–	↔	↔	↔	–	–	↔	–	–	–	–	Joch et al. (2019)

(*continued on next page*)

Table 6 (*continued*)

Phytochemical [Source]	Animal	Feeding (days)	Dose	Dry matter intake	Yield							Feed efficiency	Content			Somatic cell count	Reference
					Milk	3.5 % FCM[1]	Fat	Protein	Lactose	Total solids	Solid not fat		Fat	Protein	Lactose		
Thymol, eugenol, vanillin, guaiacol & limonene* [Unspecified]	Ewe	150	0.05, 1 or 1.5 g/kg	↔	$\uparrow^{>0.05g/kg}$	–	↔	↔	↔	–	↔	–	↔	↔	↔	↓	Giannenas et al. (2011)
Eugenol and cinnamaldehyde* [Unspecified]	Cow	70	0.525 g/d	↔	↔	↔	↔	↔	↔	–	–	↔	↔	↔	↔	↔	Tekippe et al. (2013)
			0.5 or 10 g/d	↔	↔	–	↔	↔	↔	–	–	–	↔	↔	↔	–	Tager and Krause (2011)
		63	0.2, 0.4 or 0.6 g/kg	↔	↔	–	↔	↔	↔	–	–	–	↔	↔	↔	–	Flores et al. (2013)
Capsaicin* [*Capsicum oleoresin*]	Cow	21	0.25 g/d	↔	↔	–	↔	↔	↔	–	–	–	↔	↔	↔	–	Tager and Krause (2011)
		84	0.1 g/d	↔	↔	↑	↑	↔	↔	–	–	–	↔	↔	↔	–	Takiya et al. (2023)
		31	0.5 g/d	↔	↔	↔	↔	↔	↔	–	–	↔	↔	↔	↔	↔	Foskolos et al. (2020)
		63	0.75 or 15 g/d	↑	↑	↑	↑	↑	↑	–	–	↔	↔	↔	↔	–	Vittorazzi et al. (2022)
		25	0.25, 0.5, or 1 g/d	↔	↔	↑	↔	↔	↔	↔	–	↔	↔	↔	↓	↔	Oh et al. (2015)
		28	0.1 or 0.2 g/d	↔	↔	↔	↔	↔	↔	↔	–	↑	↔	↔	↔	↔	Oh et al. (2017)
		21	1.5 g/d	↔	↑	↑	↑	↑	↑	–	–	↔	↔	↔	↔	–	Grigoletto et al. (2023)
		70	0.3 g/d	↔	↔	↔	↔	↔	↔	↔	–	↔	↔	↔	↔	↔	Martins et al. (2024)
Eugenol & Capsaicin* [Clove *(Syzygium aromaticum)* & *Capsicum oleoresin*]	Cow	70	0.3 g/d	↔	↔	↔	↔	↔	↔	↔	–	↔	↔	↔	↔	↔	
Thymol & capsaicin* [Thyme & chilli pepper]	Ewe	84	2 ml/d	↔	↑	↑	↑	↑	↑	↑	↑	↑	↓	↔	↔	–	Kholif et al. (2018)
Blend* [plantain (*Plantago major*) & peppermint (*Mentha piperita*)]	Ewe	42	2 g/d	↑	↔	↑	↑	↑	–	–	–	–	↑	↑	–	–	Mirzaei-Alamouti et al. (2021)
Eugenol, geranyl acetate & coriander*	Cow	91	1 g/d	↔	↔	↔	↔	↔	–	–	–	↓	↔	↔	–	–	Bach et al. (2023)
Cinnamaldehyde & garlic oil* [Unspecified]	Cow	28	0.3 g/d	↔	↔	–	–	–	–	–	–	↔	↔	↔	↔	↔	Blanch et al. (2016)
		56	0.6 g/d	↓	↔	↔	↔	↔	↔	–	↔	↔	↔	↔	↔	↓	Cantet et al. (2023)
Cinnamaldehyde* [Unspecified]	Cow	56	0.6 g/d	↓	↔	↔	↔	↔	↔	–	↔	↑	↔	↔	↔	↓	
Cinnamaldehyde & Capsaicin* [Cinnamon & *Capsicum oleoresin*]	Cow	84	0.055 g/kg	↔	↔	↔	↔	↔	↔	–	–	↔	↔	↔	↔	↔	van Gastelen et al. (2024)
Eugenol, geraniol & geranyl acetate* [Unspecified]	Cow	91	1 g/d	↔	↔	↔	↔	↔	↔	–	–	↔	↔	↔	↔	↔	Benchaar and Hassanat (2025)
Thymol* [Thyme (*Thymus vulgaris*)]	Cow	28	0.05 g/kg	↔	↔	↔	↔	↔	↔	–	–	↔	↔	↔	↔	–	Benchaar (2021)

(*continued on next page*)

Table 6 (*continued*)

Phytochemical [Source]	**Animal**	**Feeding (days)**	**Dose**	**Dry matter intake**	**Yield**							**Feed efficiency**	**Content**			**Somatic cell count**	**Reference**
					Milk	**3.5 % FCM**[1]	**Fat**	**Protein**	**Lactose**	**Total solids**	**Solid not fat**		**Fat**	**Protein**	**Lactose**		
Blend* (Unspecified]	Ewe	60	0.3 g/kg	↔	↑	↑	↑	↑	↑	↑	↑	↑	↔	↓	↓	–	Azzaz et al. (2025)
Unspecified* [caraway seed (*Carum carvi*)]	Cow	24	0.2 or 1 g/kg	↔	↔	↔	↔	↔	–	–	–	–	–	–	–	–	Lejonklev et al. (2016)
Carvacrol* [Oregano (*Origanum vulgare*)]				↔	↔	↔	↔	↔	–	–	–	–	–	–	–	–	
Unspecified* [Eucalyptus (*Eucalyptus globulus*), thyme (*Thymus vulgaris*) & anise (*Pimpinella anisum*)]	Cow	21	25 g/d	↔	↔	↔	–	–	–	–	–	↔	↔	↔	↔	↑	Giller et al. (2020)
Thymol, eugenol, vanillin & limonene* [Unspecified]	Cow	21	0.044 g/kg	↔	↔	↔	↔	↔	↔	–	–	↔	↔	↔	↔	–	Silva et al. (2018)
Curcumin* [*Curcuma longs* L.]	Cow	9	2 g/d	↔	↔	↔	↔	↔	↔	–	–	↔	↔	↔	↔	↔	Oh et al. (2013)
Polysorbate & organosulfur* [Garlic]				↔	↔	↔	↔	↔	↔	–	–	↔	↔	↔	↔	↔	
Capsaicin* [*Capsicum frutescens* L. and *Capsicum anum* L.]				↔	↓	↔	↔	↔	↔	–	–	↔	↔	↔	↔	↔	
Unspecified* [Cinnamon (*Cinnamomum cassia*), thyme (*Thymus vulgaris*), and peppermint (*Menthapiperita*)]	Goat	45	1.5 ml/d	–	↔	↔	↔	↔	↔	–	–	–	↔	↔	↔	–	El-Azrak et al. (2022)
Carvacrol, eugenol, thymol & capsaicin* [Unspecified]	Cow	84	0.16 g/kg	↔	↔	↔	↔	↔	↔	–	↔	↔	↔	↔	↔	–	Diepersloot et al. (2025)
Chlorogenic acid′ [*Lonicera japonica*]	Cow	70	14, 28 or 56 g/d	↔	↔	–	–	–	–	↔	↔	–	↔	↔	↔	–	Ma et al. (2020)
Condensed & hydrolyzable tannin′ [Quebracho (*Schinopsis* spp.): Chestnut (*Castanea sativa*) (2:1)]	Cow	91	4.5 or 18 g/kg	↑	↔	↔	↔	↔	↔	–	↔	↓	↔	↑$^{4.5g/kg}$	↔	–	Aguerre et al. (2020)
		21	4.5, 9 or 18 g/kg	↓	↔	↔	↔	↔	↔	–	↔	↔	↔	↔	↔	–	Aguerre et al. (2016)
Hydrolyzable tannin′ [Chestnut (*Castanea sativa* Miller)]	Ewe	43	52.8 g/kg + Pasture	↔	↔	–	–	–	–	↔	–	–	↔	↔	↔	–	Buccioni et al. (2017)
			52.8 g/kg	↔	↔	–	–	–	–	↔	–	–	↔	↔	↔	–	Buccioni et al. (2015)
Condensed tannin′ [Quebracho (*Schinopsis lorenztii*)]			52.8 g/kg + Pasture	↔	↔	–	–	–	–	↔	–	–	↔	↔	↔	–	Buccioni et al. (2017)
			52.8 g/kg	↔	↔	–	–	–	–	↔	–	–	↔	↔	↔	–	Buccioni et al. (2015)

(*continued on next page*)

Table 6 (*continued*)

Phytochemical [Source]	Animal	Feeding (days)	Dose	Dry matter intake	Yield							Feed efficiency	Content			Somatic cell count	Reference
					Milk	3.5 % FCM^{1}	Fat	Protein	Lactose	Total solids	Solid not fat		Fat	Protein	Lactose		
Hydrolyzable tannin🌿 [Pomegranate (*Punica granatum* L)]	Cow	49	10, 20 or 40 g/kg	↔	↔	–	↔	↔	↔	–	–	–	–	–	–	↔	Shabtay et al. (2012)
Condensed tannin🌿 [Quebracho (*Schinopsis lorenztii*)]	Cow	21	15 or 30 g/kg	↔	↑$^{30g/kg}$	–	↑$^{30g/kg}$	↑$^{30g/kg}$	↑$^{30g/kg}$	–	–	–	↑$^{30g/kg}$	↔	↑	–	Henke et al. (2017a)
	Ewe	28	20 g/kg	↔	↔	–	↔	↔	↔	↔	–	–	↔	↔	↔	–	Toral et al. (2013)
Condensed and Hydrolyzable tannin🌿 [Unspecified]	Ewe	42	10 g/kg	↔	↔	–	↔	↔	↔	–	–	–	↔	↔	↔	–	Toral et al. (2011)
Condensed tannin🌿 [Quebracho (*Schinopsis balansae*)]	Goat	25	20, 40 or 60 g/kg	↔	↑$^{40g/kg}$	↔	↔	↔	↔	–	–	–	↑	↔	↔	↔	Battelli et al. (2024)
Condensed tannin🌿 [Quebracho]	Cow	21	10 or 30 g/kg	↓	↔	–	↔	↔	↔	–	–	↑	↔	↔	↔	–	Dschaak et al. (2011)
Condensed tannin🌿 [*Acacia meansii*]	Cow	169	10 or 30 g/kg	↔	↔	↔	↔	↔	↔	–	–	↔	↔	↔	↔	↔	Gerlach et al. (2018)
		24	111, 222 or 444 g/d	↔	↓$^{444g/kg}$	–	–	–	–	↑$^{444g/kg}$	–	–	↔	↔	↔	–	Griffiths et al. (2013)
		48	10 g/d	↔	↔	–	–	–	–	–	–	–	↔	↔	↔	–	Orlandi et al. (2020)
		28	20 g/d	↔	↔	↔	↔	↔	–	–	–	–	↔	↔	–	–	Alves et al. (2017)
		23	141 g/kg	↔	–	↔	↔	↔	–	–	–	–	–	–	–	–	Denninger et al. (2020)
		35	7.5, 15 or 30 g/kg	↔	↔	–	–	–	–	–	–	–	–	–	–	–	Mhlongo et al. (2024)
		21	0.6, 12 or 1.8 g/kg	↔	↔	↑	↔	↔	↑	–	–	↔	↔	↔	↔	–	Rennó et al. (2025)
Condensed tannin🌿 [*Unspecified*]	Cow	21	1.4, 2.9 or 4.3 g/kg	↔	↔	↔	↔	↔	↔	↔	–	↔	↔	↔	↔	↔	Oliveira et al. (2023)
Flavonoid🌿 [Grape seed and grape marc meal]	Cow	63	10 g/kg	↔	↑	↑	↔	↑	–	–	–	–	↔	↔	↔	–	Gessner et al. (2015)
Ferulic acid🌿 [Coix seed (*Coix lacryma-jobi* L.)]	Goat	70	1.5, 3 or 4.5 g/kg	↔	↑	↑	↑	↑	↑	↑	↑	–	↔	↑$^{1.5g/kg}$	↑$^{1.5g/kg}$	–	Tian et al. (2025)
Capsaicin🌿 [Chilli pepper (*Capsicum oleoresin*)]	Cow	28	0.15, 0.3 or 0.6 g/kg	↔	↔	↔	↔	↔	↔	↔	–	↔	↔	↔	↔	↔	Silvestre et al. (2022)
		30	0.02, 0.04 or 0.06 g/kg	–	↑$^{0.04g/kg}$	–	–	–	–	↔	–	–	↔	↔	↔	↔	Abulaiti et al. (2021)
Geranyl acetate & eugenol* [Unspecified]	Cow	98	1 g/d	↔	↔	↔	↔	↔	↔	↔	–	↔	↑	↔	↑	↔	Silvestre et al. (2023)
Saikosaponin [*Radix Bupleuri*]	Cow	70	0.25, 0.5 or 1 g/kg	↑	↑	↑	↑	↑	↔	–	↔	↑	↔	↔	↔	↓	Pan et al. (2014)
Triterpenoid [Tea]	Cow	56	20, 30 or 40 g/d	↓	↓$^{>20g/d}$	↓$^{>30g/d}$	↓$^{>30g/d}$	↓	↓	–	–	↔	↑	↔	↓	↓	Wang et al. (2017)

(*continued on next page*)

Table 6 (*continued*)

Phytochemical [Source]	Animal	Feeding (days)	Dose	Dry matter intake	Yield							Feed efficiency	Content			Somatic cell count	Reference
					Milk	3.5 % FCM[1]	Fat	Protein	Lactose	Total solids	Solid not fat		Fat	Protein	Lactose		
Citation summary of directions of effects	Neutral (↔) effects			69	63	42	51	54	48	20	12	37	62	67	64	23	
	Negative (↓) effects			5	3	1	2	1	1	0	0	2	2	2	3	7	
	Positive (↑) effects			4	14	11	13	11	10	4	5	6	9	4	3	1	
Total number of citations				78	80	54	66	66	59	24	17	45	73	73	70	31	

*: Essential oil; †: flavonoid; ′: polyphenol; ᵞ: organosulfur; m: months; (↔): no significant effect; (↑): significant increase; (↓): significant decrease; (–): not reported, [1]FCM: Full cream milk

Table 7
Effects of dietary phytochemical extracts on ruminant milk fatty acid profile and citation summary of directions of effects for each parameter.

				Saturated fatty acids				18:1			CLA		*n*3			*n*6		
Phytochemical [Source]	**Animal**	**Feeding (days)**	**Dose**	**12:0**	**14:0**	**16:0**	**18:0**	**t10**	**t11**	**c9**	**c9, t11**	**t10, c12**	**18:3**	**20:5**	**22:6**	**18:2**	**20:4**	**Reference**
Anethole* [Anise (*Pimpinella anisum*)]	Goat	22	2 ml/d	↓	↔	↔	↔	–	–	↑	–	–	↑	–	–	↓	↓	El-Essawy et al. (2021)
Eugenol* [Clove (*Syzygium aromaticum*)]				↓	↔	↔	↔	–	–	↑	–	–	↑	–	–	↓	↓	
Thymol* [Thyme (*Thymus vulgaris*)]				↓	↔	↔	↔	–	–	↑	–	–	↑	–	–	↓	↓	
Carvacrol* [Oregano (*Origanum vulgare*)]	Cow	58	0.56 g/kg	↓	↔	↔	↔	–	↔	↔	↔	–	↔	↔	↔	↔	↔	Kolling et al. (2018)
		28	0.05 g/kg	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	Benchaar (2020)
Carvacrol* [Unspecified]	Cow	28	0.05 g/kg	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	
Catechinʹ [Green tea (*Camellia sinensis* L.)]	Cow	58	0.28 g/kg	↔	↔	↔	↔	–	↔	↔	↔	–	↔	↓	↔	↔	↓	Kolling et al. (2018)
Cinnamaldehyde, eugenol, capsicum oleoresin* [Unspecified]	Cow	42	1 g/d	↔	↔	↔	↔	↔	↔	↔	↔	–	↔	–	–	↔	–	Martins et al. (2023)
Cumin seed* [*Cuminum cyminum*)	Goat	32	12.7 or 25.3 g/DMI	↔	↓	↓	↓	–	↑	↑	↑	↔	↑	–	–	↑	–	Miri et al. (2013)
Eugenol* [Unspecified]	Cow	28	0.025, 0.05 or 0.075 g/kg	↔	↔	↔	↔	↔	↔	↔	↔	–	↔	↔	↔	↔	↔	Benchaar et al. (2015)
Condensed and Hydrolyzable tanninʹ [Unspecified]	Ewe	42	10 g/kg	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	Toral et al. (2011)
[*Aloe vera*]ʹ	Goat	100	20 or 40 g/kg	↓	↓	↓	↓	–	–	↑	↔	–	↑	–	–	↑	–	Banakar et al. (2023)
Condensed tanninʹ [Quebracho]	Ewe	35	100 g/kg	↔	↔	↔	↓	–	–	↓	↔	–	↔	↔	↔	↔	↔	Lobón et al. (2019)
Thymol & capsaicinʹ [Thyme & chilli pepper]	Ewe	84	2 ml/d	↔	↔	↓	↔	–	–	↑	↔	↔	↔	–	–	↔	–	Kholif et al. (2018)
Hydrolyzable tanninʹ [Chestnut (*Castanea sativa* Miller)]	Ewe	43	52.8 g/kg + Pasture	↔	↔	↔	↔	↔	↔	↔	↑	↔	↔	–	–	↔	–	Buccioni et al. (2017)
			52.8 g/kg	↓	↓	↓	↓	↔	↑	↓	↔	–	↑	–	–	↑	–	Buccioni et al. (2015)
Condensed tanninʹ [Quebracho (*Schinopsis lorenztii*)]			52.8 g/kg + Pasture	↔	↔	↔	↔	↔	↔	↔	↑	↔	↔	–	–	↔	–	Buccioni et al. (2017)
			52.8 g/kg	↔	↓	↓	↓	↔	↑	↑	↑	–	↑	–	–	↑	–	Buccioni et al. (2015)
Condensed tanninʹ [Quebracho (*Schinopsis lorenztii*)]	Cow	21	15 or 30 g/kg	↔	↓	↓$^{30g/kg}$	↑	↔	↓	↑	↑$^{30g/kg}$	–	↑	↑$^{30g/kg}$	↑	↑	↑	Henke et al. (2017b)
	Ewe	28	20 g/kg	↔	↔	↓	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↑	Toral et al. (2013)

(*continued on next page*)

Table 7 (*continued*)

Phytochemical [Source]	Animal	Feeding (days)	Dose	Saturated fatty acids				18:1			CLA		*n*3			*n*6		Reference
				12:0	14:0	16:0	18:0	t10	t11	c9	c9, t11	t10, c12	18:3	20:5	22:6	18:2	20:4	
Condensed taninʹ [Quebracho]	Cow	21	10 or 30 g/kg	–	–	↔	↔	↔	↔	↔	↔	↔	↔	–	–	↔	–	Dschaak et al. (2011)
Condensed tanninʹ [*Acacia meansii*]	Cow	28	20 g/d	↔	↔	↔	↔	↔	↔	↔	↔	–	↔	↔	↔	↔	↔	Denninger et al. (2020)
Ferulic acidʹ [Coix seed (*Coix lacryma-jobi* L.)]	Goat	70	1.5, 3 or 4.5 g/kg	$\downarrow^{1.5,\ 3g/kg}$	↓	↑	$^{1.5,\ 3g/kg}\downarrow\uparrow^{4.5g/kg}$	–	–	↔	–	–	↑	↔	↑	↓	↓	Tian et al. (2025)
Capsaicinʹ [Chilli pepper (*Capsicum oleoresin*)]	Cow	28	0.15, 0.3 or 0.6 g/kg	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	–	–	↔	–	Silvestre et al. (2022)
		25	0.25, 0.5, or 1 g/d	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	–	–	↔	–	Oh et al. (2015)
		70	0.3 g/d	↓	↓	↔	↔	↔	↓	↔	↔	↔	–	–	–	↔	–	Martins et al. (2024)
Eugenol & Capsaicin* [Clove *(Syzygium aromaticum) & Capsicum oleoresin*]	Cow	70	0.3 g/d	↔	↔	↔	↔	↔	↔	↔	↔	↔	–	–	–	↔	–	
Citral* [Lemongrass (*Cymbopogon citratus*)]	Cow	35	0.08, 0.16 or 0.24 m/kg BW	↔	↔	↔	↔	–	↔	↔	↔	–	↔	–	–	↔	–	Canaes et al. (2017)
Triterpenoid [Tea]	Cow	56	20, 30 or 40 g/d	↔	↔	↔	↔	–	–	↔	–	–	↔	↔	↔	↔	↔	Wang et al. (2017)
Citation summary of directions of effects	Neutral (↔) effects			20	21	21	22	17	16	19	19	13	18	10	10	20	8	
	Negative (↓) effects			8	7	7	6	0	2	2	0	0	0	1	0	4	5	
	Positive (↑) effects			0	0	1	2	0	3	8	5	0	9	1	2	5	2	
Total number of citations				28	28	29	30	17	21	29	24	13	27	12	12	29	15	

*: Essential oil; †: flavonoid; ʹ: polyphenol; ɣ: organosulfur; m: months; (↔): no significant effect; (↑): significant increase; (↓): significant decrease; (–): not reported.

extracts, but not with a 3 g/kg DM dose. Inclusion of 3.4 g/d of *Allium mongolicum* Regel extracts in lamb diets also increased WHC of meat (Yaxing et al., 2021).

On the one hand, feeding 1 or 1.5 g/kg DM of *C. sativa* tannin extracts to bulls (Mergeduš et al., 2022) and 2.8 or 3.4 g/d *A. mongolicum* extracts to lambs (Ding et al., 2021) reduced drip loss. On the other hand, feeding 0.13 or 0.26 g/d of oregano extracts to steers (He et al., 2023) and 0.011, 0.022 or 0.033 g/kg DM *A. mongolicum* extracts to lambs (Liu et al., 2019) increased drip loss. Regarding cooking loss (CL), *A. mongolicum* (Liu et al., 2024; Yaxing et al., 2021; Zhao et al., 2023) and essential oils from oregano (He et al., 2023) lowered water losses during cooking of meat from ruminants. Conversely, feeding essential oil extracted from *Copaifera spp* (Moura et al., 2017), *A.mongolicum* (Liu et al., 2019; Soldado et al., 2024) and CTs from *Cistus ladanifer* L (Guerreiro et al., 2020) to lambs or CTs from *A. mearnsii* (dos Santos et al., 2024) to bulls increased CL. Although half of the studies reported no discernible effect, a lack of sufficient and consistent research on the impact of DPEs on water retention in ruminant meat makes it difficult to draw definitive conclusions about their efficacy and mechanisms of action.

3.2.3. Meat shear force

Shear force (SF) is widely recognized as a standard method for assessing meat tenderness, which can vary due to several intrinsic factors such as sex, age and breed, as well as extrinsic factors including breeding, feeding and slaughter practices and post-mortem handling (Hopkins and Ertbjerg, 2023). The reviewed DPEs appear to have varying effects on meat shear force (SF) values (Table 2). Most studies (29 of 40citations) investigating the impact of DPEs on meat SF reported no significant impact (Table 2). However, studies reporting significant effects show a trend towards reductions (7 citations) in meat SF rather than increases (4 citations). To exemplify, feeding HTs or CTs reduced SF in meat from lambs (dos Santos et al., 2022b; Ma et al., 2024; Wang et al., 2023), bulls (dos Santos et al., 2024; Silva et al., 2024) and goats (Tian et al., 2022). In contrast, addition of CT and HT extracts from *A. mearnsii* (Costa et al., 2021), *Schinopsis spp.* and *C. sativa* (Castro-Pérez et al., 2021) to lamb diets increased meat SF values. On the one side, supplementing essential oils from different plant extracts reduced meat SF, as evidenced by findings from Ortiz-Heredia et al. (2023), Yaxing et al. (2021) and Zhao et al. (2023) in lambs, Liu et al. (2024) in calves and de de de Oliveira Monteschio et al., (2017)) in beef aged for 14 days. On the other side, an increase in meat SF was found when supplementing a mixture of essential oils to steers (Mottin et al., 2022) and bulls (Fugita et al., 2018) or *A. mongolicum* extracts to lambs (Liu et al., 2019). However, all ten of the reviewed studies evaluating the impact of DPEs on meat aging found neutral effects (Table 3).

The impact of essential oils and polyphenols on meat SF is likely linked to their influence on fat metabolism, muscle oxidative stress, postmortem proteolytic and collagenolytic enzyme activities. Polyphenols have been suggested to enhance antioxidant activity of the muscle (Silva et al., 2024; Wang et al., 2023), activate caspase-3 promoting apoptosis (Kemp et al., 2006; Wang et al., 2023) or reduce profibrogenic cytokine stimulating collagen production (Seymour et al., 2010; Zhao et al., 2018), thereby reducing meat SF. Nonetheless, they have also been postulated to increase meat SF by inhibiting calpains (Ma et al., 2009) and collagenase matrix metalloproteinases (Islam et al., 2025; Ronsisvalle et al., 2020; Sin and Kim, 2005), which respectively break down meat myofibrillar protein structure and intramuscular connective tissue. Taken together, these findings suggest that the effects of essential oils and polyphenols on meat tenderness depend on their dose-dependent modulation of oxidative status and post-mortem proteolytic activities. Future studies would benefit from explicitly testing mechanistic hypotheses linking specific bioactive phytochemical compounds, antioxidant and proteolytic enzyme activity, and structural-functional protein turnover in muscle under defined dietary and metabolic conditions.

3.2.4. Meat proximate composition, vitamins and minerals

In general, the impact of DPEs on the chemical composition of meat appears largely neutral (Table 2). However, 8 of the identified studies found that DPEs intake increased the content of intramuscular fat (IMF). For example, relatively low inclusion levels of essential oil increased the proportion of muscle fat when lambs or steers were fed extracts from *Oregano onites* (Ünlü et al., 2022), blends of essential oils (Wandscheer et al., 2024; Wang et al., 2020a, 2020b) or *A. angolicum* (Liu et al., 2024; Yaxing et al., 2021; Zhao et al., 2023). Feeding low levels of HTs (Ma et al., 2024) or CTs extracts (Brunetto et al., 2024) also increased IMF content of ruminant meat. The mechanisms by which essential oils and polyphenols may improve IMF in ruminants are not yet fully understood. However, they could positively influence carbohydrate and lipid metabolism in the rumen, potentially leading to increased energy efficiency and IMF deposition (Kholif and Olafadehan, 2021; Singh et al., 2024; Vasta et al., 2019).

Since fat and water content are inversely related in meat (Warner, 2024), a reduction of moisture proportion has also been observed in beef from steers supplemented with essential oils (Wang et al., 2020b, 2020a). While some results, like those by Fugita et al. (2018) and García-Salas et al. (2022) reported increases, the consensus (39 of 41 citations) is that DPEs do not significantly affect the protein content of ruminant meat. With respect to ash content, a majority of studies (31 of 33 citations) also found no significant changes when supplementing DPEs, except for García-Salas et al. (2022) and Silva et al. (2024), who noted a decline.

Despite the crucial role of vitamins in meat for both nutritional value and oxidative shelf life, very few studies (Jacondino et al., 2022; Muíño et al., 2014; Smeti et al., 2021) have investigated the content of vitamin E (tocopherol) in ruminant meat. These pioneering studies suggest that dietary polyphenols or essential oils have no significant impact on the tocopherol contents in the meat of lambs or kids. Interestingly, in a study by Valenti et al. (2019), where three different tannin extracts were included at the level of 40 g/kg DM, only the extract from *Caesalpinia spinosa* (tara) increased the content of γ-tocopherol in meat, whereas *A. mearnsii* and *C. sativa* extracts had no effect. These findings underline that even within the same class of phytochemicals (i.e., polyphenols), the deposition of tocopherols in meat can vary depending on the plant source. While research highlights the role of dietary polyphenols, essential oils and minerals in ruminant nutrition, oxidative status and meat quality (Ponnampalam et al., 2022), there is a scarcity of specific studies exploring how individual phytochemical compounds directly influence the levels of antioxidant minerals like selenium and zinc in ruminant meat.

3.2.5. Meat fatty acid composition

Fatty acids (FA) in meat can derive either from the direct absorption of dietary lipids in the digestive tract, and their subsequent deposition to muscle tissues, or from *de novo* synthesis in adipocytes starting from substrates such as carbohydrates, volatile fatty acids (VFA) or proteins (López-Bote, 2017). In ruminants, dietary FA are extensively modified in the rumen through microbial processes such as lipolysis, isomerization and saturation. Rumen microorganisms are also capable of synthesizing FA, particularly odd- and branched-chain FA. As a result, the FA profile of ruminant meat can differ significantly from that of the ingested diet, due to both the extent of rumen biohydrogenation (BH) and the microbial FA synthesis. Furthermore, both dietary and *de novo* FA can undergo desaturation and elongation processes in body tissues by specific enzymes (Shingfield et al., 2013; Vahmani et al., 2020). Dietary phytochemicals can potentially interfere with rumen BH (Frutos et al., 2020; Toral et al., 2013; Vasta and Luciano, 2011) or other endogenous metabolic processes, thus influencing meat FA composition.

Although several FA are commonly detected and quantified in ruminant meat, only a limited number are considered relevant to human health and therefore receive greater scientific attention. Accordingly, this review examined the effect of DPEs on selected individual FA or classes of FA such as saturated FA (SFA), conjugated linoleic acids (CLA) and omega(n)-3 and n-6 polyunsaturated FA that influence human health (Table 4). Majority of the identified studies (80 %) reported no effects of DPEs on meat FA profile. However, some studies have demonstrated the ability of essential oils (He et al., 2023; Wandscheer et al., 2024), polyphenols (Cimmino et al., 2018; Rana et al., 2012; Tian et al., 2022) and organosulfur compounds (Yaxing et al., 2021) to reduce the content of SFA in ruminant meat. Similarly, there is some evidence that health-enhancing unsaturated FA (UFA) content in meat can be increased by supplementing ruminants with essential oils (Dias Junior et al., 2023; Ma et al., 2023; Smeti et al., 2018) or polyphenols (Costa et al., 2021; dos Santos et al., 2024; Tian et al., 2022). This is because the most abundant polyunsaturated FA (PUFA) in the primary feedstuff, linoleic acid (LA; c9,c12–18:2) or α-linolenic (ALA; c9,c12,c15–18:3), partially escapes ruminal BH and are absorbed as such. This is evident from Table 4, which shows that studies reported that DPEs increased LA (10 of 54) and ALA (5 of 53) contents in meat. A possible explanation might lie in the ability of the DPEs to inhibit lipolysis and microbial BH activities in the rumen (Frutos et al., 2020; Vasta and Luciano, 2011) and thus a greater amount of PUFA are not fully converted into SFA.

Regarding BH intermediates, the effect of DPEs on the content of *trans*(t)-vaccenic acid (TVA; t11–18:1) and rumenic acid (RA; c9, t11–18:2) remains less clear, with most studies (TVA: 23 of 30 and RA: 25 of 31) reporting no effects. Of those showing changes, RA (6 citations) and TVA (5 citations) contents were observed to increase, while only 2 studies reported a decline in TVA (Table 4). The specific causes of these conflicting results are not clear and warrant more research. They could derive from differences in composition, chemical nature and source of phytochemicals, basal diet, dosage, time on feed, animal factors (e.g., species, breeds or age) and their interactions (Ahmed et al., 2025; Morales and Ungerfeld, 2015). Overall, it appears that DPEs have a minor positive influence on the FA profile of ruminant meat, reducing SFA and increasing PUFA. However, their impact on TVA and RA contents is minor and inconsistent. Further research is crucial to identify specific essential oils and polyphenols that effectively enhance meat FA profiles and optimize their application in ruminants. Such research should focus on understanding how individual essential oils and polyphenols influence rumen fermentation and lipid degradation and interact with the diet and animal factors, ultimately affecting the digestion-absorption process and FA composition of meat. This could aid in delivering definitive recommendations for enriching ruminant meat with health-enhancing FAs.

4. Milk yield and quality

4.1. Feed intake, milk yield and composition

Dry matter intake of dairy ruminants is dependent on various factors, including physical properties of the diet, feed allocation, access and digestibility of feed. Of the 78 studies investigating the effect of DPEs on DMI, 69 showed no change (Table 6). The impact of DPE on DMI is therefore relatively limited, with only 5 studies reporting an increase in DMI and 4 reporting a decrease. The increase or decrease on DMI may be associated with levels of individual compounds or their combination present in the diet and this area warrants more research. The impact of DPE on DMI is, therefore, relatively limited, with only 6 % of the studies reporting an increase in DMI and a similar proportion showing a decrease. Two studies where DPEs (Radix Bupleuri and Capsicum) were investigated in relation to heat stress abatement showed an increase in DMI, indicating that better heat mitigation encouraged feed intake (Pan et al., 2014; Vittorazzi et al., 2022). An increase in DMI should be linked to an increase in DM digestibility, possibly due to modulation of the rumen microbiome reported by Vittorazzi et al. (2022). The decrease of DMI in response to DPEs supplementation has been associated with a decrease in palatability, especially for CTs (*C. sativa* and *Schinopsis spp*) due to astringency (Aguerre et al., 2016; Dschaak et al., 2011). Furthermore, a delayed response to tea saponin supplementation suggests that a longer adaptation period should be implemented to ensure adaptation and limited impact on DMI and milk yield (Wang et al., 2017). Cantet et al. (2023) supplemented cinnamaldehyde with or without garlic oil, both resulting in a decrease in DMI. However, the lower DMI did not affect the energy status of dairy cows. The same authors suggested that rumen fermentation was altered, possibly resulting in increased digestibility for treatment groups. Although current studies provide valuable but limited insights, further controlled research with feeding of individual compounds or specific groups of dietary phytochemicals is crucial to understand the specific mechanisms by which DPEs influence DMI and to optimize their practical application in ruminant feeding strategies.

Milk yield should not be considered alone, but rather in relation to production efficiency and milk composition. Of the 80 studies included, 14 resulted in an increase in milk yield and only 3 resulted in a decrease in milk yield. Most studies found no impact on the content of milk fat, protein, lactose and somatic cell counts (SCC). Specifically, 9 studies showed an increase in milk fat content, and 2 reported a decrease. A similar trend is observed for protein content, with 4 reporting an increase and 2 reporting a decrease. For lactose content, 3 studies showed an increase, while a similar proportion found a decrease. Concerning SCC, only 1 study indicated an increase, 7 studies reported a decrease and a significant proportion of the studies (23) did not report any data.

Only three studies reported reductions in milk yield when supplementing DPEs. Griffiths et al. (2013) found an increase in faecal nitrogen output, indicating a reduction in protein digestibility because of *A. mearnsii* CT supplementation, possibly resulting in less metabolizable protein to support milk production. Wang et al. (2017) supplemented tea saponins (40 d/day) and noted a decrease in DMI, which could have led to a reduction in milk yield. Gessner et al. (2015) and Elcoso et al. (2019) both reported a delayed response to DPEs supplementation (coriander blend and grape seed, grape marc extract), with changes in milk yield only seen after two and three weeks of supplementation, respectively. In addition to a delay in production output, it has been postulated that the supplementation of DPEs (citrus peel) alters the rumen microbial profile and increases volatile fatty acid (VFA) production (Ju et al., 2024). However, few studies have measured these parameters concurrently with milk yield and composition.

The increase in milk fat content observed when feeding DPEs, particularly essential oils (citrus, anethole, carvacrol, eugenol and thymol; El-Essawy et al., 2021; Ju et al., 2024; Santos et al., 2010) and saponins (triterpenoid; Wang et al., 2017) to dairy ruminants is likely due to their impact on the rumen microbial population, carbohydrate and lipid metabolism. Specifically, essential oils and saponins may positively influence rumen microbial populations and their activity, leading to increased production and absorption of acetate, the primary precursor for milk fat synthesis in ruminants (El-Essawy et al., 2021). In addition, an increase in ADF digestibility and rumen pH was also reported, however, no changes in VFAs were noted (El-Essawy et al., 2021). They may also influence BH in the rumen, potentially increasing the absorption and deposition of UFA in the mammary gland, which are then used for milk fat synthesis and/ or its regulation (Hassan et al., 2020; Morales and Ungerfeld, 2015; Yu et al., 2024). The use of DPEs (Radix Bupleuri) supplementation to mitigate heat stress reported changes in energy partitioning, away from homeothermy to production. This may have led to an increase in milk protein yield (Pan et al., 2014). Further research into the optimal dosages of essential oils and saponins, as well as the changes in rumen VFA composition, could be crucial for enhancing milk component synthesis in ruminants.

4.2. *Vitamins and minerals composition of milk*

The research on vitamin and mineral content of milk has focused on animal requirements to ensure animal health and productivity (Weiss, 2017). The mineral content in milk shows minor variation in response to diet changes, due to the mineral reservoir characteristic of the skeletal structure (Timlin et al., 2021). For this reason, the mineral content of milk is not typically investigated in standard nutrition trials, much less in trials investigating DPEs supplementation. In a study by Vizzotto et al. (2021) *O. vulgare* and green tea extracts were supplemented to dairy cows over a period of 21 days, despite daily variations, overall calcium content did not differ between treatments.

Fat-soluble vitamins (except vitamin K) are more significantly influenced by diet type, especially linked to increased intake of carotenoids, which are typically higher in fresh forages (Timlin et al., 2021). Water-soluble vitamins are highly dependent on the functionality of the rumen, as they are primarily synthesized by microbes, but correlations with dietary intake have been identified (Timlin et al., 2021). Despite the possible manipulation of vitamin content in milk and the added health benefits for human consumption, there are few, if any standard nutrition trials that analyze for this nutrient. As it is possible to manipulate the vitamin content of milk, further research is valuable, especially where DPEs alter the rumen microbiome profile, potentially increasing synthesis of water-soluble vitamins.

4.3. *Physical quality of milk*

The physical appearance of milk, especially colour is a significant factor in consumer purchasing decisions, as it provides an immediate impression of a product's freshness, flavour and overall quality (Altmann et al., 2023). The opaque white colour of milk is a result of light scattering by tiny particles of finely dispersed fat globules and casein protein micelles (Nozière et al., 2006). It is primarily assessed to manage technological parameters such as fat levels, thermal treatment, homogenization, photodegradation, storage conditions and presence of additives and contaminants (Conboy Stephenson et al., 2021; Nozière et al., 2006). The L* value is affected by milk physical structure, which in turn is influenced by proximate composition, temperature and technological treatments (Conboy Stephenson et al., 2021; Nozière et al., 2006). The a* and b* values are largely affected by animal and dietary factors linked to the concentration of natural pigments (i.e., riboflavin and carotenoid) in milk (Conboy Stephenson et al., 2021; Nozière et al., 2006). For example, feeding cows carotenoid-rich forages, particularly fresh grass, results in milk with an intense yellowish coloration (higher b* value), which serves as a biomarker for pasture-based production systems (Conboy Stephenson et al., 2021; Nozière et al., 2006).

To the authors' knowledge, there are hardly any studies that have assessed the impact of DPEs on the coloration of ruminant milk. The scarcity of studies on the colour of ruminant milk is mainly attributed to subtle variations of its inherent colour and the common practice of storing and selling milk in non-transparent packaging (Altmann et al., 2023). Future studies ought to investigate how supplementing ruminants with pigmented phytochemicals such as carotenoids (yellow) and anthocyanins (red, purple or blue) affects milk colour and consumer acceptance. Besides influencing visual appearance, these pigmented phytochemicals could play a role in enhancing oxidative shelf life and sensory quality of milk, and improve human health through their antioxidant, anti-inflammatory, and immunomodulatory properties (Tian et al., 2022; Tian and Lu, 2022).

The pH of raw milk from ruminants that typically ranges from 6.6 to 6.8 is another key indicator of freshness and overall quality. The pH of milk is related to the mineral and protein content of milk, as well as the SCC (Kasapidou et al., 2023; Timlin et al., 2021). Few nutritional studies consider milk pH, unless they are directly looking at processability of milk. Vizzotto et al. (2021) reported a tendency for decreased milk pH in cows fed *O. vulgare* extract. However, this was suspected to be due to the lower SCC, changing the permeability of the mammary gland, and it was within the acceptable range. Further research is required to confirm if individual phytochemical compounds directly affect the pH of raw milk from ruminants.

4.4. Fatty acid composition of milk

The FA composition of milk is of particular interest to processors, as the FA profile affects the quantity and quality of manufactured milk products (McCarthy et al., 2024). Polyunsaturated FA have long been recognized for their positive effect on human health (Mititelu et al., 2025) and their close link to polyphenols has been researched widely. Where changes in FA composition were observed in response to DPEs supplementation (Table 7), these were seen in an increase in PUFA content in milk, with positive implications for human health. It has been suggested that DPEs decrease the rate of BH in the rumen, thereby allowing greater PUFA uptake into the mammary gland (McCarthy et al., 2024; Valenti et al., 2025). However, the mechanism of action by which individual DPEs alter the rate of BH remains a research gap, with potential alternatives, such as selective microbial enzyme activation and changes in the rumen microbiota composition, abundance and diversity (McCarthy et al., 2024; Vasta et al., 2007). Generally, the effect of DPE supplementation in ruminants was neutral for milk oleic acid (19 of 29), ALA (18 of 27), and LA (20 of 29). Of interest, the decrease in oleic acid and LA were only observed in ewes and goats, respectively. The ewes were fed quebracho CTs (100 g/kg, Lobón et al., 2019) and chestnut HTs (52.8 g/kg, Buccioni et al., 2015). The goats received 2 ml/d of essential oils blend (anethol, eugenol, thymol and cumin seeds; El-Essawy et al., 2021) and polyphenols (i.e., 4.5 g/kg of ferulic acid, coix seed; Tian et al., 2025). Although these results may be species-specific, the tannin inclusion level for the ewes exceeded the recommended limit of < 40 g/kg DM (Al Rharad et al., 2025; Orzuna-Orzuna et al., 2023). Further investigations is important to establish if these results are dependent on phytochemical type, dose, species or their interactions. Overall, SFAs were reported to be neutral (21 of 28) or decreased (7 of 28) with DPE inclusion. The results for polyphenol compounds were more variable, however, the supplementation of CTs (*S. lorenztii*) and HTs (*C. sativa*) resulted in an increase in PUFA, specifically rumenic acid, LA and ALA (Buccioni et al., 2017, 2015; Henke et al., 2017b). More research into the response of rumen to DPEs supplementation is important to establish their impact on BH and the potential for improving milk quality for human consumption.

5. Antioxidant activity and shelf life of meat and milk

5.1. Activity and shelf life of antioxidants in meat

Phytochemicals have been suggested to exert antioxidant benefits and are generally bioavailable throughout the animal's system (Piao et al., 2023; Semwogerere et al., 2020). Antioxidant phytochemicals can play a crucial role in enhancing the immune capacity of animals, alleviating oxidative stress and inflammation, and prolonging the oxidative and microbial shelf life of the resultant product, including meat and milk (Pena-Bermudez et al., 2020; Piao et al., 2023; Wandscheer et al., 2024). Phytochemicals, including essential oils, polyphenols, saponins and organosulfur compounds, have been reported to exert antioxidative functions through several mechanisms, which include inhibiting lipoxygenase, activating antioxidant enzymes, scavenging free radicals, donating electrons to free radicals, quenching singlet oxygen and/ or chelating prooxidative metals (Piao et al., 2023; Santhiravel et al., 2022).

While the bioavailability of phytochemicals in diet, intestines, serum, and meat is well-documented (Gao et al., 2024; Soldado et al., 2024; Tang et al., 2024), studies specifically evaluating their transfer efficiency into animal tissues and edible products are limited. Out of the 21 identified studies that reported on the effect of supplementing DPEs to ruminants on meat antioxidant activity, 13 that mostly supplemented essential oils and polyphenols indicated an enhancement (Table 2). However, only 2 of the identified studies assessed antioxidant shelf life in ruminant meat (Table 3) and found neutral (Mottin et al., 2022) or positive (Rivaroli et al., 2020) effects. The variation in the study outcomes regarding antioxidant activity and extended shelf-life in ruminant meat is complex and influenced by multiple interacting variables including type, dosage and bioavailability of the phytochemical, dietary and animal factors, assay type and storage conditions such as display period, packaging atmosphere, temperature and lighting, which merit further investigation.

Table 2 shows that antioxidant activity was largely assessed through ferric reducing antioxidant power (FRAP), Trolox equivalent antioxidant capacity (TEAC), 2,2′-azinobis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) and/ or 2,2-diphenyl-1-picrylhydrazyl (DPPH; Aouadi et al., 2014; de de de Oliveira Monteschio et al., 2017; Muñoz-cuautle and Herrera-haro, 2022). However, some studies used reactive oxygen species (ROS; Wandscheer et al., 2024), antioxidant enzymes (i.e., glutathione, catalase, and peroxidase) activity (Tian et al., 2022) or the content of phytochemicals (e.g., tocopherols, polyphenols or their metabolites; Kearney et al., 2025) in meat as proxy measures for antioxidant activity. These studies concluded that the increase in antioxidant activity was reflective of the phytochemical content in meat resulting from the diet. Nonetheless, the number of studies evaluating the effect of phytochemical supplementation on meat antioxidant activity is insufficient to draw definitive conclusions regarding their overall impact due to high variability in phytochemical sources, methodological evaluation inconsistencies across studies and the complex interplay of various pre- and post-mortem factors.

5.2. Activity and shelf life of antioxidants in milk

The transfer of dietary natural antioxidants into milk is a significant area of research, as it offers a means to enhance milk's nutritional value and boost its antioxidant capacity, thereby extending its shelf life and improving its health benefits for consumers. Though limited studies have investigated these parameters in milk from animals fed DPEs, Cohen-Zinder et al. (2025) reported an increase in milk antioxidant activity of goats fed moringa silage that had a high concentration of flavonoids and phenolic acids. This suggests a potential transfer of DPEs into milk, thereby enhancing antioxidant activity, which indicates potential future applications warranting further investigation. The benefits of increasing antioxidant capacity in raw and processed milk products are promising, offering consumers a healthier product with a longer shelf life (Kasapidou et al., 2023; Ponnampalam et al., 2022).

Of note, knowledge gaps persist in understanding how dietary phytochemicals are incorporated into ruminant edible products (i.e., meat and milk) and how this influences their long-term antioxidant efficacy within these matrices. It is strongly recommended to use multiple antioxidant assays when evaluating the antioxidant activity and shelf life of phytochemicals in animal feed, tissues, meat and milk. This is because phytochemicals exhibit multiple and diverse antioxidant mechanisms primarily through electron and hydrogen atom transfer (Piao et al., 2023). Thus, multiple assays are inevitable to capture the various antioxidant mechanisms, phytochemical specificity, reaction conditions and matrix effects that no single test can fully represent and understand the complex effects. Thus, it provides a more accurate, comprehensive, and reliable assessment of antioxidant activity within complex biological systems, such as milk and meat matrices. Further research should also investigate the relationships between antioxidant assays and long-term efficacy of individual phytochemical compounds in meat and milk matrices, offering valuable insights into their underlying mechanisms of action.

5.3. Oxidative stability of meat and milk

5.3.1. Meat colour and myoglobin oxidation

Meat colour is of ultimate importance to consumers and a main determinant of freshness at the point of purchase. The bright cherry-red colour is strongly associated with the freshness of meat. This colour is primarily dictated by the content and oxidative state of myoglobin, and objectively quantified by the CIE Lab* colour system, which includes lightness (L*), redness (a*), chroma (C*), and hue angle (h*) coordinates (King et al., 2023). As the retail display time progresses, metmyoglobin dominates the meat surface, which decreases the redness while the increasing myofibril degradation allows more light to disperse through the meat matrix, resulting in increased lightness (King et al., 2023). This is perceived as undesirable discoloration of meat by consumers. Only two studies evaluated myoglobin oxidation (Table 2) in meat from ruminants fed DPEs, with one showing positive effects (Biondi et al., 2019) and the other negative effects (Tabke et al., 2017). In both studies, the authors did not attribute the differences in myoglobin oxidation directly to DPEs supplementation.

Most of the reviewed studies (~90 %) concurred that DPEs had no effect on colour coordinates (L*: 47 of 54; a*: 51 of 54; b*: 48 of 53) of fresh ruminant meat (Table 2). However, one study showed a decline in L* (Torrecilhas et al., 2021), while six studies noted increases in L* when supplementing essential oils (Garcia-galicia et al., 2020; Wang et al., 2020b, 2020a) or polyphenolic extracts (Castro-Pérez et al., 2021; Costa et al., 2021; Guerreiro et al., 2020; Liu et al., 2016). Only three of the reviewed studies showed a significant impact of DPEs on a*, with Costa et al. (2021) reporting a decrease, whereas Rivaroli et al. (2016) and Garcia-galicia et al. (2020) indicated an increase. For b*, one study reported a decrease (Güney et al., 2021) whereas four studies showed an increase (dos Santos et al., 2022b; Garcia-galicia et al., 2020; Liu et al., 2016; Pena-Bermudez et al., 2022). Again, none of these studies linked the variations in meat colour indices directly to DPEs. The increase in L* was ascribed to low meat pH_u, resulting in myofibril shrinkage and/ or degradation, while the decreases in a* and b* were attributed to an increase in meat metmyoglobin content.

Table 3 presents effects DPE on myoglobin and colour stability of ruminant meat. Only three studies investigated myoglobin stability and reported neutral effects (Biondi et al., 2019; Pena-Bermudez et al., 2022; Tabke et al., 2017). While a few studies demonstrated a decline in L* (Ortuño et al., 2015, 2014) and b* (dos Santos et al., 2022b; Maggiolino et al., 2020; Ortuño et al., 2014; Smeti et al., 2021) values, and an increase in a* values (Ortuño et al., 2014) over time in meat from ruminants supplemented with DPEs, most studies (17 out of 20) showed no significant changes in colour or shelf life. While most studies suggest a neutral impact of DPE on fresh colour, myoglobin status and their stability in ruminant meat, there is a noticeable data scarcity and variability, which potentially limit application of these findings. Moreover, it is a known phenomenon that the presence of phytochemicals such as essential oils and polyphenols in meat can have a direct influence on its myoglobin status and stability. This because is largely attributed to their antioxidant properties, which can inhibit the oxidation of myoglobin, thereby preserving the desirable red colour of fresh meat and improving its shelf life. The fact that none of the reviewed studies attributed myoglobin state and stability changes to DPEs, highlights potential areas for further investigation.

5.3.2. Oxidative stability of lipids in meat

It is well established that lipid oxidation in meat is regulated by the complex balance between antioxidants, prooxidants and composition of biomolecules (i.e., lipids, proteins, pigments and cholesterol) in meat (Ponnampalam et al., 2022). Lipid oxidation secondary compounds, particularly malondialdehyde, are often estimated using the thiobarbituric acid-reactive substances (TBARS) through colorimetric or fluorometric analysis. Fifty-one studies assessed the impact of DPEs on lipid oxidation in ruminant meat within the reviewed period (Table 2). Of these, 38 found no effect, while 11 indicated reductions and 2 reported increases in lipid oxidation in ruminant meat. Specifically, supplementing ruminant diets with extracts rich in essential oils such as 1,8 cineole (Al-Obaidi et al., 2021), carvacrol (Muñoz-cuautle and Herrera-haro, 2022), eugenol (Al-Obaidi et al., 2021), a blend of essential oils (de de de Oliveira Monteschio et al., 2017; Wandscheer et al., 2024) or unspecified essential oils (Smeti et al., 2021) reduced lipid oxidation. Similarly, diets rich in polyphenols, especially diterpenes (i.e., carnosic acid and carnosol; Ortuño et al., 2014), CTs (Biondi et al., 2019; Brunetto et al., 2024; dos Santos et al., 2024) or HTs (Liu et al., 2016) seems to delay lipid oxidation in ruminant meat.

Most of the reviewed studies (31 of 39) show neutral effects of DPEs on lipid oxidative stability in ruminant meat, while 8 reported positive results (Table 3). Again, unspecified essential oils (Smeti et al., 2021) and polyphenols such as diterpenes (Morán et al., 2012;

Ortuño et al., 2015, 2014), CTs (Brogna et al., 2014; Maggiolino et al., 2020) and ferulic acid (González-Ríos et al., 2016) enhanced lipid oxidative stability in ruminant meat. Amidst limited consistency and heterogeneity in phytochemical composition, dosing strategies, basal diets and experimental conditions, essential oils and polyphenols tend to have potential to enhance the lipid oxidative stability of ruminant meat. Evidence suggesting that essential oils and polyphenols can reduce or delay lipid oxidation in ruminant meat is linked to their previously mentioned antioxidant properties. Though it is currently challenging to give precise indications on the type of phytochemical or dose to be used, as many other factors interfere with the outcome (e.g., plant source, bioactive compound, animal species, amount ingested and basal diet), this deserves further evaluation.

5.3.3. *Oxidative stability of proteins in meat*

Over the last three decades, research has increasingly highlighted the significant role of protein oxidation (POX) in meat deterioration, alongside the well-established effects of lipid oxidation and microbial spoilage. Protein oxidation is a covalent modification of proteins in food system that can occur *in situ* (autooxidation) or during handling, processing and storage (Xiong and Guo, 2020). This modification is propagated through direct attack of reactive oxygen and nitrogen species, as well as through indirect reaction with oxidative byproducts of lipids and sugar (Domínguez et al., 2022). Subsequently, it manifests as amino acid side chain modifications (e.g., protein carbonyls and protein hydroperoxides), cleavages of peptide bonds and the formation of covalent intermolecular cross-linked protein derivatives (e.g., disulfides and dityrosine; Soladoye et al., 2015; Zhang et al., 2013). All this results in physicochemical, techno-functional and nutritional alterations of proteins and hence, changes in meat sensory and overall quality (Lund et al., 2011).

During the period under review, only six studies explored the impact of DPEs on POX in ruminant meat using the protein carbonyl assay (Table 2). Among these studies, Wang et al. (2023) fed *C. sativa* extracts high in HTs and recorded a reduction in POX, whereas Muíño et al. (2014) fed red wine extracts high in flavanols and found an increase in POX. However, the remaining studies feeding polyphenolic extracts, including diterpenes (Ortuño et al., 2014), CTs (dos Santos et al., 2022b) or HTs (Pena-Bermudez et al., 2020) showed no impact. Regarding protein stability in terms of accumulation of the undesired carbonyls in meat (Table 3), half of the studies (4 of 8) observed a longer protein shelf life when feeding diets containing extracts rich in diterpenes (Ortuño et al., 2014, 2015) and HTs (Wang et al., 2023; Maggiolino et al., 2020) than the control. The rest of the studies did not find significant changes in protein stability when supplementing polyphenol extracts in ruminant diets (dos Santos et al., 2022b; Muíño et al., 2014; Pena-Bermudez et al., 2020; Morán et al., 2012). Although there is limited evidence suggesting that DPEs may limit POX in meat, the lack of consensus in the literature and the low number of studies necessitate further research to establish optimal levels of DPE for different animal species and meat storage conditions.

5.3.4. *Oxidation and shelf life of lipids and proteins in milk*

The oxidative stability of lipids and proteins in milk is of importance for the processability and shelf life of raw and processed milk products. Extensive research has been carried out on the application of various phytochemicals postharvest, with several reviews available (García-Lomillo and González-SanJosé, 2017; Kurćubić et al., 2024; Lobo et al., 2010; Lopes et al., 2025; Salehi, 2021; Zagoskina et al., 2023). No studies were identified in which DPEs were fed to dairy ruminants, and oxidation and shelf life of lipids and proteins in milk were measured, indicating a significant research gap.

5.4. *Microbial safety and shelf life of ruminant edible products*

The antimicrobial properties of DPEs have been proven in the meat livestock industry through their ability to regulate gut microbiota by selectively suppressing the growth of pathogenic and storage spoilage microbes while enhancing the proliferation of the rumen beneficial ones (Burt, 2004; Wang et al., 2024). Evidence demonstrating the transfer of antimicrobial properties from DPEs into meat is limited. To illustrate, a reduction in spoilage microbes was reported in meat from lambs supplemented with dietary extracts rich in quercetin (Andrés et al., 2013) or *R. officinalis* diterpenes (Ortuño et al., 2015). Essential oils and polyphenols modulate microbial load in meat primarily through direct antimicrobial effects by disrupting bacterial cell structures and metabolism and can have an indirect effects through immune system modulation and changes in gut microbiota (Nastoh et al., 2024; Valenti et al., 2021). Other 3 studies that explored feeding Tara (*Caesalpinia spinosa*) or *Acacia mearnsii* (Biondi et al., 2019), Rosemary leaves (*Rosmarinus officinalis* (Ortuño et al., 2014) and Cinnamon (*Cinnamonum zeylanicum* Simitzis et al., 2014) found no significant differences in either spoilage or pathogenic microbes. The same five studies found that DPEs had no impact on microbial shelf life, except for Biondi et al. (2019), who observed lower counts of spoilage microbes for both Tara and *Acacia mearnsii* diets at 4–7 days of storage compared to the control (Table 3). These 5 studies exhibited wide methodological variation. For example, Ortuño et al. (2015), (2014) stored samples under modified atmospheric packaging, while others simulated retail display conditions. The microbial groups enumerated varied across all studies, and Simitzis et al. (2014) inoculated minced meat from DPE-fed animals with specific microorganisms. Given the limited number of these studies and the wide methodological variability, further research into the responses of ruminant species to individual phytochemical dose levels is crucial for optimizing microbial safety, with special emphasis on the potential mechanisms of action of DPEs that modulate microbial load to extend the shelf life of ruminant meat. To the authors' knowledge, there are limited, if any, studies that have evaluated the impact of DPEs on pathogenic and spoilage microbes in raw milk, this merits investigation.

6. Volatile compounds, sensory profiles and consumer perceptions of ruminant edible products

6.1. Volatile compounds and sensory quality of meat

Meat flavour, a key sensory quality attribute, is a complex mixture of many diverse volatile compounds belonging to various chemical classes, including aldehydes, alcohols, ketones, organic acids, hydrocarbons, esters, ethers, furans, sulfur- and nitrogen-containing heterocyclic compounds (Bleicher et al., 2022; Sun et al., 2022). These volatile compounds are mainly formed through Maillard reactions, Strecker degradation, lipid oxidation and the degradation of carbohydrates, thiamine and nucleotides. The content and composition of volatile compounds are influenced by several pre-slaughter factors such as diet, animal species, breed, age, sex and muscle type, as well as post-slaughter factors like aging, storage conditions and cooking methods (Bleicher et al., 2022; Sun et al., 2022). Although individual or groups of phytochemicals in ruminant diets may influence volatile flavour compounds in meat, their specific effects remain insufficiently characterized (Vasta and Luciano, 2011). Only 6 studies assessed the effect of dietary DPEs on lamb meat volatile compounds during the review period (Table 5). Of these, only two studies supplementing diterpenes extracts from *R. officinalis* reported a decline in volatile compounds in meat, which was attributed to a reduction in lipid and protein oxidation with increasing inclusion levels of DPEs (Morán et al., 2013; Ortuño et al., 2014) while the rest found no significant effects. The main methodological variation among the reviewed studies was the use of raw or cooked meat samples. Although limited in number, most studies indicate that DPEs have no effect on volatile compounds, leaving a gap for further research to validate both the neutral and negative effects of DPEs on meat volatile compounds.

Flavour, tenderness and juiciness are widely recognized as the primary sensory quality attributes determining consumer satisfaction and purchase decisions for fresh meat (de Araújo et al., 2022). Thus, understanding how DPEs impact these sensory attributes could influence acceptance and purchasing of ruminant meat by consumers. During the period under review, thirteen studies examined the influence of DPEs on the descriptive sensory quality of ruminant meat, with the majority finding neutral effects for juiciness (10 of 12 studies), tenderness (11 of 12), flavour (12 of 13) and overall acceptability (9 of 11; Table 5). Only a study by Guerreiro et al. (2020), which fed *Cistus ladanifer* CT extract to lambs, reported a decline in juiciness at a dietary inclusion level of 20.5 g/kg DM. The authors attributed the significant change to dietary tannins altering the pH fall pattern, thus influencing myofibrillar water loss through drip and cooking loss. However, these juiciness results contradict those of Wang et al. (2020b), who fed a blend of essential oil extracts to steers and observed increased beef juiciness and tenderness. The variation in the juiciness results might be ruminant species-related, and this warrants further investigation. *Rosmarinus officinalis* diterpenes (Smeti et al., 2018) have been shown to increase flavour in lamb meat, while meat overall acceptability was increased by supplementing *C. ladanifer* CT extracts to lambs (Guerreiro et al., 2020) and *R. officinalis* diterpenes (Smeti et al., 2018).

The minor differential effects of DPEs on the sensory quality of ruminant meat among the reviewed studies can be ascribed to a combination of confounding factors, including the specific properties of the phytochemicals, animal physiology, post-slaughter processing and methodological limitations. In the context of the current review, sensory quality evaluation typically involved trained panels screened for sensory acuity. Descriptive sensory analysis (DSA) was the most applied methodology, involving structured training, often through ballot and consensus techniques, followed by test-retest data collection (Lawless and Heymann, 2010). Although DSA follows a standard protocol, minor protocol modifications such as changes in muscle type, panel size and training level, storage conditions, ageing and cooking protocols might have resulted in the observed minor differences among the reviewed studies. The overall neutral impact of DPEs on ruminant meat sensory quality is supported by a small data set; hence, additional research is recommended before definitive conclusions can be drawn.

6.2. Volatile compounds and sensory quality of milk

The composition of milk is strongly influenced by feeding practices, with phytochemical-enriched diets potentially contributing to a more favourable balance of bioactive compounds, including polyphenols and essential fatty acids (Linehan et al., 2024). These plant-derived bioactive compounds may contribute to richer milk aromatic profiles by modulating lipid oxidation and enzymatic reactions (Linehan et al., 2024). Unfortunately, few studies have been conducted on the volatile compounds and sensory profiles of milk from animals supplemented with DPEs. It was reported that dietary caraway and organum essential oil treatment during a 25-day feeding trial increased cow milk fresh aroma and flavour and decreased corn aroma, UHT milk aroma, and stored aroma and flavour (Lejonklev et al., 2016). The impact of DPEs on milk's volatile and sensory quality cannot be concluded based on a single study. More so, the DPEs' effects were observed over a short-term duration. Although these results suggest that essential oils do not negatively affect the sensory profile of milk, future research should validate these results. Investigating the long-term impact of supplementing dairy animals with DPEs on milk volatile and sensory quality, as well as its implications for product development in the evolving dairy market could be valuable.

6.3. Consumers' perceptions of ruminant edible products

Meat and milk from animals fed diets rich in essential oils and polyphenols have the potential to enhance flavour and texture profiles, aligning with today's consumer preferences for high-quality dairy and meat products. To the authors' knowledge, only eight studies have evaluated consumers' perceptions of meat from ruminants fed 10 different DPEs, with one focusing on bulls and heifers (Table 5). However, no studies were found on milk. Regarding meat, DPEs only had neutral effects on juiciness (5 out of 5), while many flavour attributes were also neutral (7 out of 10) and the rest were negative. The 13 studies on consumer perception on tenderness and overall acceptability yielded minor contradictory results. Two studies feeding lambs with quercetin (Andrés et al., 2014 and *A. mearnsii* CTs (Costa et al., 2021) reported a negative effect while 3 reported a positive effect. Only 2 studies supplementing heifers with an essential oil blend (Guerrero et al. 2018 and Eugenol, thymol, and vanillin) + Rosemary + clove; de de de Oliveira Monteschio et al., 2020) and the other feeding *A. mearnsii* CTs to goats, had a positive effect (Pimentel et al., 2021).

Overall consumer acceptability was different in only 2 of 13 studies, with one feeding *Sophora japonica* quercetin extracts to lambs showing a negative effect (Andrés et al. (2014) and the other feeding *A. mearnsii* CTs to goats, having a positive effect (Pimentel et al., 2021). Although these studies showed minimal balance among the evaluated species, species-dependent variation as a source of contradictory results cannot be ruled out. Moreover, the wide range of participants (28–155) in the consumer sensory study is noted. With the limited number of studies on the effects of DPEs on consumer sensory quality, high methodological variability and lack of explanations on the mechanisms of action, there is a narrow window for drawing conclusions, but this opens a gap for further investigation.

7. Future directions for research, innovation and adoption

Though the current comprehensive systematic review is not exhaustive, it highlights that the effects of DPEs on ruminant production and product quality remain controversial, largely due to variations in phytochemical composition, dose, form, delivery, and their interactions, as well as differences in diet, rumen microbiota and animal factors. Few studies address safety, mechanisms and transfer efficiency, while many lack precise reporting of phytochemical compounds and application conditions. Nevertheless, current research suggests that essential oils and polyphenols have promising potential for improving productive performance, FA profile, antioxidant and lipid stability, provided that future research applies standardized methodologies and advanced analytical and computational tools to consistently yield reliable results. This includes rigorous statistical designs, adequate animal replication, controlled feeding experiments and validated presentation of results showing the deposition of dietary phytochemicals in animal tissues and their transformation into meat and milk. The claim in some research articles that pastures, fodders, marine products and agriculture by-products from legume crops, wineries, oilseeds or berries have sufficient phytochemicals for ruminant applications is not satisfactory. Validated reports showing *in vivo* studies carried out in small laboratory animals (i.e., mice, rats and rabbits) and large farm animals (i.e., ruminants and monogastrics), showcasing the transformation of individual phytochemical compounds from feeds to animal tissues and their deposition in meat and milk for better animal health or product quality, are important to strengthen reproducibility and avoid misleading conclusions.

Future research on DPEs should use standardized, sustainable recovery techniques that enhance yield, purity and potency (Maddaloni et al., 2025; Mungwari et al., 2025) in conducting large-scale, long-term *in vivo* studies across production systems and different species to optimize application conditions (Mapiye et al., 2025; Ponnampalam et al., 2025). Chronic and acute toxicological assessments should be prioritized to define safe inclusion levels, as some phytochemicals can cause pharmacological effects and poisoning of microbiomes, as well as the host animal. Tailored nanotechnology can be leveraged to enhance phytochemical stability, bioavailability and targeted delivery for ruminant production and product quality enhancement (Gelaye, 2024; Teli et al., 2024). Well-designed whole-farm studies are required to simultaneously capture DPEs' effects on greenhouse gas emissions, animal performance, health and welfare, quality of meat and milk, and consumer acceptability. It is also important to estimate the bioaccessibility potential of individual phytochemicals for human consumption using the INFOGEST *in vitro* model, which simulates gastrointestinal tract digestion (Rasera et al., 2023; Zhou et al., 2023). Detailed molecular and microbiome-level studies are necessary to elucidate mechanisms of action, interactions and dose–response dynamics. Given complex interactions between DPEs, the rumen microbiome, and the host, integrating multi-omics and bioinformatics (Badhan et al., 2025; Omondi et al., 2024), AI and machine learning (Joshi et al., 2024; Varghese et al., 2025; Yu et al., 2024) will be key in identifying optimal compounds, doses and animal factors for customized diet formulations and product fortifications.

Consumer perceptions of meat and milk appearance and sensory quality strongly influence preferences and purchase decisions (Altmann et al., 2023; de Araújo et al., 2022; Schiano et al., 2017). Since DPEs can affect these attributes, it is crucial to assess consumer acceptance before launching products on the market. If DPEs are found to adversely influence meat and milk quality, research to boost consumer acceptance should be prioritized. Given the growing interest in functional foods fortified with bioactive compounds (Rashidinejad, 2024) and the increasing sophistication of food authentication technologies (Saleem et al., 2025). If DPEs enhance meat and milk quality, products could be certified, labeled and sold at a premium value. The combination of spectroscopy with chemometrics, machine learning and AI could offer accurate, rapid and sustainable opportunities for meat certification (Saleem et al., 2025). Life cycle sustainability assessments contrasting DPEs with synthetic additives in ruminant production systems could provide valuable insights into their environmental trade-offs, socio-economic impacts, economic feasibility, scalability and adoption.

Theoretically, using DPEs derived from plant byproducts to enhance ruminant production and product quality aligns with the principles of clean labeling and a sustainable circular economy. Demonstrating positive impacts through evidence-based research coupled with participatory education and awareness campaigns along the ruminant production value-chains could drive the adoption of DPEs and create new agripreneurship opportunities which are appealing to health- and sustainability-conscious consumers. For societal acceptance, innovations must ensure efficacy, safety and sustainability, supported by harmonized regulatory frameworks and policies that safeguard food safety, control the use of genetic resources and indigenous knowledge systems, and promote fair benefit-sharing. A transdisciplinary, value-chain-wide approach, guided by national and/or regional institutions, is essential for managing research, innovation and adoption of DPEs in ruminant production systems.

8. Conclusions

The current comprehensive systematic review generally indicates neutral effects and a lack of studies on safety, mechanisms and transfer efficiency of dietary phytochemicals in ruminant production and product quality. Going forward, it is recommended to optimize application conditions and employ holistic, large-scale and long-term *in vivo* studies in both small laboratory animals and large farm animals to ensure consistently reliable results. Emerging multi-omics, AI and machine learning technologies should be harnessed to customize ruminant diet formulations with DPEs and enhance product fortification. Life cycle sustainability assessments can be conducted to aid understanding of the trade-offs of using DPE-based diets in ruminant production systems. For the rapid, widespread and long-term adoption of the DPE-based diets for ruminant production and product quality enhancement, it could be important to educate value-chain actors, enact harmonized regulations and policies, foster transdisciplinary collaboration and establish institutions that coordinate research and innovation initiatives.

CRediT authorship contribution statement

Olugbenga P. Soladoye: Writing – review & editing, Writing – original draft. **Alessandro Priolo:** Writing – review & editing, Writing – original draft. **Eric N. Ponnampalam:** Writing – review & editing, Writing – original draft, Conceptualization. **Cletos Mapiye:** Writing – review & editing, Writing – original draft, Conceptualization. **Farouk Semwogerere:** Writing – review & editing, Writing – original draft. **Lobke Steyn:** Writing – review & editing, Writing – original draft. **Hasitha Priyashantha:** Writing – review & editing, Writing – original draft. **Nalatello Antonio:** Writing – review & editing, Writing – original draft. **Jeannne Marais:** Writing – review & editing, Writing – original draft.

Consent

The authors have nothing to report.

Ethics statement

The authors have nothing to report.

Funding

No funding was received for this manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors declare that there are no actual or potential conflicts of interest including financial, personal or other relationships with other people or organizations that could inappropriately influence, or be perceived to influence, this work.

Acknowledgments

Nothing to declare.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.anifeedsci.2025.116609.

References

Abulaiti, A., Ahmed, Z., Naseer, Z., El-Qaliouby, H.S., Iqbal, M.F., Hua, G.H., Yang, L.G., 2021. Effect of capsaicin supplementation on lactational and reproductive performance of Holstein cows during summer. Anim. Prod. Sci. 61, 1321–1328. https://doi.org/10.1071/AN20439.

Aguerre, M.J., Capozzolo, M.C., Lencioni, P., Cabral, C., Wattiaux, M.A., 2016. Effect of quebracho-chestnut tannin extracts at 2 dietary crude protein levels on performance, rumen fermentation, and nitrogen partitioning in dairy cows. J. Dairy Sci. 99, 4476–4486. https://doi.org/10.3168/jds.2015-10745.

Aguerre, M.J., Duval, B., Powell, J.M., Vadas, P.A., Wattiaux, M.A., 2020. Effects of feeding a quebracho–chestnut tannin extract on lactating cow performance and nitrogen utilization efficiency. J. Dairy Sci. 103, 2264–2271. https://doi.org/10.3168/jds.2019-17442.

Ahmed, O., Hassen, A., Lehloenya, K., 2025. Tannin extract dietary thresholds for preventing unacceptable suppression in intake, digestibility, and growth in sheep and cattle: a meta-analysis. S. Afr. J. Anim. Sci. 55, 188–211. https://doi.org/10.4314/sajas.v55i4.03.

Al Rharad, A., El Aayadi, S., Avril, C., Souradjou, A., Sow, F., Camara, Y., Hornick, J.-L., Boukrouh, S., 2025. Meta-analysis of dietary tannins in small ruminant diets: effects on growth performance, serum metabolites, antioxidant status, ruminal fermentation, meat quality, and fatty acid profile. Animals 15. https://doi.org/10.3390/ani15040596.

Al-Obaidi, A.S.A., Mahmood, A.B., Khidhir, Z.K., Zahir, H.G., Al-Doori, Z.T., Dyary, H.O., 2021. Effect of different plants' aromatic essential oils on frozen Awassi lamb meat's chemical and physical characteristics. Ital. J. Food Sci. 33, 98–106. https://doi.org/10.15586/IJFS.V33I4.2099.

Altmann, B.A., Trinks, A., Mörlein, D., 2023. Consumer preferences for the color of unprocessed animal foods. J. Food Sci. 88, 909–925. https://doi.org/10.1111/1750-3841.16485.

Alves, T.P., Dall-Orsoletta, A.C., Ribeiro-Filho, H.M.N., 2017. The effects of supplementing Acacia mearnsii tannin extract on dairy cow dry matter intake, milk production, and methane emission in a tropical pasture. Trop. Anim. Health Prod. 49, 1663–1668. https://doi.org/10.1007/s11250-017-1374-9.

Andrés, S., Morán, L., Aldai, N., Tejido, M.L., Prieto, N., Bodas, R., Giráldez, F.J., 2014. Effects of linseed and quercetin added to the diet of fattening lambs on the fatty acid profile and lipid antioxidant status of meat samples. Meat Sci. 97, 156–163.

Andrés, S., Tejido, M.L., Bodas, R., Morán, L., Prieto, N., Blanco, C., Giráldez, F.J., 2013. Quercetin dietary supplementation of fattening lambs at 0.2 % rate reduces discolouration and microbial growth in meat during refrigerated storage. Meat Sci. 93, 207–212. https://doi.org/10.1016/j.meatsci.2012.08.023.

Andri, F., Huda, A.N., Marjuki, M., 2020. The use of essential oils as a growth promoter for small ruminants: a systematic review and meta-analysis. F1000Research 9, 486. https://doi.org/10.12688/f1000research.24123.2.

Aouadi, D., Luciano, G., Vasta, V., Nasri, S., Brogna, D.M.R., Abidi, S., Priolo, A., Salem, H.Ben, 2014. The antioxidant status and oxidative stability of muscle from lambs receiving oral administration of Artemisia herba alba and Rosmarinus officinalis essential oils. Meat Sci. 97, 237–243. https://doi.org/10.1016/j.meatsci.2014.02.005.

Azzaz, H.H., Hassaan, N.A., Gouda, G.A., Chen, Y., Kholif, A.E., 2025. A phytogenic feed additive blend as a replacement for monensin in lactating Rahmani ewes' diets: effects on feed utilization and milk production. Anim. Feed Sci. Technol. 326. https://doi.org/10.1016/j.anifeedsci.2025.116397.

Bach, A., Elcoso, G., Escartín, M., Spengler, K., Jouve, A., 2023. Modulation of milking performance, methane emissions, and rumen microbiome on dairy cows by dietary supplementation of a blend of essential oils. Animal 17, 100825. https://doi.org/10.1016/j.animal.2023.100825.

Badhan, A., Wang, Y., Terry, S., Gruninger, R., Guan, L.L., McAllister, T.A., 2025. Invited review: interplay of rumen microbiome and the cattle host in modulating feed efficiency and methane emissions. J. Dairy Sci. 108, 5489–5501. https://doi.org/10.3168/jds.2024-26063.

Banakar, P.S., Kumar, S., Varada, V.V., Dixit, S., Tyagi, N., Tyagi, A.K., 2023. Dietary supplementation of Aloe vera extract modulates rumen microbes and improves the functional food value of milk by altering phenolic content, antioxidant capacity, and fatty acid profile in lactating goats. Anim. Biotechnol. 34, 3027–3038.

Banakar, P.S., Kumar, S., Vinay, V.V., Dixit, S., Tyagi, N., Tyagi, A.K., 2021. Supplementation of Aloe vera extract in lactating goats' diet: effects on rumen fermentation efficiency, nutrient utilization, lactation performance, and antioxidant status. Trop. Anim. Health Prod. 53. https://doi.org/10.1007/s11250-021-02894-x.

Battelli, M., Colombini, S., Crovetto, G.M., Galassi, G., Abeni, F., Petrera, F., Manfredi, M.T., Rapetti, L., 2024. Condensed tannins fed to dairy goats: effects on digestibility, milk production, blood parameters, methane emission, and energy and nitrogen balances. J. Dairy Sci. 107, 3614–3630. https://doi.org/10.3168/jds.2023-24076.

Benchaar, C., 2020. Feeding oregano oil and its main component carvacrol does not affect ruminal fermentation, nutrient utilization, methane emissions, milk production, or milk fatty acid composition of dairy cows. J. Dairy Sci. 103, 1516–1527. https://doi.org/10.3168/jds.2019-17230.

Benchaar, C., 2021. Diet supplementation with thyme oil and its main component thymol failed to favorably alter rumen fermentation, improve nutrient utilization, or enhance milk production in dairy cows. J. Dairy Sci. 104, 324–336. https://doi.org/10.3168/jds.2020-18401.

Benchaar, C., Hassanat, F., Petit, H.V., 2015. Dose-response to eugenol supplementation to dairy cow diets: Methane production, N excretion, ruminal fermentation, nutrient digestibility, milk production, and milk fatty acid profile. Anim. Feed Sci. Technol. 209, 51–59. https://doi.org/10.1016/j.anifeedsci.2015.07.027.

Benchaar, C., Hassanat, F., 2025. Diet supplementation with a mixture of essential oils: Effects on enteric methane emissions, apparent total-tract nutrient digestibility, nitrogen utilization, and lactational performance. J. Dairy Sci. 108, 3560–3572. https://doi.org/10.3168/jds.2024-25447.

Besharati, M., Maggiolino, A., Palangi, V., Kaya, A., Jabbar, M., Eseceli, H., De Palo, P., Lorenzo, J.M., 2022. Tannin in Ruminant Nutrition: Review. Molecules 27, 1–26. https://doi.org/10.3390/molecules27238273.

Bešlo, D., Došlić, G., Agić, D., Rastija, V., Šperanda, M., Gantner, V., Lučić, B., 2022. Polyphenols in Ruminant Nutrition and Their Effects on Reproduction. Antioxid. (Basel Switz. 11. https://doi.org/10.3390/antiox11050970.

Biondi, L., Randazzo, C.L., Russo, N., Pino, A., Natalello, A., Hoorde, K.Van, Caggia, C., 2019. Dietary Supplementation of Tannin-Extracts to Lambs: Effects on Meat Fatty Acids Composition and Stability and on Microbial Characteristics. Foods 8, 1–13.

Blanch, M., Carro, M.D., Ranilla, M.J., Viso, A., Vázquez-Añón, M., Bach, A., 2016. Influence of a mixture of cinnamaldehyde and garlic oil on rumen fermentation, feeding behavior and performance of lactating dairy cows. Anim. Feed Sci. Technol. 219, 313–323. https://doi.org/10.1016/j.anifeedsci.2016.07.002.

Bleicher, J., Ebner, E.E., Bak, K.H., 2022. Formation and Analysis of Volatile and Odor Compounds in Meat—A Review. Molecules 27. https://doi.org/10.3390/molecules27196703.

Brogna, D.M.R., Tansawat, R., Cornforth, D., Ward, R., Bella, M., Luciano, G., Priolo, A., Villalba, J., 2014. The quality of meat from sheep treated with tannin- and saponin-based remedies as a natural strategy for parasite control. Meat Sci. 96, 744–749. https://doi.org/10.1016/j.meatsci.2013.10.019.

Brunetto, A.L.R., Luiza, A., Santos, F., Zago, I., Deolino, G.L., Nora, L., Molosse, V.L., Lago, R.V.P., Machado, A.D.C., Wagner, R., Nauderer, J.N., Bissacotti, B.F., Kempka, A.P., Klein, B., Silva, A.S., Da, 2024. Intake of Condensed Tannins (Acacia mearnsii) by Lambs in Confinement and Its Impact on Growth Performance, Rumen Environment, and Meat. Fermentation 10, 1–19.

Buccioni, A., Pauselli, M., Minieri, S., Roscini, V., Mannelli, F., Rapaccini, S., Lupi, P., Conte, G., Serra, A., Cappucci, A., Brufani, L., Ciucci, F., Mele, M., 2017. Chestnut or quebracho tannins in the diet of grazing ewes supplemented with soybean oil: Effects on animal performances, blood parameters and fatty acid composition of plasma and milk lipids. Small Rumin. Res. 153, 23–30. https://doi.org/10.1016/j.smallrumres.2017.05.006.

Buccioni, A., Pauselli, M., Viti, C., Minieri, S., Pallara, G., Roscini, V., Rapaccini, S., Marinucci, M.T., Lupi, P., Conte, G., Mele, M., 2015. Milk fatty acid composition, rumen microbial population, and animal performances in response to diets rich in linoleic acid supplemented with chestnut or quebracho tannins in dairy ewes. J. Dairy Sci. 98, 1145–1156. https://doi.org/10.3168/jds.2014-8651.

Burt, S., 2004. Essential oils: their antibacterial properties and potential applications in foods—a review. Int. J. Food Microbiol 94, 223–253. https://doi.org/10.1016/j.ijfoodmicro.2004.03.022.

Canaes, T.S., Zanferari, F., Maganhe, B.L., Takiya, C.S., Silva, T.H., Del Valle, T.A., Rennó, F.P., 2017. Increasing dietary levels of citral oil on nutrient total tract digestibility, ruminal fermentation, and milk composition in Saanen goats. Anim. Feed Sci. Technol. 229, 47–56. https://doi.org/10.1016/j.anifeedsci.2017.05.002.

Cantet, J.M., Yu, Z., Tucker, H.A., Ríus, A.G., 2023. A cinnamaldehyde feed additive improved feed use-efficiency in lactating dairy cows. Livest. Sci. 272, 105236. https://doi.org/10.1016/j.livsci.2023.105236.

Carvalho, P.H.V., Latack, B.C., Ferraz, M.V.C., Nolasco, L.J.R.P., Meireles, W.R., Oliveira, H.O.M., Zinn, R.A., 2024. Influence of low-level tannin supplementation on comparative growth performance of Holstein and Angus × Holstein cross calf-fed concentrate-based finishing diets for 328 d. J. Anim. Sci. 102. https://doi.org/10.1093/jas/skae087.

Castro-Pérez, B. i, Rojas-román, L.A., Estrada-anguLo, Al, CarriLLo-muro, O., Barreras, A., PLascencia, Al, 2021. Effects of Long-Term Supplementation of Different Levels of Tannins Extract on Meat Quality and Carcass Traits of Hairy Lambs. Adv. Anim. Vet. Sci. 9, 1973–1977.

Cimmino, R., Barone, C.M.A., Claps, S., Varricchio, E., Rufrano, D., Caroprese, M., Albenzio, M., De Palo, P., Campanile, G., Neglia, G., 2018. Effects of dietary supplementation with polyphenols on meat quality in Saanen goat kids. BMC Vet. Res. 14. https://doi.org/10.1186/s12917-018-1513-1.

Cohen-Zinder, M., Shor-Shimoni, E., Glasser, T., Leibovich, H., David, T., Argov-Argaman, N., Shabtay, A., 2025. Dietary Moringa oleifera improves goat milk quality: Benefits for human nutrition and the dairy industry. Food Chem. 479, 143786. https://doi.org/10.1016/j.foodchem.2025.143786.

Conboy Stephenson, R., Ross, R.P., Stanton, C., 2021. Carotenoids in Milk and the Potential for Dairy Based Functional Foods. Foods (Basel Switz.) 10. https://doi.org/10.3390/foods10061263.

Costa, E.I., de, S., Ribiero, C.V.D.M., Silva, T.M., Ribeiro, R.D.X., Vieira, J.F., De, A.G.V., Barbosa, A.M., Silva Júnior, J.M. d, Bezerra, L.R., Oliveira, R.L., 2021. Intake, nutrient digestibility, nitrogen balance, serum metabolites and growth performance of lambs supplemented with Acacia mearnsii condensed tannin extract. Anim. Feed Sci. Technol. 272, 114744. https://doi.org/10.1016/j.anifeedsci.2020.114744.

Cuchillo-Hilario, M., Fournier-Ramírez, M.-I., Díaz Martínez, M., Montaño Benavides, S., Calvo-Carrillo, M.-C., Carrillo Domínguez, S., Carranco-Jáuregui, M.-E., Hernández-Rodríguez, E., Mora-Pérez, P., Cruz-Martínez, Y.R., Delgadillo-Puga, C., 2024. Animal Food Products to Support Human Nutrition and to Boost Human Health: The Potential of Feedstuffs Resources and Their Metabolites as Health-Promoters. Metabolites 14. https://doi.org/10.3390/metabo14090496.

de Araújo, P.D., Araújo, W.M.C., Patarata, L., Fraqueza, M.J., 2022. Understanding the main factors that influence consumer quality perception and attitude towards meat and processed meat products. Meat Sci. 193, 108952. https://doi.org/10.1016/j.meatsci.2022.108952.

de Oliveira Monteschio, J., de Souza, K.A., Vital, A.C.P., Guerrero, A., Valero, M.V., Kempinski, E.M.B.C., Barcelos, V.C., Nascimento, K.F., do Prado, I.N., 2017. Clove and rosemary essential oils and encapsuled 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.

de Oliveira Monteschio, J., Passetti, R.A.C., de Souza, K.A., Guerrero, A., de Moraes Pinto, L.A., Valero, M.V., Vital, A.C.P., Osório, J.C.S., de Araújo Castilho, R., Sañudo, C., do Prado, I.N., Monteschio, J.D.O., Cortez, A., Souza, K.A., De, Guerrero, A., Moraes, A., De, Valero, M.V., Pelaes, C., Carlos, J., Osório, S., Castilho, D. A., 2020. Acceptability by sensory and visual analyses of meat from Nellore heifers fed with natural additives and finished in feedlots. J. Sci. Food Agric. 100, 4782–4790. https://doi.org/10.1002/jsfa.10537.

de Zawadzki, A., Arrivetti, L.O.R., Vidal, M.P., Catai, J.R., Nassu, R.T., Tullio, R.R., Berndt, A., Oliveira, C.R., Ferreira, A.G., Neves-Junior, L.F., Colnago, L.A., Skibsted, L.H., Cardoso, D.R., 2017. Mate extract as feed additive for improvement of beef quality. Food Res. Int. 99, 336–347. https://doi.org/10.1016/j.foodres.2017.05.033.

Denninger, T.M., Schwarm, A., Birkinshaw, A., Terranova, M., Dohme-Meier, F., Münger, A., Eggerschwiler, L., Bapst, B., Wegmann, S., Clauss, M., Kreuzer, M., 2020. Immediate effect of Acacia mearnsii tannins on methane emissions and milk fatty acid profiles of dairy cows. Anim. Feed Sci. Technol. 261. https://doi.org/10.1016/j.anifeedsci.2019.114388.

Dentinho, M.T.P., Paulos, K., Francisco, A., Belo, A.T., Jerónimo, E., Almeida, J., Bessa, R.J.B., Santos-silva, J., 2020. Effect of soybean meal treatment with Cistus ladanifer condensed tannins in growth performance, carcass and meat quality of lambs. Livest. Sci. 236, 104021. https://doi.org/10.1016/j.livsci.2020.104021.

Dias Junior, P.C.G., da Silva, A.L.A., dos Santos, I.J., Soares, L.C.B., Carlis, M.S.P., Vicente, A.C.S., de Souza, T.T., de Assis, R.G., Biava, J.S., Quigley, S., Pires, A.V., Ferreira, E.M., 2024. Orange (Citrus sinensis) essential oil inclusion in high-energy diets for feedlot lambs: productivity, eating behavior, carcass characteristics, rumen morphometry, and fatty acid profile of the meat. Small Rumin. Res. 238. https://doi.org/10.1016/j.smallrumres.2024.107326.

Dias Junior, P.C.G., dos Santos, I.J., da Silva, A.L.A., de Assis, R.G., Vicente, A.C.S., Carlis, M.S.P., Soares, L.C.B., Comelli, J.H., Biava, J.S., Araujo, R.C., Pires, A.V., Ferreira, E.M., 2023. Essential oil from Arnica montana on feedlot performance, ingestive behavior, carcass characteristics, rumen morphometrics characteristics and meat fatty acids profile of lambs. Small Rumin. Res. 220. https://doi.org/10.1016/j.smallrumres.2023.106920.

Diepersloot, E.C., Pupo, M.R., Heinzen, C., Souza, M.S., Ferraretto, L.F., 2025. Effects of monensin and essential oil blend supplementation on lactation performance and feeding behavior in dairy cows. J. Dairy Sci. 108, 2517–2526. https://doi.org/10.3168/jds.2024-25834.

Ding, H., Ao, C., Zhang, X., 2023. Potential use of garlic products in ruminant feeding: A review. Anim. Nutr. (Zhongguo xu mu shou yi xue hui) 14, 343–355. https://doi.org/10.1016/j.aninu.2023.04.011.

Ding, H., Liu, W., Erdene, K., Du, H., Ao, C., 2021. Effects of dietary supplementation with Allium mongolicum Regel extracts on growth performance, serum metabolites, immune responses, antioxidant status, and meat quality of lambs. Anim. Nutr. 7, 530–538. https://doi.org/10.1016/j.aninu.2021.04.001.

Divekar, P.A., Narayana, S., Divekar, B.A., Kumar, R., Gadratagi, B.G., Ray, A., Singh, Achuit, Kumar, Rani, Singh, V., Singh, V., Kumar, Akhilesh, Kumar, A., Singh, R. P., Meena, R.S., Behera, T.K., 2022. Plant Secondary Metabolites as Defense Tools against Herbivores for Sustainable Crop Protection. Int. J. Mol. Sci. 23. https://doi.org/10.3390/ijms23052690.

Domínguez, R., Pateiro, M., Munekata, P.E.S., Zhang, W., Garcia-Oliveira, P., Carpena, M., Prieto, M.A., Bohrer, B., Lorenzo, J.M., 2022. Protein Oxidation in Muscle Foods: A Comprehensive Review. Antioxidants. https://doi.org/10.3390/antiox11010060.

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. https://doi.org/10.3390/vetsci9090475.

dos Santos, F.M., Bezerra, L.R., Vieira, J.F., Marcelino, P.D.R., Barbosa, A.M., Filho, P.M., Arce-cordero, J.A., Ribeiro, C.V.D.M., Silva, T.M., Oliveira, R.L., 2024. Fatty acid profile, physicochemical composition and carcass traits of young Nellore bulls fed Acacia mearnsii extract. Meat Sci. 216. https://doi.org/10.1016/j.meatsci.2024.109579.

dos Santos, S.K., de Fátima França Biz, J., Salgado, J.A., de Macedo, R.E.F., Sotomaior, C.S., 2022a. Intake and performance of growing lambs supplemented with quebracho tannins. Trop. Anim. Health Prod. 54. https://doi.org/10.1007/s11250-022-03043-8.

dos Santos, S.K., Rosset, M., Miqueletto, M.M., de Jesus, M.R.M., Sotomaior, C.S., de Macedo, R.E.F., 2022b. Effects of dietary supplementation with quebracho tannins on oxidation parameters and shelf life of lamb meat. Food Sci. Technol. 2061, 1–9.

Dschaak, C.M., Williams, C.M., Holt, M.S., Eun, J.-S., Young, A.J., Min, B.R., 2011. Effects of supplementing condensed tannin extract on intake, digestion, ruminal fermentation, and milk production of lactating dairy cows. J. Dairy Sci. 94, 2508–2519. https://doi.org/10.3168/jds.2010-3818.

El-Azrak, K.E.D.M., Morsy, A.S., Soltan, Y.A., Hashem, N.M., Sallam, S.M.A., 2022. Impact of specific essential oils blend on milk production, serum biochemical parameters and kid performance of goats. Anim. Biotechnol. 33, 1344–1352. https://doi.org/10.1080/10495398.2021.1898978.

Elcoso, G., Zweifel, B., Bach, A., 2019. Effects of a blend of essential oils on milk yield and feed efficiency of lactating dairy cows. Appl. Anim. Sci. 35, 304–311. https://doi.org/10.15232/aas.2018-01825.

El-Essawy, A.M., Anele, U.Y., Abdel-Wahed, A.M., Abdou, A.R., Khattab, I.M., 2021. Effects of anise, clove and thyme essential oils supplementation on rumen fermentation, blood metabolites, milk yield and milk composition in lactating goats. Anim. Feed Sci. Technol. 271, 114760.

Enshaie, E., Nigam, S., Patel, S., Rai, V., 2025. Livestock Antibiotics Use and Antimicrobial Resistance. Antibiotics 14. https://doi.org/10.3390/antibiotics14060621.

FAO, 2023. GLEAM 3.0 Assessment of greenhouse gas emissions and mitigation potential, in: Global Livestock Environmental Assessment Model (GLEAM). Food and Agriculture Organisation.

Flores, A.J., Garciarena, A.D., Hernández Vieyra, J.M., Beauchemin, K.A., Colombatto, D., 2013. Effects of specific essential oil compounds on the ruminal environment, milk production and milk composition of lactating dairy cows at pasture. Anim. Feed Sci. Technol. 186, 20–26. https://doi.org/10.1016/j.anifeedsci.2013.09.001.

Formato, M., Cimmino, G., Brahmi-Chendouh, N., Piccolella, S., Pacifico, S., 2022. Polyphenols for Livestock Feed: Sustainable Perspectives for Animal Husbandry? Molecules 27. https://doi.org/10.3390/molecules27227752.

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, 1–14. 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.

Fugita, C.A., do Prado, R.M., Valero, M.V., Bonafé, E.G., Carvalho, C.B., Guerrero, A., Sañudo, C., do Prado, I.N., 2018. Effect of the inclusion of natural additives on animal performance and meat quality of crossbred bulls (Angus × Nellore) finished in feedlot. Anim. Prod. Sci. 58, 2076–2083.

Gao, C., Qi, M., Zhou, Y., 2024. Chestnut tannin extract modulates growth performance and fatty acid composition in finishing Tan lambs by regulating blood antioxidant capacity, rumen fermentation, and biohydrogenation. BMC Vet. Res. 20, 1–15.

Garcia-galicia, I.A., Arras-acosta, J.A., Huerta-jimenez, M., Renter, A.L., Loya-olguin, J.L., Carrillo-lopez, L.M., 2020. Natural Oregano Essential Oil May Replace Antibiotics in Lamb Diets: Effects on Meat Quality. antibiotics 9, 1–18.

García-Lomillo, J., González-SanJosé, M.L., 2017. Applications of Wine Pomace in the Food Industry: Approaches and Functions. Compr. Rev. Food Sci. Food Saf. 16, 3–22. https://doi.org/10.1111/1541-4337.12238.

García-Salas, A., Bárcena-Gama, J.R., Hernández-Sánchez, D., Cobos-Peralta, M.A., González-Muñoz, S.S., Vaquera-Huerta, H., Arias-Margarito, L., 2022. Fattening performance and carcass characteristics of lambs supplemented with condensed tannins from Acacia mearnsii extract. S. Afr. J. Anim. Sci. 52, 498–505.

Gelaye, Y., 2024. Application of nanotechnology in animal nutrition: Bibliographic review. Cogent Food Agric. 10, 2290308. https://doi.org/10.1080/23311932.2023.2290308.

Gerlach, K., Pries, M., Tholen, E., Schmithausen, A.J., Büscher, W., Südekum, K.-H., 2018. Effect of condensed tannins in rations of lactating dairy cows on production variables and nitrogen use efficiency. Animal 12, 1847–1855. https://doi.org/10.1017/S1751731117003639.

Gessner, D.K., Koch, C., Romberg, F.-J., Winkler, A., Dusel, G., Herzog, E., Most, E., Eder, K., 2015. The effect of grape seed and grape marc meal extract on milk performance and the expression of genes of endoplasmic reticulum stress and inflammation in the liver of dairy cows in early lactation. J. Dairy Sci. 98, 8856–8868. https://doi.org/10.3168/jds.2015-9478.

Giannenas, I., Skoufos, J., Giannakopoulos, C., Wiemann, M., Gortzi, O., Lalas, S., Kyriazakis, I., 2011. Effects of essential oils on milk production, milk composition, and rumen microbiota in Chios dairy ewes. J. Dairy Sci. 94, 5569–5577. https://doi.org/10.3168/jds.2010-4096.

Giller, K., Rilko, T., Manzocchi, E., Hug, S., Bolt, R., Kreuzer, M., 2020. Effects of mixed essential oils from eucalyptus, thyme and anise on composition, coagulation properties and antioxidant capacity of the milk of dairy cows. J. Anim. Feed Sci. 29, 3–10. https://doi.org/10.22358/JAFS/118208/2020.

González-Ríos, H., Dávila-Ramírez, J.L., Pẽna-Ramos, E.A., Valenzuela-Melendres, M., Zamorano-García, L., Islava-Lagarda, T.Y., Valenzuela-Grijalva, N.V., 2016. Dietary supplementation of ferulic acid to steers under commercial feedlot feeding conditions improves meat quality and shelf life. Anim. Feed Sci. Technol. 222, 111–121. https://doi.org/10.1016/j.anifeedsci.2016.10.011.

Griffiths, W.M., Clark, C.E.F., Clark, D.A., Waghorn, G.C., 2013. Supplementing lactating dairy cows fed high-quality pasture with black wattle (Acacia mearnsii) tannin. Animal 7, 1789–1795. https://doi.org/10.1017/S1751731113001420.

Grigoletto, N.T.S., Takiya, C.S., Bugoni, M., Nunes, A.T., Junior, P.C.V., Chesini, R.G., da Silva, G.G., Mariane dos Santos, F., Rennó, F.P., 2023. Influence of encapsulated pepper on ruminal fermentation, nutrient digestibility, and performance in dairy cows. Livest. Sci. 267. https://doi.org/10.1016/j.livsci.2022.105140.

Guerreiro, O., Alves, S.P., Soldado, D., Cachucho, L., Almeida, J.M., Francisco, A., Santos-Silva, J., Bessa, R.J.B., Jerónimo, E., 2020. Inclusion of the aerial part and condensed tannin extract from Cistus ladanifer L. in lamb diets – Effects on growth performance, carcass and meat quality and fatty acid composition of intramuscular and subcutaneous fat. Meat Sci. 160, 107945. https://doi.org/10.1016/j.meatsci.2019.107945.

Guerrero, A., Rivaroli, D.C., Sañudo, C., Campo, M.M., Valero, M.V., Jorge, A.M., Prado, I.N., 2018. Consumer acceptability of beef from two sexes supplemented with essential oil mix. Anim. Prod. Sci. 58, 1700–1707. https://doi.org/10.1071/AN15306.

Güney, M., Karaca, S., Erdogan, S., Kor, A., Kale, C., Onalan, S., Demirel, M., Bingol, N.T., 2021. Effects of dietary supplementation with rosemary oil on methanogenic bacteria density, blood and rumen parameters and meat quality of fattening lambs. Ital. J. Anim. Sci. 20, 794–805. https://doi.org/10.1080/1828051X.2021.1906165.

Hassan, A., Abu Hafsa, S.H., Elghandour, M.M.Y.Y., Kanth Reddy, P.R., Salem, M.Z.M.M., Anele, U.Y., Ranga Reddy, P.P., Salem, A.Z.M.M., 2020. Influence of Corymbia citriodora leaf extract on growth performance, ruminal fermentation, nutrient digestibility, plasma antioxidant activity and faecal bacteria in young calves. Anim. Feed Sci. Technol. 261, 114394. https://doi.org/10.1016/j.anifeedsci.2020.114394.

Havlin, J.M., Robinson, P.H., 2015. Intake, milk production and heat stress of dairy cows fed a citrus extract during summer heat. Anim. Feed Sci. Technol. 208, 23–32. https://doi.org/10.1016/j.anifeedsci.2015.06.022.

He, P., Lei, Y., Zhang, K., Zhang, R., Bai, Y., Li, Z., Jia, L., Shi, J., Cheng, Q., Ma, Y., 2023. Dietary oregano essential oil supplementation alters meat quality, oxidative stability, and fatty acid profiles of beef cattle. Meat Sci. 205, 109317.

Henke, A., Dickhoefer, U., Westreicher-Kristen, E., Knappstein, K., Molkentin, J., Hasler, M., Susenbeth, A., 2017a. Effect of dietary Quebracho tannin extract on feed intake, digestibility, excretion of urinary purine derivatives and milk production in dairy cows. Arch. Anim. Nutr. 71, 37–53. https://doi.org/10.1080/1745039X.2016.1250541.

Henke, A., Westreicher-Kristen, E., Molkentin, J., Dickhoefer, U., Knappstein, K., Hasler, M., Susenbeth, A., 2017b. Effect of dietary quebracho tannin extract on milk fatty acid composition in cows. J. Dairy Sci. 100, 6229–6238. https://doi.org/10.3168/jds.2016-12149.

Hopkins, D.L., Ertbjerg, P., 2023. Chapter 12 - The eating quality of meat: II—Tenderness. In: Toldrá, F.B.T.-L.M.S., Ninth, E. (Eds.), Woodhead Publishing Series in Food Science, Technology and Nutrition. Woodhead Publishing, pp. 393–420. https://doi.org/10.1016/B978-0-323-85408-5.00022-4.

Iommelli, P., Spina, A.A., Vastolo, A., Infascelli, L., Lotito, D., Musco, N., Tudisco, R., 2025. Functional and Economic Role of Some Mediterranean Medicinal Plants in Dairy Ruminants' Feeding: A Review of the Effects of Garlic, Oregano, and Rosemary. Animals 15. https://doi.org/10.3390/ani15050657.

Islam, M.T., Vo, H.V.T., Lee, H.J., 2025. Regulation of Matrix Metalloproteinases by Wine-Derived Compounds: Implications for Cancer Therapy. Biomolecules 15. https://doi.org/10.3390/biom15060781.

Jacondino, L.R., Poli, C.H.E.C., Tontini, J.F., Corr, G.F., Somacal, S., 2022. Acacia mearnsii tannin extract and α -tocopherol supplementation in lamb diet: Effects on growth performance, serum lipid peroxidation and meat quality. Anim. Feed Sci. Technol. 294, 1–14. https://doi.org/10.1016/j.anifeedsci.2022.115483.

Jerónimo, E., Alfaia, C.M.M., Alves, S.P., Dentinho, M.T.P., Prates, J.A.M., Vasta, V., Santos-silva, J., Bessa, R.J.B., 2012. Effect of dietary grape seed extract and Cistus ladanifer L. in combination with vegetable oil supplementation on lamb meat quality. Meat Sci. 92, 841–847. https://doi.org/10.1016/j.meatsci.2012.07.011.

Jerónimo, E., Alves, Susana P., Dentinho, M.T.P., Martins, S.V., Prates, J.A.M., Vasta, V., Santos-Silva, J., Bessa, R.J.B., 2010. Effect of Grape Seed Extract, Cistus ladanifer L., and Vegetable Oil Supplementation on Fatty Acid Composition of Abomasal Digesta and Intramuscular Fat of Lambs. J. Agric. Food Chem. 58, 10710–10721. https://doi.org/10.1021/jf1021626.

Joch, M., Kudrna, V., Hakl, J., Božik, M., Homolka, P., Illek, J., Tyrolová, Y., Výborná, A., 2019. In vitro and in vivo potential of a blend of essential oil compounds to improve rumen fermentation and performance of dairy cows. Anim. Feed Sci. Technol. 251, 176–186. https://doi.org/10.1016/j.anifeedsci.2019.03.009.

Joshi, T., Sehgal, H., Puri, S., Karnika, Mahapatra, T., Joshi, M., Deepa, P.R., Sharma, P.K., 2024. ML-based technologies in sustainable agro-food production and beyond: Tapping the (semi) arid landscape for bioactives-based product development. J. Agric. Food Res. 18, 101350. https://doi.org/10.1016/j.jafr.2024.101350.

Ju, L., Shao, Q., Fang, Z., Trevisi, E., Chen, M., Song, Y., Gao, W., Lei, L., Li, X., Liu, G., Du, X., 2024. Dietary supplementation with citrus peel extract in transition period improves rumen microbial composition and ameliorates energy metabolism and lactation performance of dairy cows. J. Anim. Sci. Biotechnol. 15, 1–14. https://doi.org/10.1186/s40104-024-01110-8.

Kamel, H.E.M., Al-dobaib, S.N., Salem, A.Z.M., López, S., Alaba, P.A., 2018. Influence of dietary supplementation with sun flower oil and quebracho tannins on growth performance and meat fatty acid pro fi le of Awassi lambs. Anim. Feed Sci. Technol. 235, 97–104. https://doi.org/10.1016/j.anifeedsci.2017.11.006.

Kasapidou, E., Stergioudi, R.-A., Papadopoulos, V., Mitlianga, P., Papatzimos, G., Karatzia, M.-A., Amanatidis, M., Tortoka, V., Tsiftsi, E., Aggou, A., Basdagianni, Z., 2023. Effect of Farming System and Season on Proximate Composition, Fatty Acid Profile, Antioxidant Activity, and Physicochemical Properties of Retail Cow Milk. Animals 13. https://doi.org/10.3390/ani13233637.

Kearney, S.E., Brunton, N.P., Rai, D.K., 2025. Challenges and opportunities in characterisation of phytochemicals in pasture-fed meat produce. Meat Sci. 225, 109816. https://doi.org/10.1016/j.meatsci.2025.109816.

Kemp, C.M., Bardsley, R.G., Parr, T., 2006. Changes in caspase activity during the postmortem conditioning period and its relationship to shear force in porcine longissimus muscle. J. Anim. Sci. 84, 2841–2846. https://doi.org/10.2527/jas.2006-163.

Khajali, F., Rafiei, F., 2024. A review of plant anti-nutritional factors in animal health and production: The classification, biological properties, and the passivation strategy. J. Agric. Food Res. 18, 101290. https://doi.org/10.1016/j.jafr.2024.101290.

Kholif, A.E., 2023. A Review of Effect of Saponins on Ruminal Fermentation, Health and Performance of Ruminants. Vet. Sci. 10. https://doi.org/10.3390/vetsci10070450.

Kholif, A.E., Kassab, A.Y., Azzaz, H.H., Matloup, O.H., Hamdon, H.A., Olafadehan, O.A., Morsy, T.A., 2018. Essential oils blend with a newly developed enzyme cocktail works synergistically to enhance feed utilization and milk production of Farafra ewes in the subtropics. Small Rumin. Res. 161, 43–50. https://doi.org/10.1016/j.smallrumres.2018.02.011.

Kholif, A.E., Olafadehan, O.A., 2021. Essential oils and phytogenic feed additives in ruminant diet: chemistry, ruminal microbiota and fermentation, feed utilization and productive performance. Phytochem. Rev. 20, 1087–1108. https://doi.org/10.1007/s11101-021-09739-3.

King, D.A., Hunt, M., Barbut, S., Claus, J. (Jim), Cornforth, D., Joseph, P., Kim, B., Lindahl, G., Mancini, R.A., N. Nair, M., Merok, K., Milkowski, A., Mohan, A., Pohlman, F., Ramanathan, R., Raines, C., Seyfert, M., Sorheim, O., Suman, S.P., Weber, M., 2023. American Meat Science Association guidelines for meat color measurement. Meat Muscle Biol. 6, 1–81. https://doi.org/10.22175/mmb.12473.

Kolling, G.J., Stivanin, S.C.B., Gabbi, A.M., Machado, F.S., Ferreira, A.L., Campos, M.M., Tomich, T.R., Cunha, C.S., Dill, S.W., Pereira, L.G.R., Fischer, V., 2018. Performance and methane emissions in dairy cows fed oregano and green tea extracts as feed additives. J. Dairy Sci. 101, 4221–4234. https://doi.org/10.3168/jds.2017-13841.

Kurćubić, V.S., Stanišić, N., Stajić, S.B., Dmitrić, M., Živković, S., Kurćubić, L.V., Živković, V., Jakovljević, V., Mašković, P.Z., Mašković, J., 2024. Valorizing Grape Pomace: A Review of Applications, Nutritional Benefits, and Potential in Functional Food Development. Foods 13. https://doi.org/10.3390/foods13244169.

Lawless, H.T., Heymamn, H., 2010. Sensory Evaluation of food: Priciples and practises, 2nd ed. Springer Science and Business Media. Springer. https://doi.org/10.1038/167029a0.

Lei, Z., Zhang, K., Li, C., Wu, J., Davis, D., Casper, D., Jiang, H., Jiao, T., Wang, X., Wang, J., 2018. Dietary supplementation with Essential-oils-cobalt for improving growth performance, meat quality and skin cell capacity of goats. Sci. Rep. 8, 11634. https://doi.org/10.1038/s41598-018-29897-3.

Lejonklev, J., Kidmose, U., Jensen, S., Petersen, M.A., Helwing, A.L.F., Mortensen, G., Weisbjerg, M.R., Larsen, M.K., 2016. Short communication: Effect of oregano and caraway essential oils on the production and flavor of cow milk. J. Dairy Sci. 99, 7898–7903. https://doi.org/10.3168/jds.2016-10910.

Li, W., Wang, F., Han, Y., Sun, F., Liu, C., Zhu, Y., Zhong, P., 2025. Effects of essential oils on calf growth, ruminal fermentation, and antioxidative status: a meta-analysis. Front. Vet. Sci. 12. https://doi.org/10.3389/fvets.2025.1573846.

Linehan, K., Patangia, D.V., Ross, R.P., Stanton, C., 2024. Production, Composition and Nutritional Properties of Organic Milk: A Critical Review. Foods 13. https://doi.org/10.3390/foods13040550.

Lisitsyn, A.B., Chernukha, I.M., Lunina, O.I., 2017. Fatty Acid Composition of Meat from Various Animal Species and The Role of Technological Factors in Trans-Isomerization of Fatty Acids. Foods Raw Mater. 5, 54–61. https://doi.org/10.21603/2308-4057-2017-2-54-61.

Liu, W., Ao, C., 2021. Effect of dietary supplementation with Allium mongolicum Regel extracts on growth performance, carcass characteristics, and the fat color and flavor-related branched-chain fatty acids concentration in ram lambs. Anim. Biosci. 34, 1134–1145. https://doi.org/10.5713/ajas.20.0246.

Liu, W., Ding, H., Erdene, K., Chen, R., Mu, Q., Ao, C., 2019. Effects of flavonoids from allium mongolicum regel as a dietary additive on meat quality and composition of fatty acids related to flavor in lambs. Can. J. Anim. Sci. 99, 15–23. https://doi.org/10.1139/cjas-2018-0008.

Liu, W., Gao, H., He, J., Yu, A., Sun, C., Xie, Y., Yao, H., Wang, H., Duan, Y., Hu, J., Tang, D., Ran, T., Lei, Z., 2024. Effects of dietary Allium mongolicum Regel powder supplementation on the growth performance, meat quality, antioxidant capacity and muscle fibre characteristics of fattening Angus calves under heat stress conditions. Food Chem. 453, 139539. https://doi.org/10.1016/j.foodchem.2024.139539.

Liu, H., Li, K., Mingbin, L., Zhao, J., Xiong, B., 2016. Effects of chestnut tannins on the meat quality, welfare, and antioxidant status of heat-stressed lambs. Meat Sci. 116, 236–242. https://doi.org/10.1016/j.meatsci.2016.02.024.

Liu, H., Li, K., Zhao, J., Deng, W., 2018a. Effects of polyphenolic extract from Eucommia ulmoides Oliver leaf on growth performance, digestibility, rumen fermentation and antioxidant status of fattening lambs. Anim. Sci. J. 89, 888–894. https://doi.org/10.1111/asj.12998.

Liu, C., Qu, Y. hua Y.-H., Guo, P. ting P.-T., Xu, C.-C.C. chen, Ma, Y., Luo, H.-L.H. ling, 2018b. Effects of dietary supplementation with alfalfa (Medicago sativa L.) saponins on lamb growth performance, nutrient digestibility, and plasma parameters. Anim. Feed Sci. Technol. 236, 98–106. https://doi.org/10.1016/j.anifeedsci.2017.12.006.

Liu, H., Vaddella, V., Zhou, D., 2011. Effects of chestnut tannins and coconut oil on growth performance, methane emission, ruminal fermentation, and microbial populations in sheep. J. Dairy Sci. 94, 6069–6077. https://doi.org/10.3168/jds.2011-4508.

Lobo, V., Patil, A., Phatak, A., Chandra, N., 2010. Free radicals, antioxidants and functional foods: Impact on human health. Pharmacogn. Rev. 4, 118–126. https://doi.org/10.4103/0973-7847.70902.

Lobón, S., Joy, M., Sanz, A., Álvarez-Rodríguez, J., Blanco, M., 2019. The fatty acid composition of ewe milk or suckling lamb meat can be used to discriminate between ewes fed different diets. Anim. Prod. Sci. 59, 1108–1118. https://doi.org/10.1071/AN18082.

Lopes, J. da C., Madureira, J., Margaça, F.M.A., Cabo Verde, S., 2025. Grape Pomace: A Review of Its Bioactive Phenolic Compounds, Health Benefits, and Applications. Molecules 30. https://doi.org/10.3390/molecules30020362.

López-Bote, C., 2017. Chapter 4 - Chemical and Biochemical Constitution of Muscle. In: Toldrá, F.B.T.-L.M.S., Eighth, E. (Eds.), Woodhead Publishing Series in Food Science, Technology and Nutrition. Woodhead Publishing, pp. 99–158. https://doi.org/10.1016/B978-0-08-100694-8.00004-2.

Lund, M.N., Heinonen, M., Baron, C.P., Estévez, M., 2011. Protein oxidation in muscle foods: A review. Mol. Nutr. Food Res. 55, 83–95. https://doi.org/10.1002/mnfr.201000453.

Ma, J., Li, T., Lin, L., Lu, Y., Chen, X., Li, S., Wei, C., Yin, F., Cao, G., Gan, S., 2024. High-concentrate diet supplemented with hydrolysable tannin improves the slaughter performance, intestinal antioxidant ability and barrier function of fattening lambs. Front. Vet. Sci. 11, 1. https://doi.org/10.3389/fvets.2024.1464314.

Ma, Z., Meng, Y., Li, F., Ungerfeld, E., Lv, J., 2023. Effects of an essential oil blend rich in cinnamaldehyde and carvacrol on rumen biohydrogenation and fatty acid profile in the longissimus lumborum of growing lambs. J. Sci. Food Agric. 9581–9591. https://doi.org/10.1002/jsfa.13782.

Ma, F.T., Shan, Q., Jin, Y.H., Gao, D., Li, H.Y., Chang, M.N., Sun, P., 2020. Effect of Lonicera japonica extract on lactation performance, antioxidant status, and endocrine and immune function in heat-stressed mid-lactation dairy cows. J. Dairy Sci. 103, 10074–10082. https://doi.org/10.3168/jds.2020-18504.

Macías-Cruz, U., Perard, S., Vicente, R., Álvarez, F.D., Torrentera-Olivera, N.G., González-Ríos, H., Soto-Navarro, S.A., Rojo, R., Meza-Herrera, C.A., Avendaño-Reyes, L., 2014. Effects of free ferulic acid on productive performance, blood metabolites, and carcass characteristics of feedlot finishing ewe lambs. J. Anim. Sci. 92, 5762–5768. https://doi.org/10.2527/jas.2014-8208.

Maddaloni, L., Gobbi, L., Vinci, G., Prencipe, S.A., 2025. Natural Compounds from Food By-Products in Preservation Processes: An Overview. Processes 13. https://doi.org/10.3390/pr13010093.

Maggiolino, A., Lorenzo, J.M., Salzano, A., Faccia, M., Blando, F., Serrano, M.P., Latorre, M.A., 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, 713–724.

Mandal, G.P., Roy, A., Patra, A.K., 2014. Effects of feeding plant additives rich in saponins and essential oils on the performance, carcass traits and conjugated linoleic acid concentrations in muscle and adipose tissues of Black Bengal goats. Anim. Feed Sci. Technol. 197, 76–84.

Mandolesi, S., Naspetti, S., Arsenos, G., Caramelle-Holtz, E., Latvala, T., Martin-Collado, D., Orsini, S., Ozturk, E., Zanoli, R., 2020. Motivations and barriers for sheep and goat meat consumption in europe: A means–end chain study. Animals 10, 1–16. https://doi.org/10.3390/ANI10061105.

Mao, H.L., Wang, J.K., Lin, J., Liu, J.X., 2012. Fatty Acid Profiles and Stearoyl-CoA Desaturase Gene Expression in Longissimus dorsi Muscle of Growing Lambs Influenced by Addition of Tea Saponins and Soybean Oil. AsianAustralas. J. Anim. Sci. 25, 648–652. https://doi.org/10.5713/ajas.2011.11386.

Mapiye, C., Semwogerere, F., Mahachi, L.N., Mwale, M., Marufu, M.C., 2025. Indigenous ethno-nutraceutical plants: Potential game-changers for the dual management of ruminant helminths and undernutrition in sub-saharan africa. J. Ethnopharmacol. 351, 120077. https://doi.org/10.1016/j.jep.2025.120077.

Martins, L.F., Cueva, S.F., Silvestre, T., Stepanchenko, N., Wasson, D.E., Wall, E., Hristov, A.N., 2024. Lactational performance, enteric methane emission, and nutrient utilization of dairy cows supplemented with botanicals. J. Dairy Sci. 107, 242–257. https://doi.org/10.3168/jds.2023-23719.

Martins, L.F., Oh, J., Melgar, A., Harper, M., Wall, E.W., Hristov, A.N., 2023. Effects of phytonutrients and yeast culture supplementation on lactational performance and nutrient use efficiency in dairy cows. J. Dairy Sci. 106, 1746–1756. https://doi.org/10.3168/jds.2022-22482.

Matarneh, S.K., Scheffler, T.L., Gerrard, D.E., 2023. Chapter 5 - The conversion of muscle to meat. In: Toldrá, F.B.T.-L.M.S., Ninth, E. (Eds.), Woodhead Publishing Series in Food Science, Technology and Nutrition. Woodhead Publishing, pp. 159–194. https://doi.org/10.1016/B978-0-323-85408-5.00010-8.

McCarthy, K.M., Walsh, N., Serra, E., Fahey, A.G., Lynch, M.B., Pierce, K.M., Boland, T.M., Sheridan, H., Markiewicz-Keszycka, M., Mulligan, F.J., 2024. Including clover and herb species in grazing forages – effects on milk production, milk processability and milk fatty acid profile of late lactation dairy cows supplemented with grass silage and concentrate. J. Agric. Sci. 162, 105–117. https://doi.org/10.1017/S0021859624000133.

Mergeduš, A., Janžekovǐ, M., Škorjanc, D., Šumenjak, T.K., 2022. Growth Performance, Meat Quality, and Fecal Microbial Population in Limousin Bulls Supplemented with Hydrolyzable Tannins. Agriculture 12, 1–16.

Mhlongo, L.C., Mseleku, C., Tenza, T., Fomum, S.W., Mcgaw, L.J., Hassen, A., Nsahlai, I.V., 2024. A Review of Ethnomedicinal Plants as Potential Anthelmintic Agents to Alternatively Control Gastrointestinal Nematodes of Ruminants in South Africa. J. Parasitol. Res. 2024. https://doi.org/10.1155/2024/7955692.

Miri, V.H., Tyagi, A.K., Ebrahimi, S.H., Mohini, M., 2013. Effect of cumin (Cuminum cyminum) seed extract on milk fatty acid profile and methane emission in lactating goat. Small Rumin. Res. 113, 66–72. https://doi.org/10.1016/j.smallrumres.2013.01.015.

Mirzaei-Alamouti, H., Namdarpour, H., Abdollahi, A., Amanlou, H., Patra, A.K., Shahir, M.H., Aliyari, D., Vazirigohar, M., 2021. Nutrient digestibility, blood metabolites, and production performance of peripartal ewes fed dietary plant extract and monensin. Small Rumin. Res. 202, 106453. https://doi.org/10.1016/j.smallrumres.2021.106453.

Mititelu, M., Lupuliasa, D., Neacșu, S.M., Olteanu, G., Busnatu, Ș.S., Mihai, A., Popovici, V., Măru, N., Boroghină, S.C., Mihai, S., Ioniță-Mîndrican, C.-B., Scafa-Udriște, A., 2025. Polyunsaturated fatty acids and human health: A key to modern nutritional balance in association with polyphenolic compounds from food sources. Foods 14 (1), 46. https://doi.org/10.3390/foods14010046.

Monteschio, J.O., Vargas-junior, F.M., Almeida, F.L.A., Pinto, L.A.D.M., Kaneko, I.N., Almeida, A.A., Freitas, L.W., Alves, S.P.A., Bessa, R.J.B., Prado, I.N., 2019. The effect of encapsulated active principles (eugenol, thymol and vanillin) and clove and rosemary essential oils on the structure, collagen content, chemical composition and fatty acid profile of Nellore heifers muscle. Meat Sci. 155, 27–35. https://doi.org/10.1016/j.meatsci.2019.04.019.

Morales, R., Ungerfeld, E.M., 2015. Use of tannins to improve fatty acids profile of meat and milk quality in ruminants: A review. Chil. J. Agric. Res. 75, 239–248.

Morán, L., Andrés, S., Bodas, R., Prieto, N., Giráldez, F.J., 2012. Meat texture and antioxidant status are improved when carnosic acid is included in the diet of fattening lambs. Meat Sci. 91, 430–434. https://doi.org/10.1016/j.meatsci.2012.02.027.

Morán, L., Giráldez, F.J., Bodas, R., Benavides, J., Prieto, N., Andrés, S., 2013. Metabolic acidosis corrected by including antioxidants in diets of fattening lambs. Small Rumin. Res. 109, 133–135. https://doi.org/10.1016/j.smallrumres.2012.08.009.

Mottet, A., de Haan, C., Falcucci, A., Tempio, G., Opio, C., Gerber, P., 2017. Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. Glob. Food Sect. 14, 1–8. https://doi.org/10.1016/j.gfs.2017.01.001.

Mottin, C., Ornaghi, M.G., Carvalho, V.M., Guerrero, A., Vital, A.C.P., Ramos, T.R., Bonin, E., Lana de Araújo, F., de Araújo Castilho, R., do Prado, I.N., 2022. Carcass characteristics and meat evaluation of cattle finished in temperate pasture and supplemented with natural additive containing clove, cashew oil, castor oils, and a microencapsulated blend of eugenol, thymol, and vanillin (England). J. Sci. Food Agric.. https://doi.org/10.1002/jsfa.11465.

Moura, L.V., Oliveira, E.R., Fernandes, A.R.M., Gabriel, A.M.A., Silva, L.H.X., Takiya, C.S., Cônsolo, N.R.B., Rodrigues, G.C.G., Lemos, T., Gandra, J.R., 2017. Feed efficiency and carcass traits of feedlot lambs supplemented either monensin or increasing doses of copaiba (Copaifera spp.) essential oil. Anim. Feed Sci. Technol. 232, 110–118. https://doi.org/10.1016/j.anifeedsci.2017.08.006.

Muíño, I., Apeleo, E., de la Fuente, J., Pérez-Santaescolástica, C., Rivas-Cañedo, A., Pérez, C., Díaz, M.T., Cañeque, V., Lauzurica, S., 2014. Effect of dietary supplementation with red wine extract or vitamin E, in combination with linseed and fish oil, on lamb meat quality. Meat Sci. 98, 116–123. https://doi.org/10.1016/j.meatsci.2014.05.009.

Mungwari, C.P., King'ondu, C.K., Sigauke, P., Obadele, B.A., 2025. Conventional and modern techniques for bioactive compounds recovery from plants: Review. Sci. Afr. 27, e02509. https://doi.org/10.1016/j.sciaf.2024.e02509.

Muñoz-cuautle, A., Herrera-haro, J.G., 2022. Effect of Oregano (Lippia graveolens) Essential Oil as a Phytogenic Feed Additive on Productive Performance, Ruminal Fermentation, and Antioxidant Activity in Lamb Meat. Agriculture 12, 1–12. https://doi.org/10.3390/agriculture12070973.

Nastoh, N.A., Waqas, M., Çinar, A.A., Salman, M., 2024. The impact of phytogenic feed additives on ruminant production: A review. J. Anim. Feed Sci. 33, 431–453. https://doi.org/10.22358/jafs/191479/2024.

Naumann, H.D., Tedeschi, L.O., Zeller, W.E., Huntley, N.F., 2017. The role of condensed tannins in ruminant animal production: Advances, limitations and future directions. Rev. Bras. Zootec. 46, 929–949. https://doi.org/10.1590/S1806-92902017001200009.

Ngámbi, J.W., Selapa, M.J., Brown, D., Manyelo, T.G., 2022. The effect of varying levels of purified condensed tannins on performance, blood profile, meat quality and methane emission in male Bapedi sheep fed grass hay and pellet - based diet. Trop. Anim. Health Prod. 1–10. https://doi.org/10.1007/s11250-022-03268-7.

Nishikawa-Pacher, A., 2022. Research Questions with PICO: A Universal Mnemonic. Publications 10, 1–10. https://doi.org/10.3390/publications10030021.

Nozière, P., Graulet, B., Lucas, A., Martin, B., Grolier, P., Doreau, M., 2006. Carotenoids for ruminants: From forages to dairy products. Anim. Feed Sci. Technol. 131, 418–450. https://doi.org/10.1016/j.anifeedsci.2006.06.018.

Oh, J., Giallongo, F., Frederick, T., Pate, J., Walusimbi, S., Elias, R.J., Wall, E.H., Bravo, D., Hristov, A.N., 2015. Effects of dietary Capsicum oleoresin on productivity and immune responses in lactating dairy cows. J. Dairy Sci. 98, 6327–6339. https://doi.org/10.3168/jds.2014-9294.

Oh, J., Harper, M., Hristov, A.N., 2019. Effects of lowering crude protein supply alone or in a combination with essential oils on productivity, rumen function and nutrient utilization in dairy cows. Animal 13, 2510–2518. https://doi.org/10.1017/S1751731119001083.

Oh, J., Harper, M., Giallongo, F., Bravo, D.M., Wall, E.H., Hristov, A.N., 2017. Effects of rumen-protected Capsicum oleoresin on productivity and responses to a glucose tolerance test in lactating dairy cows. J. Dairy Sci. 100, 1888–1901. https://doi.org/10.3168/jds.2016-11665.

Oh, J., Hristov, A.N., Lee, C., Cassidy, T., Heyler, K., Varga, G.A., Pate, J., Walusimbi, S., Brzezicka, E., Toyokawa, K., Werner, J., Donkin, S.S., Elias, R., Dowd, S., Bravo, D., 2013. Immune and production responses of dairy cows to postruminal supplementation with phytonutrients. J. Dairy Sci. 96, 7830–7843. https://doi.org/10.3168/jds.2013-7089.

Oliveira, L.N., Pereira, M.A.N., Oliveira, C.D.S., Oliveira, C.C., Silva, R.B., Pereira, R.A.N., DeVries, T.J., Pereira, M.N., 2023. Effect of low dietary concentrations of Acacia mearnsii tannin extract on chewing, ruminal fermentation, digestibility, nitrogen partition, and performance of dairy cows. J. Dairy Sci. 106, 3203–3216. https://doi.org/10.3168/jds.2022-22521.

Omondi, V.O., Bosire, G.O., Onyari, J.M., Kibet, C., Mwasya, S., Onyonyi, V.N., Getahun, M.N., 2024. Multi-omics analyses reveal rumen microbes and secondary metabolites that are unique to livestock species. mSystems 9, e0122823. https://doi.org/10.1128/msystems.01228-23.

Orlandi, T., Stefanello, S., Mezzomo, M.P., Pozo, C.A., Kozloski, G.V., 2020. Impact of a tannin extract on digestibility and net flux of metabolites across splanchnic tissues of sheep. Anim. Feed Sci. Technol. 261, 114384. https://doi.org/10.1016/j.anifeedsci.2019.114384.

Ornaghi, M.G., Guerrero, A., Vital, A.C.P., de Souza, K.A., Passetti, R.A.C., Mottin, C., de Araújo Castilho, R., Sañudo, C., do Prado, I.N., 2020. Improvements in the quality of meat from beef cattle fed natural additives. Meat Sci. 163, 108059. https://doi.org/10.1016/j.meatsci.2020.108059.

Ornaghi, M.G., Passetti, R.A.C., Torrecilhas, J.A., Mottin, C., Vital, A.C.P., Guerrero, A., Sañudo, C., del Mar Campo, M., Prado, I.N., 2017. Essential oils in the diet of young bulls: Effect on animal performance, digestibility, temperament, feeding behaviour and carcass characteristics. Anim. Feed Sci. Technol. 234, 274–283. https://doi.org/10.1016/j.anifeedsci.2017.10.008.

Ortiz-Heredia, M.A., Bárcena-Gama, J.R., Martínez-Hernández, P.A., Guerrero-Rodríguez, J.D., González-Muñoz, S.S., Vázquez-Mendoza, O.V., 2023. Physico-chemical characteristics of meat after dietary supplementation of lambs with essential oils and calcium malate. S. Afr. J. Anim. Sci. 53, 541–549. https://doi.org/10.4314/sajas.v53i4.08.

Ortiz-López, B., Mariezcurrena-Berasain, M.D., Barajas-Cruz, R., Velázquez-Garduño, G., Pliego, A.B., Adegbeye, M.J., Salem, A.Z.M., Mariezcurrena-Berasain, M.A., 2024. Sustainable evaluation of tannin extract biomass as a feed product additive: effects on growth performance, meat fatty acid profile, and lipid oxidation in bullocks. Biomass Convers. Biorefinery 5101–5107. https://doi.org/10.1007/s13399-022-02478-1.

Ortuño, J., Serrano, R., Bañón, S., 2015. Antioxidant and antimicrobial effects of dietary supplementation with rosemary diterpenes (carnosic acid and carnosol) vs vitamin E on lamb meat packed under protective atmosphere. Meat Sci. 110, 62–69. https://doi.org/10.1016/j.meatsci.2015.07.011.

Ortuño, J., Serrano, R., Jordán, M.J., Bañón, S., 2014. Shelf life of meat from lambs given essential oil-free rosemary extract containing carnosic acid plus carnosol at 200 or 400mgkg-1. Meat Sci. 96, 1452–1459. https://doi.org/10.1016/j.meatsci.2013.11.021.

Orzuna-Orzuna, J.F., Lara-Bueno, A., Mendoza-Martínez, G.D., Miranda-Romero, L.A., 2023. Meta-analysis of hydroxycinnamic acids into finishing lambs' diet: Growth performance, antioxidant status, and meat quality. Small Rumin. Res. 223. https://doi.org/10.1016/j.smallrumres.2023.106963.

Page, M.J., McKenzie, J.E., Bossuyt, P., Boutron, I., Hoffmann, T.C., Mulrow, C.D., Shamseer, L., Tetzlaff, J.M., Akl, E., Brennan, S.E., Chou, R., Glanville, J., Grimshaw, J.M., Hróbjartsson, A., Lalu, M.M., Li, T., Loder, E.W., Mayo-Wilson, E., McDonald, S., McGuinness, L., Stewart, L.A., Thomas, J., Tricco, A.C., Welch, V.A., Whiting, P., Moher, D., 2021. The prisma 2020 statement: An updated guideline for reporting systematic reviews. Med. Flum. 57, 444–465. https://doi.org/10.21860/medflum2021_264903.

Pan, L., Bu, D.P., Wang, J.Q., Cheng, J.B., Sun, X.Z., Zhou, L.Y., Qin, J.J., Zhang, X.K., Yuan, Y.M., 2014. Effects of Radix Bupleuri extract supplementation on lactation performance and rumen fermentation in heat-stressed lactating Holstein cows. Anim. Feed Sci. Technol. 187, 1–8. https://doi.org/10.1016/j.anifeedsci.2013.09.008.

Parvar, R., Ghoorchi, 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.

Patra, A.K., Yu, Z., 2012. Effects of essential oils on methane production and fermentation by, and abundance and diversity of, rumen microbial populations. Appl. Environ. Microbiol 78, 4271–4280. https://doi.org/10.1128/AEM.00309-12.

Pena-Bermudez, Y.A., Lobo, R.R., de Amorim, T.R., Rojas-Moreno, D.A., Rodriguez-Aguilar, D., Poleti, M.D., Pereira, A.S.C., Pinheiro, R.S.B., Claudio da silva Bueno, I., 2022. Effect of yerba mate (Ilex paraguariensis) in lamb diets on fatty acid profile, physical and sensory characteristics of the Longissimus muscle. Livest. Sci. 265. https://doi.org/10.1016/j.livsci.2022.105095.

Pena-Bermudez, Y.A., Lobo, R.R., Rojas-Moreno, D.A., Poleti, M.D., de, Amorim, T.R., Rosa, A.F., Pereira, A.S.C., Pinheiro, R.S.B., Bueno, I.C.S., 2020. Effects of feeding increasing levels of yerba mate on lamb meat quality and antioxidant activity. Animals 10, 1–14. https://doi.org/10.3390/ani10091458.

Peña-Torres, E.F., Dávila-Ramírez, J.L., Peña-Ramos, E.A., Valenzuela-Melendres, M., Pinelli-Saavedra, A., Avendaño-Reyes, L., González-Ríos, H., 2021. Effects of dietary ferulic acid on growth performance, carcass traits and meat quality of heifers. J. Sci. Food Agric. 101, 548–554. https://doi.org/10.1002/jsfa.10666.

Piao, M., Tu, Y., Zhang, N., Diao, Q., Bi, Y., 2023. Advances in the Application of Phytogenic Extracts as Antioxidants and Their Potential Mechanisms in Ruminants. Antioxidants 12. https://doi.org/10.3390/antiox12040879.

Pimentel, P.R.S., Pellegrini, C.B., Lanna, D.P.D., Brant, L.M.S., Ribeiro, C.V.D.M., Silva, T.M., Barbosa, A.M., da Silva Júnior, J.M., Bezerra, L.R., Oliveira, R.L., 2021. Effects of Acacia mearnsii extract as a condensed-tannin source on animal performance, carcass yield and meat quality in goats. Anim. Feed Sci. Technol. 271, 114733. https://doi.org/10.1016/j.anifeedsci.2020.114733.

Poli, C.H.E.C., Thornton-Kurth, K.J., Legako, J.F., Bremm, C., Hampel, V.S., Hall, J., Ipharraguerre, I.R., Villalba, J.J., 2021. The effect of plant bioactive compounds on lamb performance, intake, gastrointestinal parasite burdens, and lipid peroxidation in muscle. J. Anim. Sci. 99. https://doi.org/10.1093/jas/skab009.

Ponnampalam, E.N., Jairath, G., Alves, S.P., Gadzama, I.U., Santhiravel, S., Mapiye, C., Holman, B.W.B., 2025. Sustainable livestock production by utilising forages, supplements, and agricultural by-products: Enhancing productivity, muscle gain, and meat quality – A review. Meat Sci. 229, 109921. https://doi.org/10.1016/j.meatsci.2025.109921.

Ponnampalam, E.N., Kearns, M., Kiani, A., Santhiravel, S., Vahmani, P., Prache, S., Monahan, F.J., Mapiye, C., 2024. Enrichment of ruminant meats with health enhancing fatty acids and antioxidants: feed-based effects on nutritional value and human health aspects – invited review. Front. Anim. Sci. 5, 1–19. https://doi.org/10.3389/fanim.2024.1329346.

Ponnampalam, E.N., Kiani, A., Santhiravel, S., Holman, B.W.B., Lauridsen, C., Dunshea, F.R., 2022. The Importance of Dietary Antioxidants on Oxidative Stress, Meat and Milk Production, and Their Preservative Aspects in Farm Animals: Antioxidant Action, Animal Health, and Product Quality—Invited Review. Animals 12. https://doi.org/10.3390/ani12233279.

Pukrop, J.R., Campbell, B.T., Schoonmaker, J.P., 2019. Effect of essential oils on performance, liver abscesses, carcass characteristics and meat quality in feedlot steers. Anim. Feed Sci. Technol. 257, 114296. https://doi.org/10.1016/j.anifeedsci.2019.114296.

Rajabi, M., Rouzbehan, Y., Rezaei, J., 2017. A strategy to improve nitrogen utilization, reduce environmental impact, and increase performance and antioxidant capacity of fattening lambs using pomegranate peel extract. J. Anim. Sci. 95, 499–510. https://doi.org/10.2527/jas2016.1069.

Ramdani, D., Yuniarti, E., Jayanegara, A., Chaudhry, A.S., 2023. Roles of Essential Oils, Polyphenols, and Saponins of Medicinal Plants as Natural Additives and Anthelmintics in Ruminant Diets: A Systematic Review. Animals 13, 1–35. https://doi.org/10.3390/ani13040767.

Rana, M.S., Tyagi, A., Hossain, S.A., Tyagi, A.K., 2012. Effect of tanniniferous Terminalia chebula extract on rumen biohydrogenation, {increment} 9-desaturase activity, CLA content and fatty acid composition in longissimus dorsi muscle of kids. Meat Sci. 90, 558–563. https://doi.org/10.1016/j.meatsci.2011.09.016.

Rasera, G.B., de Camargo, A.C., de Castro, R.J.S., 2023. Bioaccessibility of phenolic compounds using the standardized INFOGEST protocol: A narrative review. Compr. Rev. Food Sci. Food Saf. 22, 260–286. https://doi.org/10.1111/1541-4337.13065.

Rashidinejad, A., 2024. The road ahead for functional foods: Promising opportunities amidst industry challenges. Futur. Postharvest Food 1, 266–273. https://doi.org/10.1002/fpf2.12022.

Rennó, F.P., Takiya, C.S., Ceron, B.M., Poletti, G., Vitor, A.C.S., da Silva, J.R., Grigoletto, N.T.S., da Silva, G.G., Pereira, N.M., Brutti, D.D., da Silva, V.M., Maysonnave, G.S., 2025. Low levels of condensed tannins enhance lactation performance in dairy cows. Anim. Feed Sci. Technol. 325. https://doi.org/10.1016/j.anifeedsci.2025.116349.

Rivaroli, D.C., Del Mar Campo, M., Sañudo, C., Guerrero, A., Jorge, A.M., Vital, A.C.P., Valero, M.V., Do Prado, R.M., Do Prado, I.N., 2020. Effect of an essential oils blend on meat characteristics of crossbred heifers finished on a high-grain diet in a feedlot. Anim. Prod. Sci. 60, 595–602. https://doi.org/10.1071/AN18620.

Rivaroli, D.C., Guerrero, A., Velandia Valero, M., Zawadzki, F., Eiras, C.E., Campo, M. del M., Sañudo, C., Mendes Jorge, A., Nunes do 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.

Rizwan, D., Kirmani, S.B.R., Masoodi, F.A., 2025. Circular Economy in the Food Systems: A Review. Environ. Qual. Manag 34, e70096. https://doi.org/10.1002/tqem.70096.

Rojas-Román, L.A., Castro-Pérez, B.I., Estrada-Angulo, A., Angulo-Montoya, C., Yocupicio-Rocha, J.A., López-Soto, M.A., Barreras, A., Zinn, R.A., Plascencia, A., 2017. Influence of long-term supplementation of tannins on growth performance, dietary net energy and carcass characteristics: Finishing lambs. Small Rumin. Res. 153, 137–141. https://doi.org/10.1016/j.smallrumres.2017.06.010.

Ronsisvalle, S., Panarello, F., Longhitano, G., Siciliano, E.A., Montenegro, L., Panico, A., 2020. Natural Flavones and Flavonols: Relationships among Antioxidant Activity, Glycation, and Metalloproteinase Inhibition. Cosmetics 7. https://doi.org/10.3390/cosmetics7030071.

Saleem, A., Imtiaz, A., Yaqoob, S., Awais, M., Awan, K.A., Naveed, H., Khalifa, I., Ercisli, S., Mugabi, R., Alotaibi, S.S., Nayik, G.A., Qian, J.-Y., Shen, Q., 2025. Integration of non-invasive and conventional systems for quality assessment and authentication of meat stuffs: A review with bibliometric analysis. Food Chem. X 29, 102778. https://doi.org/10.1016/j.fochx.2025.102778.

Salehi, F., 2021. Quality, physicochemical, and textural properties of dairy products containing fruits and vegetables: A review. Food Sci. Nutr. 9, 4666–4686. https://doi.org/10.1002/fsn3.2430.

Salem, A.Z.M., Olivares, M., Lopez, S., Gonzalez-Ronquillo, M., Rojo, R., Camacho, L.M., Cerrillo, S.M.A., Mejia, H.P., 2011. Effect of natural extracts of Salix babylonica and Leucaena leucocephala on nutrient digestibility and growth performance of lambs. Anim. Feed Sci. Technol. 170, 27–34. https://doi.org/10.1016/j.anifeedsci.2011.08.002.

Santhiravel, S., Bekhit, A.E.-D.A., Mendis, E., Jacobs, J.L., Dunshea, F.R., Rajapakse, N., Ponnampalam, E.N., 2022. The impact of plant phytochemicals on the gut microbiota of humans for a balanced life. Int. J. Molecular Sci. 23 (15), 8124. https://doi.org/10.3390/ijms23158124.

Santos, M.B., Robinson, P.H., Williams, P., Losa, R., 2010. Effects of addition of an essential oil complex to the diet of lactating dairy cows on whole tract digestion of nutrients and productive performance. Anim. Feed Sci. Technol. 157, 64–71. https://doi.org/10.1016/j.anifeedsci.2010.02.001.

Schiano, A.N., Harwood, W.S., Drake, M.A., 2017. A 100-Year Review: Sensory analysis of milk. J. Dairy Sci. 100, 9966–9986. https://doi.org/10.3168/jds.2017-13031.

Semwogerere, F., Katiyatiya, C.L.F., Chikwanha, O.C., Marufu, M.C., Mapiye, C., 2020. Bioavailability and Bioefficacy of Hemp By-Products in Ruminant Meat Production and Preservation: A Review. Front. Vet. Sci. 7, 1–15. https://doi.org/10.3389/fvets.2020.572906.

Serra, V., Salvatori, G., Pastorelli, G., 2021. Dietary polyphenol supplementation in food producing animals: Effects on the quality of derived products. Animals 11, 1–44. https://doi.org/10.3390/ani11020401.

Seymour, E.M., Bennink, M.R., Watts, S.W., Bolling, S.F., 2010. Whole grape intake impacts cardiac peroxisome proliferator-activated receptor and nuclear factor kappaB activity and cytokine expression in rats with diastolic dysfunction. Hypertens. (Dallas Tex. 1979) 55, 1179–1185. https://doi.org/10.1161/HYPERTENSIONAHA.109.149393.

Shabtay, A., Nikbachat, M., Zenou, A., Yosef, E., Arkin, O., Sneer, O., Shwimmer, A., Yaari, A., Budman, E., Agmon, G., Miron, J., 2012. Effects of adding a concentrated pomegranate extract to the ration of lactating cows on performance and udder health parameters. Anim. Feed Sci. Technol. 175, 24–32. https://doi.org/10.1016/j.anifeedsci.2012.04.004.

Shingfield, K.J., Bonnet, M., Scollan, N.D., 2013. Recent developments in altering the fatty acid composition of ruminant-derived foods. Animal 7, 132–162. https://doi.org/10.1017/S1751731112001681.

Silva, T.H., Magnani, E., de Andrade, J.G.P., Amâncio, B.R., Meurer, G.W., Reolon, H.G., Benedeti, P.D.B., Paula, E.M., Branco, R.H., 2024. Evaluation of increasing levels of condensed tannin extracted from Acacia mearnsii on performance, carcass traits, meat quality, methane emission, and health of finishing Nellore bulls. Anim. Feed Sci. Technol. 315, 116046.

Silva, G.G., Takiya, C.S., Del Valle, T.A., de Jesus, E.F., Grigoletto, N.T.S., Nakadonari, B., Cortinhas, C.S., Acedo, T.S., Rennó, F.P., 2018. Nutrient digestibility, ruminal fermentation, and milk yield in dairy cows fed a blend of essential oils and amylase. J. Dairy Sci. 101, 9815–9826. https://doi.org/10.3168/jds.2018-14789.

Silvestre, T., Martins, L.F., Cueva, S.F., Wasson, D.E., Stepanchenko, N., Räisänen, S.E., Sommai, S., Hile, M.L., Hristov, A.N., 2023. Lactational performance, rumen fermentation, nutrient use efficiency, enteric methane emissions, and manure greenhouse gas-emitting potential in dairy cows fed a blend of essential oils. J. Dairy Sci. 106, 7661–7674. https://doi.org/10.3168/jds.2022-23181.

Silvestre, T., Räisänen, S.E., Cueva, S.F., Wasson, D.E., Lage, C.F.A., Martins, L.F., Wall, E., Hristov, A.N., 2022. Effects of a combination of Capsicum oleoresin and clove essential oil on metabolic status, lactational performance, and enteric methane emissions in dairy cows. J. Dairy Sci. 105, 9610–9622. https://doi.org/10.3168/jds.2022-22203.

Simitzis, P.E., Bronis, M., Charismiadou, M.A., Mountzouris, K.C., Deligeorgis, S.G., 2014. Effect of cinnamon (Cinnamomum zeylanicum) essential oil supplementation on lamb growth performance and meat quality characteristics. Animal 8, 1554–1560. https://doi.org/10.1017/S1751731114001335.

Sin, B.Y., Kim, H.P., 2005. Inhibition of collagenase by naturally-occurring flavonoids. Arch. Pharm. Res. 28, 1152–1155. https://doi.org/10.1007/BF02972978.

Singh, A.K., Choubey, M., Chaudhary, S.K., Ojha, L., Kumari, P., 2024. Phytochemicals as Natural Feed Additives for Ruminants. Feed Addit. Suppl. Rumin. https://doi.org/10.1007/978-981-97-0794-2_8.

Smeti, S., Atti, N., Mahouachi, M., Munoz, F., 2013. Use of dietary rosemary (Rosmarinus officinalis L.) essential oils to increase the shelf life of Barbarine light lamb meat. Small Rumin. Res. 113, 340–345. https://doi.org/10.1016/j.smallrumres.2013.04.001.

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.

Smeti, S., Tibaoui, S., Bertolín, J.R., Yagoubi, Y., Mekki, I., Joy, M., Atti, N., 2021. Effects of myrtle (Myrtus communis L.) essential oils as dietary antioxidant supplementation on carcass and meat quality of goat meat. J. Anim. Physiol. Anim. Nutr. (Berl.). 105, 452–461. https://doi.org/10.1111/jpn.13483.

Soladoye, O.P., Juárez, M.L., Aalhus, J.L., Shand, P., Estévez, M., 2015. Protein oxidation in processed meat: Mechanisms and potential implications on human health. Compr. Rev. Food Sci. Food Saf. https://doi.org/10.1111/1541-4337.12127.

Soldado, D., Guerreiro, O., Fialho, L., Cachucho, L., 2024. Inclusion of the Cistus ladanifer L. plant and its condensed tannin extract in lamb diets - Effects on animal antioxidant status and oxidative stability of meat. Anim. Feed Sci. Technol. 316. https://doi.org/10.1016/j.anifeedsci.2024.116070.

Soltan, Y.A., Patra, A.K., 2024. Advancements in Methane-Mitigating Feed Additives in Ruminants. In: Mahesh, M.S., Yata, V.K. (Eds.), BT - Feed Additives and Supplements for Ruminants. Springer Nature Singapore, Singapore, pp. 119–141. https://doi.org/10.1007/978-981-97-0794-2_6.

Soroor, E.N., Rouzbehan, Y., Alipour, D., 2013. Effect of Echium amoenum extract on the growth rate and fermentation parameters of mehraban lambs. Anim. Feed Sci. Technol. 184, 49–57. https://doi.org/10.1016/j.anifeedsci.2013.06.002.

Stempfle, S., Carlucci, D., Borrello, M., Cembalo, L., de Gennaro, B.C., Roselli, L., Giannoccaro, G., 2024. Agri-food systems in transition: Potentialities and challenges of moving towards circular models. J. Clean. Prod. 479, 144005. https://doi.org/10.1016/j.jclepro.2024.144005.

Sun, A., Wu, W., Soladoye, O.P., Aluko, R.E., Bak, K.H., Fu, Y., Zhang, Y., 2022. Maillard reaction of food-derived peptides as a potential route to generate meat flavor compounds: A review. Food Res. Int. 151, 110823. https://doi.org/10.1016/j.foodres.2021.110823.

Tabke, M.C., Sarturi, J.O., Galyean, M.L., Trojan, S.J., Brooks, J.C., Johnson, B.J., Martin, J., Baggerman, J., Thompson, A.J., 2017. Effects of tannic acid on growth performance, carcass characteristics, digestibility, nitrogen volatilization, and meat lipid oxidation of steers fed steam-flaked corn-based finishing diets. J. Anim. Sci. 95, 5124–5136. https://doi.org/10.2527/jas2017.1464.

Tager, L.R., Krause, K.M., 2011. Effects of essential oils on rumen fermentation, milk production, and feeding behavior in lactating dairy cows. J. Dairy Sci. 94, 2455–2464. https://doi.org/10.3168/jds.2010-3505.

Takiya, C.S., Grigoletto, N.T.S., Chesini, R.G., Sbaralho, O.Pietro, Bugoni, M., Vittorazzi, P.C., Nunes, A.T., da Silva, G.G., Vieira, D.J.C., de Freitas, A.C., Acetoze, G., Rennó, F.P., 2023. Feeding rumen-protected Capsicum oleoresin to dairy cows during the transition period and early lactation: Effects on nutrient digestibility, blood metabolites, and performance. Anim. Feed Sci. Technol. 305, 1–8. https://doi.org/10.1016/j.anifeedsci.2023.115758.

Tang, Y., Huang, L., Sun, X., Ren, C., Liu, T.W., Wu, W., Zhang, Z., Zhu, W., 2024. Effects of allicin on growth performance, antioxidant profile, and microbiota compared to monensin of growing goats. Anim. Sci. J. 95, 1–9. https://doi.org/10.1111/asj.13917.

Tedeschi, Luis O., Muir, J.P., Naumann, H.D., Norris, A.B., Ramírez-Restrepo, C.A., Mertens-Talcott, S.U., Ramirez-Restrepo, C.A., Mertens-Talcott, S.U., 2021. Nutritional Aspects of Ecologically Relevant Phytochemicals in Ruminant Production. Front. Vet. Sci. 8, 628445. https://doi.org/10.3389/fvets.2021.628445.

Tekippe, J.A., Tacoma, R., Hristov, A.N., Lee, C., Oh, J., Heyler, K.S., Cassidy, T.W., Varga, G.A., Bravo, D., 2013. Effect of essential oils on ruminal fermentation and lactation performance of dairy cows. J. Dairy Sci. 96, 7892–7903. https://doi.org/10.3168/jds.2013-7128.

Teli, D., Satasia, R., Patel, V., Nair, R., Khatri, R., Gala, D., Balar, P.C., Patel, K., Sharma, A., Vadodariya, P., Chavda, V.P., 2024. Nature meets technology: Harnessing nanotechnology to unleash the power of phytochemicals. Clin. Tradit. Med. Pharm. 5, 200139. https://doi.org/10.1016/j.ctmp.2024.200139.

Tian, X., Li, J., Luo, Q., Wang, X., Wang, T., Zhou, D., Xie, L., Ban, C., Lu, Q., 2022. Effects of purple corn anthocyanin on growth performance, meat quality, muscle antioxidant status, and fatty acid profiles in goats. Foods 11, 1255.

Tian, X., Lu, Q., 2022. Anthocyanins in Dairy Cow Nutrition: A Review. Agriculture 12. https://doi.org/10.3390/agriculture12111806.

Tian, X., Xu, Y.Q., Qin, J.X., Wang, X., Xie, S.L., Chen, R., Lu, Q., Chen, X., 2025. Effects of coix seed polyphenol extract on rumen fermentation, milk production, fatty acid profile, antioxidant activity, and polyphenol content in dairy goats. J. Dairy Sci. 108, 2407–2421. https://doi.org/10.3168/jds.2024-25366.

Timlin, M., Tobin, J.T., Brodkorb, A., Murphy, E.G., Dillon, P., Hennessy, D., O'Donovan, M., Pierce, K.M., O'Callaghan, T.F., 2021. The Impact of Seasonality in Pasture-Based Production Systems on Milk Composition and Functionality. Foods 10. https://doi.org/10.3390/foods10030607.

Toral, P.G., Hervás, G., Belenguer, A., Bichi, E., Frutos, P., 2013. Effect of the inclusion of quebracho tannins in a diet rich in linoleic acid on milk fatty acid composition in dairy ewes. J. Dairy Sci. 96, 431–439. https://doi.org/10.3168/jds.2012-5622.

Toral, P.G., Hervás, G., Bichi, E., Belenguer, Á., Frutos, P., 2011. Tannins as feed additives to modulate ruminal biohydrogenation: Effects on animal performance, milk fatty acid composition and ruminal fermentation in dairy ewes fed a diet containing sunflower oil. Anim. Feed Sci. Technol. 164, 199–206. https://doi.org/10.1016/j.anifeedsci.2011.01.011.

Torrecilhas, J.A., Ornaghi, M.G., Passetti, R.A.C., Mottin, C., Guerrero, A., Ramos, T.R., Vital, A.C.P., Sañudo, C., Malheiros, E.B., Prado, I.N. do, 2021. Meat quality of young bulls finished in a feedlot and supplemented with clove or cinnamon essential oils. Meat Sci. 174. https://doi.org/10.1016/j.meatsci.2020.108412.

Ünlü, H.B., İpçak, H.H., Kandemir, 2022. Effects of oregano essential oil and capsicum extract supplementation on slaughter characteristics, meat quality, and fatty acid composition of lambs. S. Afr. J. Anim. Sci. 52, 780–791. https://doi.org/10.4314/sajas.v52i6.04.

Vahmani, P., Ponnampalam, E.N., Kraft, J., Mapiye, C., Bermingham, E.N., Watkins, P.J., Proctor, S.D., Dugan, M.E.R., 2020. Bioactivity and health effects of ruminant meat lipids. Invited Review. Meat Sci. 165, 108114. https://doi.org/10.1016/j.meatsci.2020.108114.

Valadez-García, K.M., Avendaño-Reyes, L., Meza-Herrera, C.A., Mellado, M., Díaz-Molina, R., González-Ríos, H., Macías-Cruz, U., 2021. Ferulic acid in animal feeding: Mechanisms of action, productive benefits, and future perspectives in meat production. Food Biosci. 43. https://doi.org/10.1016/j.fbio.2021.101247.

Valenti, B., Campidonico, L., Natalello, A., Lanza, M., Salami, S.A., Priolo, A., Serra, A., Pauselli, M., Luciano, G., 2021. Fatty acid metabolism in lambs supplemented with different condensed and hydrolysable tannin extracts. PLoS One 16, e0258265.

Valenti, B., Natalello, A., Vasta, V., Campidonico, L., Roscini, V., Mattioli, S., Pauselli, M., Priolo, A., Lanza, M., Luciano, G., 2019. Effect of different dietary tannin extracts on lamb growth performances and meat oxidative stability: Comparison between mimosa, chestnut and tara. Animal 13, 435–443. https://doi.org/10.1017/S1751731118001556.

Valenti, B., Scicutella, F., Viti, C., Daghio, M., Mannelli, F., Gigante, D., Buccioni, A., Bolletta, V., Morbidini, L., Turini, L., Natalello, A., Servili, M., Selvaggini, R., Pauselli, M., 2025. Olive tree leaves in dairy sheep diet: effects on rumen metabolism, microbiota composition and milk quality. animal 19, 101435. https://doi.org/10.1016/j.animal.2025.101435.

Valero, M.V., Torrecilhas, J.A., Zawadzki, F., Bonafé, E.G., Madrona, G.S., do Prado, R.M., Passetti, R.A.C., Rivaroli, D.C., Visentainer, J.V., do Prado, I.N., 2014. 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.

van Gastelen, S., Yáñez-Ruiz, D., Khelil-Arfa, H., Blanchard, A., Bannink, A., 2024. Effect of a blend of cinnamaldehyde, eugenol, and Capsicum oleoresin on methane emission and lactation performance of Holstein-Friesian dairy cows. J. Dairy Sci. 107, 857–869. https://doi.org/10.3168/jds.2023-23406.

Varghese, R., Shringi, H., Efferth, T., Ramamoorthy, S., 2025. Artificial intelligence driven approaches in phytochemical research: trends and prospects. Phytochem. Rev. https://doi.org/10.1007/s11101-025-10096-8.

Vasta, V., Aouadi, D., Brogna, D.M.R., Scerra, M., Luciano, G., Priolo, A., Salem, H.Ben, 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, 235–241.

Vasta, V., Daghio, 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, 3781–3804. https://doi.org/10.3168/jds.2018-14985.

Vasta, V., Luciano, G., 2011. The effects of dietary consumption of plants secondary compounds on small ruminants' products quality. Small Rumin. Res. 101, 150–159. https://doi.org/10.1016/j.smallrumres.2011.09.035.

Vasta, V., Mele, M., Serra, A., Scerra, M., Luciano, G., Lanza, M., Priolo, A., 2007. Metabolic fate of fatty acids involved in ruminal biohydrogenation in sheep fed concentrate or herbage with or without tannins 1 1, 2674–2684. https://doi.org/10.2527/jas.2008-1761.

Vendramini, T.H.A., Takiya, C.S., Silva, T.H., Zanferari, F., Rentas, M.F., Bertoni, J.C., Consentini, C.E.C., Gardinal, R., Acedo, T.S., Rennó, F.P., 2016. Effects of a blend of essential oils, chitosan or monensin on nutrient intake and digestibility of lactating dairy cows. Anim. Feed Sci. Technol. 214, 12–21. https://doi.org/10.1016/j.anifeedsci.2016.01.015.

Venter, M., Hassen, A., Pophiwa, P., Webb, E.C., 2024. Effects of dietary supplementation with Acacia mearnsii tannin extract on carcass characteristics and meat quality of lambs. CABI Agric. Biosci. 5, 1–10. https://doi.org/10.1186/s43170-024-00253-y.

Vera, N., Suescun-Ospina, S.T., Allende, R., Gutiérrez-Gómez, C., Junod, T., Williams, P., Fuentealba, C., Ávila-Stagno, J., 2023. A short-term supplementation with a polyphenol-rich extract from radiata pine bark improves fatty acid profiles in finishing lambs. Animals 13. https://doi.org/10.3390/ani13020188.

Vittorazzi, P.C., Takiya, C.S., Nunes, A.T., Chesini, R.G., Bugoni, M., Silva, G.G., Silva, T.B.P., Dias, M.S.S., Grigoletto, N.T.S., Rennó, F.P., 2022. Feeding encapsulated pepper to dairy cows during the hot season improves performance without affecting core and skin temperature. J. Dairy Sci. 105, 9542–9551. https://doi.org/10.3168/jds.2022-22078.

Vizzotto, E.F., Stivanin, S.C.B., de Paris, M., Passos, L.T., Werncke, D., Klein, C.P., Stone, V., Matté, C., Zanela, M.B., Fischer, V., 2021. Supplementation with green tea and oregano extracts on productive characteristics, blood metabolites, and antioxidant status of Jersey cows during the transition period. Animal 15. https://doi.org/10.1016/j.animal.2020.100032.

Wandscheer, J.G.W., Turcatto, N., Deolindo, G.L., Signor, M.H., Fritzen, A., Vedovatto, M., Jung, C.T.K., Kozloski, G.V., Xavier, A.C.H., Wagner, R., Bissacotti, B.F., Copetti, P.M., da Silva, A.S., 2024. Combination of essential oils and extracts enriched with tocopherols in diet of holstein steers and its effect on ruminal fermentation, antioxidant and anti-inflammatory response, feed efficiency and fatty acid profile in meat. Fermentation 10. https://doi.org/10.3390/fermentation10120616.

Wang, J., Deng, L., Chen, M., Che, Y., Li, L., Zhu, L., Chen, G., Feng, T., 2024. Phytogenic feed additives as natural antibiotic alternatives in animal health and production: a review of the literature of the last decade. Anim. Nutr. 17, 244–264. https://doi.org/10.1016/j.aninu.2024.01.012.

Wang, Z., Guo, L., Ding, X., Li, F., Xu, H., Li, S., Wang, X., Li, K., Yue, X., 2023. Supplementation of chestnut tannins in diets can improve meat quality and antioxidative capability in Hu lambs. Meat Sci. 206, 109342. https://doi.org/10.1016/j.meatsci.2023.109342.

Wang, L.M., Huang, S., Chalupa-Krebzdak, S., Vásquez Mejía, S.M., Mandell, I.B., Bohrer, B.M., 2020a. Effects of essential oils and(or) benzoic acid in beef finishing cattle diets on the fatty acid profile and shelf life stability of ribeye steaks and ground beef. Meat Sci. 168, 108195. https://doi.org/10.1016/j.meatsci.2020.108195.

Wang, L.M., Mandell, I.B., Bohrer, B.M., 2020b. Effects of feeding essential oils and benzoic acid to replace antibiotics on finishing beef cattle growth, carcass characteristics, and sensory attributes. Appl. Anim. Sci. 36, 145–156. https://doi.org/10.15232/aas.2019-01908.

Wang, B., Tu, Y., Zhao, S.P., Hao, Y.H., Liu, J.X., Liu, F.H., Xiong, B.H., Jiang, L.S., 2017. Effect of tea saponins on milk performance, milk fatty acids, and immune function in dairy cow. J. Dairy Sci. 100, 8043–8052. https://doi.org/10.3168/jds.2016-12425.

Wang, Y., Wang, W., Wang, R., Meng, Z., Duan, Y., An, X., Qi, J., 2019. Dietary supplementation of ferulic acid improves performance and alleviates oxidative stress of lambs in a cold environment. Can. J. Anim. Sci. 99 (4), 705–712. https://doi.org/10.1139/cjas-2018-0200.

Warner, J.O., 2024. Artificial food additives: hazardous to long-term health? Arch. Dis. Child 109, 882–885. https://doi.org/10.1136/archdischild-2023-326565.

Webb, E.C., Hassen, A., Olaniyi, M.O., Pophiwa, P., 2022. Effect of dietary inclusion of azadirachta indica and moringa oleifera leaf extracts on the carcass quality and fatty acid composition of lambs fed high forage total mixed rations. Animals 12. https://doi.org/10.3390/ani12162039.

Weiss, W.P., 2017. A 100-Year Review: From ascorbic acid to zinc—Mineral and vitamin nutrition of dairy cows. J. Dairy Sci. 100, 10045–10060. https://doi.org/10.3168/jds.2017-12935.

Wells, C.W., 2024. Effects of essential oils on economically important characteristics of ruminant species: a comprehensive review. Anim. Nutr. 16, 1–10. https://doi.org/10.1016/j.aninu.2023.05.017.

Wu, J., Bai, Y., Lang, X., Wang, C., Shi, X., Casper, D.P., Zhang, L., Liu, H., Liu, T., Gong, X., Liang, T., Zhang, R., 2020. Dietary supplementation with oregano essential oil and monensin in combination is antagonistic to growth performance of yearling Holstein bulls. J. Dairy Sci. 103, 8119–8129. https://doi.org/10.3168/jds.2020-18211.

Xiong, Y.L., Guo, A., 2020. Animal and plant protein oxidation: chemical and functional property significance. Foods 10. https://doi.org/10.3390/foods10010040.

Yaxing, Z., Erdene, K., Changjin, A., Zhibi, B., Hongxi, D., Zejun, F., Umair, A., Chen, B., 2021. Effects of Allium mongolicum Regel and its extracts supplementation on the growth performance, carcass parameters and meat quality of sheep. Ital. J. Anim. Sci. 20, 1899–1908. https://doi.org/10.1080/1828051X.2021.1971572.

Yu, Y., Fu, R., Jin, C., Gao, H., Han, L., Fu, B., Qi, M., Li, Q., Suo, Z., Leng, J., 2024. Regulation of milk fat synthesis: key genes and microbial functions. Microorganisms 12. https://doi.org/10.3390/microorganisms12112302.

Yuan, Chao, Wu, X., Wu, L., Yang, Y., Han, Y., Su, C., Long, Y., 2025. Effects of allicin on growth performance, slaughter performance, antioxidant, immune parameters and economic benefits of black goats. Anim. Feed Sci. Technol. 324, 116310. https://doi.org/10.1016/j.anifeedsci.2025.116310.

Yuan, C., Wu, X., Wu, L., Yang, Y., Han, Y., Su, C., Long, Y., 2025. Effects of allicin on growth performance, slaughter performance, antioxidant, immune parameters and economic benefits of black goats. Anim. Feed Sci. Technol. 324. https://doi.org/10.1016/j.anifeedsci.2025.116310.

Zagoskina, N.V., Zubova, M.Y., Nechaeva, T.L., Kazantseva, V.V., Goncharuk, E.A., Katanskaya, V.M., Baranova, E.N., Aksenova, M.A., 2023. Polyphenols in plants: structure, biosynthesis, abiotic stress regulation, and practical applications (Review). Int. J. Mol. Sci. 24. https://doi.org/10.3390/ijms241813874.

Zhang, T., Wang, S., Liu, R., Liu, T., Zhang, Y., Yang, L., Kang, L., Xie, J., Jin, Y., Duan, Y., 2023. Effects of different feeds on growth performance and meat quality of hybrid lambs. Qual. Assur. Saf. Crop. Foods 15, 182–192. https://doi.org/10.15586/QAS.V15I1.1252.

Zhang, W., Xiao, S., Ahn, D.U., 2013. Protein oxidation: basic principles and implications for meat quality. Crit. Rev. Food Sci. Nutr. 53, 1191–1201. https://doi.org/10.1080/10408398.2011.577540.

Zhang, S., Zheng, N., Zhao, S., Wang, J., 2025. Allicin enhances urea-N conversion to microbial-N by inhibiting urease activity and modulating the rumen microbiome in cattle. Microbiome 13, 124. https://doi.org/10.1186/s40168-025-02111-z.

Zhao, J.X., Li, Q., Zhang, R.X., Liu, W.Z., Ren, Y.S., Zhang, C.X., Zhang, J.X., 2018. Effect of dietary grape pomace on growth performance, meat quality and antioxidant activity in ram lambs. Anim. Feed Sci. Technol. 236, 76–85. https://doi.org/10.1016/j.anifeedsci.2017.12.004.

Zhao, Y., Zhang, Y., Bai, C., Ao, C., Qi, S., Cao, Q., Erdene, K., 2023. Effects of the dietary inclusion of allium mongolicum regel extract on serum index and meat quality in small-tailed han sheep. Animals 13, 1–12. https://doi.org/10.3390/ani13010110.

Zhou, H., Tan, Y., McClements, D.J., 2023. Applications of the INFOGEST in vitro digestion model to foods: a review. Annu. Rev. Food Sci. Technol. 14, 135–156. https://doi.org/10.1146/annurev-food-060721-012235.