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The impact of phytogenic feed additives on ruminant production: A review

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ABSTRACT. Ruminant livestock, a vital source of high-value proteins such as red meat and milk, requires efficient and sustainable farming practices. To enhance production and quality, researchers have turned to various feed additives, with phytogenic feed additives (PFA) gaining significant attention following the European Union's ban on antibiotics in 2006. PFA, which are plant-derived products, are also often referred to as phytonutrients, phytochemical, plant natural compounds, plant bioactive compounds, or herbal feed additives, and are natural and safe alternatives to synthetic antibiotics. The review highlights the diverse benefits of PFA in ruminant livestock production. These compounds can improve ruminant performance, rumen fermentation, milk production, reproductive health, blood profiles, antioxidant and antimicrobials properties, immunity and meat quality. Specific bioactive compounds in PFA, such as essential oils, polyphenols and flavonoids, exhibit significant antimicrobial, antifungal, antioxidant and antiparasitic properties. They also modulate ruminal fermentation, reduce methane emission, and enhance feed intake and palatability. The mechanisms through which PFA function include improving feed utilisation and growth performance, as well as mitigating oxidative stress and inflammation. The mechanism behind this effect is based on donating hydrogen atoms, activating detoxifying enzymes and quenching reactive oxygen species. The review underscores the need for further research to fully understand these processes. Considering the rising global demand for meat and dairy products, PFA present a viable solution for sustainable livestock farming. They offer a natural effective and safe alternative to antibiotics, promising improved productivity, animal health, and food quality. This review aims to provide a comprehensive characterization of PFA and their potential in ruminant nutrition and production.

Introduction

The production of ruminant livestock is crucial to meet the growing demand for high-value proteins and to ensure food security and safety, both of which are essentials for human health (Caprarulo et al., 2022). Animal products such as meat, milk and eggs provide proteins of high biological value, which are easily digestible and contain all essential amino acids (Pulina et al., 2017). These products are also rich in critical nutrients like heme-iron, vitamin B_{12}, D_3, zinc and calcium. The main objective of advancing dairy farming is to enhance the sustainability and efficiency of agricultural practices by producing ecological products free from hormones, antibiotics, and other xenobiotics. Utilising biologically active compounds (BAS) as feed additives is a practical, cost-effective, and scientifically robust method of achieving this goal (Boyko et al., 2021). Feed additives are intentionally incorporated into livestock diets or drinking water to improve feed quality, enhance growth performance, aid digestion of anti-nutritive factors, prevent nutrient depletion, and positively impact animal production. These additives also increase animal resistance to diseases and parasites and can optimise energy consumption (Singh, 2015; Silveira et al., 2021). One of the most important challenges in animal husbandry is formulating a balanced diet that meets all the nutritional needs of animals (Pandey et al., 2019). Modern intensive farming systems have yielded excellent results in terms of obtaining high-quality animal products. However, even greater benefits related to fertility, daily weight gain, and disease resistance can be achieved by enriching diets with appropriate supplements (Singh, 2015). Due to these positive effects, Mihaylova et al. (2020) have predicted that global meat production would increase from 258 mln t in 2005–2007 to 374 mln t by 2030. Animal feed additives are categorised as technological, sensory, nutritional, zootechnical, and coccidiostats/histomonostats (Karásková et al., 2015; Pandey et al., 2019; Purba et al., 2020). They also include antioxidants, antimicrobials, immunomodulators, enzymes, prebiotics, probiotics, hormones, organic acids, mycotoxin binders, emulsifiers, metabolic modifiers, essential oils, phytogenic herbs, and pellet binders (Singh, 2015). Historically, humans used herbs to care for and feed domestic animals, with evidence of plant-based treatments dating back to Mesopotamia around 2600 BC (Hussein et al., 2015; Franz et al., 2020). In modern animal husbandry, the focus remains on increasing productivity, profitability, and farm efficiency to meet the rising nutrient demand driven by the growing global population. Various growth stimulants, including antibiotic growth promoters (AGP), have been employed to boost production. However, concerns about human health risks led the European Commission to ban in-feed antibiotics in 2006 (Hussein et al., 2015; Karásková et al., 2015; Steiner and Syed, 2015; Lillehoj et al., 2018; Stevanović et al., 2018; Pandey et al., 2019; Franz et al., 2020; Skoufos et al., 2020). As a result, livestock producers and researchers have sought safe, effective, and affordable alternatives to antibiotics. Fragrant plants, herbs, plant secondary metabolites, and aromatic vegetables, along with their essential oils (EO), have emerged as promising growth enhancers (Caroprese et al., 2020; Purba et al., 2020). These plant-derived compounds, known as phytobiotics, phytogenic feed additives (PFA), phytogenic compounds (PC), plant secondary metabolites (PSM), and phytochemical compounds (PCC), can offer significant nutraceutical and nutritional benefits for animal health and nutrition (Yang et al., 2015; Stevanović et al., 2018).

Phytochemicals from herbs and vegetables serve as natural protection against pathogens and spoilage organisms. Compounds such as polyphenols, quinines, flavonoids, alkaloids, and polypeptides exhibit key bioactive properties essential for maintaining animal health. Feed additives help manage environmental stressors and improve food utilisation (Caroprese et al., 2020). Essential oils and other plant-based additives play a significant role in increasing livestock productivity by improving feed efficiency and performance indices such as milk yield, digestibility, and growth rate (Vasta et al., 2019; Purba et al., 2020). Phytobiotic compounds offer antimicrobial, antifungal, antioxidant, and antiparasitic benefits. They can alter rumen fermentation and microflora, reducing methane emissions and protein degradation, while improving feed intake and palatability in ruminants (Stevanović et al., 2018; Artuso-Ponte et al., 2020). Although the exact mechanisms of action of PFA are not yet fully elucidated, they are considered safe for animal nutrition. For example, the phytonutrient (PN) is known for its antimicrobial properties, which are effective against protozoa, fungi, and bacteria, as well as for its ability to modulate rumen fermentation and decrease ammonia levels (Oh et al., 2017; Purba et al., 2020). PFA contain essential oils and various plant secondary compounds. These volatile aromatic metabolites, including terpenoids and flavonoids, possess antimicrobial properties, enhance feed utilisation, modify rumen fermentation, inhibit methanogenesis, and improve overall animal performance (Singh and Gaikwad, 2020). For instance, the inclusion of limonene and carvacrol in the diets of lactating ewes has been shown to significantly enhance weight gain of weaned lambs, likely due to improved energy utilisation by the ewes (Varga-Visi et al., 2023). Additionally, incorporating winery waste products and citrus into ruminant diets as feed additives has been found to increase dry matter intake, improve nutrient digestibility, rumen fermentation, growth performance, and both health status and meat quality (Tayengwa and Mapiye, 2018). The use of *Coleus amboinicus* Lour in lamb diets was shown to reduce methane production, improve rumen environment, and meat quality due to increased n-3 PUFA content (Yanza et al., 2022). The latter authors also showed that a composite plant extract (CPE) containing horse gram seed, Shatavari root, Rohitaka bark, and pomegranate peel could enhance rumen fermentation, lactation, and nutrient utilisation efficiency, all while reducing methane emissions. Considering these substantially beneficial properties, phytogenic feed additives are an excellent alternative to synthetic antibiotic growth promoters in increasing animal performance (Steiner and Syed, 2015). The objective of this review is to provide a comprehensive summary of the impact and applicability of PFA as alternatives to AGP in ruminant nutrition. The article discusses PFA effects on growth performance, antioxidant capacity, antimicrobial activity, milk production and composition, immunomodulation, blood profile, carcass characteristics, methane and ammonia emissions, rumen fermentation and volatile fatty acid production, gut microbiota reproduction, palatability, and feed intake. Given the lack of comprehensive reviews covering all these parameters in a single article, this study aims to fill this gap. The data collected will provide a compendium of knowledge on the use of various types of PFA in ruminant nutrition and how to optimise dietary strategies to improve productivity while reducing environmental pollution from methane, nitrogen, and other greenhouse gases.

Literature search methods

To gather comprehensive data regarding the effects of dietary supplementation with PFA on various aspects of ruminant health and performance, we conducted an extensive literature review, and eventually included 180 studies from different sources. Our aim was to capture a detailed picture of how these natural additives influence parameters such as rumen fermentation, methane and ammonia emissions, milk production, reproduction, blood profile, antioxidant and antimicrobial properties, immunity, as well as meat composition and quality. We utilised several major databases, including ScienceDirect, PubMed, Scopus, Google Scholar, and Web of Science, ensuring a thorough query. Searches were carefully developed using specific keywords tailored to each database. The terms used included 'phytogenic feed additives', 'ruminants', 'cow', 'sheep', 'goat', 'buffalo', 'growth performance', 'carcass traits', 'ruminal fermentation', 'antioxidant', 'immunity', 'anti-microbial', 'methane and ammonia emission', 'milk composition', 'blood metabolites', and 'meat quality'. This approach to data collection has allowed us to compile a robust dataset of recent studies, providing valuable insights into the multifaceted effects of PFA on ruminant livestock.

Brief definition, classification, and application of phytogenic feed additives

Medicinal and aromatic plants have contributed significantly to the development of human societies by improving living conditions from ancient times. Historical manuscripts, such as the Hippocratic Corpus by Hippocrates and De Causis Plantarum and Historia Plantarum by Theophrastus, dating from 300 to 500 BC, highlight their historical importance (Inoue et al., 2017). Phytogenic compositions are plant-derived bioactive substances that positively affect animal health and growth. These substances are typically utilised in the form of essential oils (EO) and extracts derived from herbs. Some are considered to possess antioxidant, antimicrobial, antifungal, and antiviral properties (Yang et al., 2015). Plant-derived additives are also added to animal's diets to improve their production and can generally be classified as spices, herbs, essential oils, and oleoresins (Hussein et al., 2015; Franz et al., 2020; Pashtetsky et al., 2020). Phytogenic, phytobiotic, and phytochemicals are natural bioactive compounds originating from plants, supplemented into livestock diets to improve performance and profitability (Lillehoj et al., 2018). These compounds are sourced from spices, herbs, and essential oils such as anise, cloves, thyme, or melissa (Steiner and Syed, 2015). Phytobiotics, also known as PN, are organic compounds produced by plant as secondary metabolites that have a wide range of properties protecting against bacteria, fungi, and yeasts. They are also used as rumen environment modifiers and methane mitigators in ruminants (Oh et al., 2017; Purba et al., 2020). These additives are studied in four main areas: nutritional supplementing (minerals, vitamins, herbal enzymes), animal husbandry supplementation (immunomodifiers, digestive stimulants, growth enhancers), technological supplementation (coccidiostats, antioxidants), and sensory replacements (Karásková et al., 2015; Stevanović et al., 2018). PFA include essential oils (EO) and many other plant-secondary compounds (PSC). The antimicrobial properties of the plants they are extracted from are often attributed to their EO, which contain terpenoids and phenylpropanoids (Huang et al., 2018). Herbs produce a wide array of metabolites crucial for their survival and growth. These metabolites are primarily categorised into two parts: primary and secondary metabolites (PPM and PSM, respectively). The former are necessary for the growth and development of plants, while the latter protect plants from threats such as predators, stress, and environmental factors. In other words, secondary metabolites provide defence against insects, microorganisms, and other harmful animals (Karásková et al., 2015; Valenzuela-Grijalva et al., 2017; Pashtetsky et al., 2020). PSM are divided into three main classes: terpenes, phenolics, and nitrogen-containing compounds. PSM include various biologically active compounds that enhance plant defence against diseases and are used as flavouring agents (Singh and Singh, 2018; Nawrot-Chorabik et al., 2022). Classification of plant secondary metabolites is illustrated in Figure 1.

Many studies have documented the inhibitory role of PN in deaminating amino acids and methane production in the rumen, as well as enhancing the production of propionate and butyrate through fermentation. Active components such as cinnamaldehyde, eugenol, capsaicin, and allicin in some phytochemicals can activate transient receptor potentials in mammals, leading to changes in neurons, intestines, and pancreas (Oh et al., 2017). Interest in using PFA as natural alternatives for synthetic additives has recently increased (Singh, 2015). However, Yang et al. (2015) expressed some concerns regarding their use, including cost-related-effects, side effects, and regulatory obstacles. According to Stevanović et al. (2018), to align the market for animal production with consumer expectations, the 'CGE' concept must be applied, where 'C' stands for clean, 'G' for green, and 'E' for ethical. These authors also believe that despite some toxic and deleterious effects, PFA can be considered safe and may serve as the primary alternative to AGP. A fundamental restriction in using PFA is the lack of understanding of the optimal dose necessary for improving the growth performance of animals and the adaptation of ruminal microbes; additionally, the chemical structure of feed additives can influence their dosage requirements (Kholif and Olafadehan, 2021). Similarly, Steiner and Syed (2015) referenced European regulations highlighting improvements in digestibility, animal production, and animal health status by PFA application. Phytochemical compounds are usually applied in dry, solid, and ground form, or as extracts (Lillehoj et al., 2018; Franz et al., 2020). Recently, encapsulation techniques have been developed to protect active ingredients against heat to prevent the release of odours until they reach the digestive tract (Steiner and Syed, 2015). Figure 2 demonstrates the reasons for using PFA.

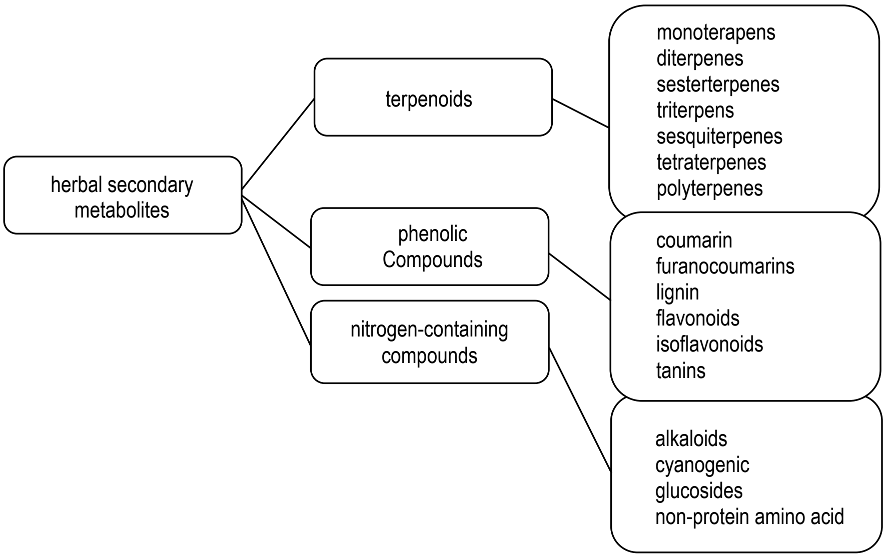

Figure 1. Classification of plant secondary metabolites (Nawrot-Chorabik et al., 2022)

Medicinal and aromatic plants (MAP) have a wide global distribution, including America, Africa, Europe, Australia, India, and China. Reports indicate the presence of 7 500 species in India, 6 000 species in China, 5 000 species in Africa, and 2 000 species in Europe (Pandey et al., 2020). According to estimates, 70 000 herbal species are currently utilised in traditional medicine (Inoue et al., 2017). These plants are used directly or in the form of PSM, with approximately 200 000 PSM identified worldwide (Singh and Singh, 2018). In addition, Steiner and Syed (2015) reported the presence of 320 000 PSM worldwide and noted that 1 mln

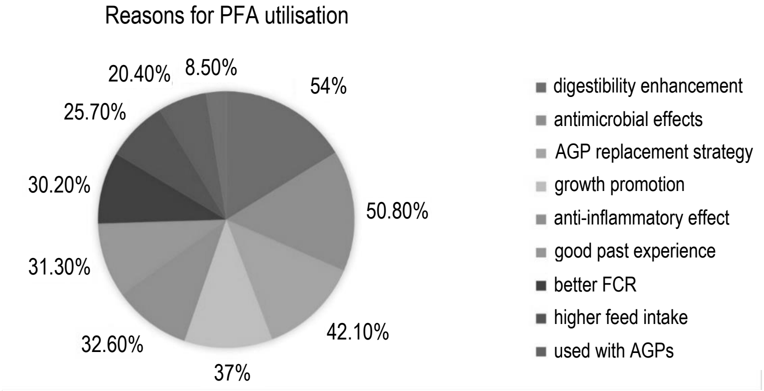

Figure 2. Primary reasons for using phytogenic feed additives (PFA, %) (Pandey et al., 2019)
AGP/AGPs – antimicrobial growth promoters, FCR – feed conversion ratio

compounds are produced in accordance with European legislation (1831/2003). According to Gessner et al. (2015), regulations define the use of plants in animal diets. Currently, the most applicable plant families in livestock feed include *Lamiaceae*, *Apiaceae*, *Rosaceae*, *Asteraceae*; other prevalent plant families are *Alliaceae*, *Brassicaceae*, *Cannabaceae*, *Fabaceae*, *Gentianaceae*, *Lauraceae*, *Myrtaceae*, *Papaveraceae*, *Rosaceae*, *Solanaceae*, *Zingiberaceae*, and some species with limited distribution (Franz et al., 2020).

PFA effects on ruminant performance parameters

Medications containing antibiotics have increasingly been replaced by aromatic plants and the EO they produce. These plants are gaining significance due to their antibacterial properties and stimulating effects on animal digestive systems (Al-Kassie, 2009). Recently, PFA have gained attention as a substitute dietary strategy to AGP. Feed additives that promote growth primarily function by maintaining feed hygiene (e.g., through organic acids) and, more importantly, by positively influencing the ecology of the gastrointestinal microbiota by managing possible infections (Hussein et al., 2015). Herbs and their extracts, as MAP, offer innovative methods to enhance ruminant production and feed utilisation, while improving the quality of their products, such as milk and meat, possibly by affecting rumen digestion (Skoufos et al., 2020). The precise mechanisms of PFA as AGP are not yet fully elucidated. These mechanisms depend on factors such as pharmacokinetics, structure, dosage, animal species, production stage, and administration time (Skoufos et al., 2020). Phytogenic compounds, especially when combined with EO, can potentially increase feed intake by improving palatability through enhanced flavour and aroma (Yang et al., 2015). The addition of 44.1 ppm of a prebiotic (cobalt lactate and arabinogalactons) and EO (carvacrol, caryophyllene, p-cymete, cineole, terpinene, and thymol) to the starter of newborn Holstein calves resulted in a linear increase in feed conversion ratio (FCR), dry matter intake (DMI), and average daily gain (ADG), along with an increase in body frame measurements (Liu et al., 2020). Similar results were obtained by Hashemzadeh et al. (2022), who observed that supplementing heat-stressed lambs with a mixture of cinnamon, turmeric, rosemary, and clove buds at 1% to 2% led to improvements in DMI, ADG, and body weight (BW). Adding 3 g/head/day of red propolis extract to the late pregnancy diet of Santa Iens ewes increased ($P = 0.02$) crude protein and organic matter digestibility, as well as nitrogen intake ($P = 0.03$) (Morsy et al., 2021). Conversely, increased consumption of a quebracho and chestnut tannin extract mixture exerted a negative impact on milk output, actual protein content, DMI, fat and protein-corrected milk (FPCM), and apparent nutritional digestibility, primarily when supplied at 0.90 and 1.80% diet DM (Aguerre et al., 2016). The growth performance of Sewa sheep was improved by adding 300 mg/kg of oregano essential oil (OEO) concentrate to their diets, which modified the structure and composition of their intestinal flora (Sun et al., 2022). The effects of PFA on ruminant performance are presented in Table 1.

PFA effect on rumen fermentation and volatile fatty acid profile

The production of high-quality proteins for ruminants is mainly associated with ruminal microbial activity. However, this process can lead to significant protein and energy losses due to microbial fermentation, resulting in the release of ammonia and methane – two major environmental contami-

Table 1. Effects of phytogenic feed additives (PFA) on ruminant performance

PFA source	Dosage	Study type	Animal species	Diet	Result	References
Foeniculum vulgare seed powder	0.75 and 1.5% of diet	*in vivo*	male lambs	forage-concentrate 40:60	DMI, LDG, FBW, and FCR ↑ ($P < 0.05$) at 1.5%	Hajalizadeh et al., 2019
Lippia alba hay	30-60-90 g/kg of total DMI	*in vivo*	Alpine goat	TMR	DMI, acid detergent fibre, feed efficiency ↑ ($P < 0.05$); the intake of total carbohydrates, NDF, and NFC ↓ ($P < 0.001$)	Da Silva et al., 2022
Echinacea purpurea leaf (EP)	4–8-12 g/head/day	*in vivo*	Ossimi lambs	TMR	BW ↑ 11.82, 13.80, and 12.26% for 4, 8 and 12 g EP, respectively; WG and growth rate ↑ (36.99 and 37.48%), respectively by 8 g EP	Tantawi et al., 2023
Blend of PFA (Digestarom, DSM) and Monensin M	0.5 g/head/day PFA, 0.3 g/head/day monensin	*in vivo*	Angus steers	TMR	similar DMI and ADG, but ↓ FI as monensin in the beginning phase but performance in the end	Yang et al., 2023
Grape pomace (GP)	5–10% of diet	*in vivo*	Churra ewe	TMR forage-concentrate 40:60	BBW-FBW and ADG ↕ not significant	Gómez-Cortés et al., 2018
Woodfordia fruticose, *Solanum nigrum*, *Trigonella foenum-graecum*	2–3% of total DMI	*in vivo*	Jamunapari goat	concentrate and roughage	all nutrients digestibility ↑ ($P < 0.05$); DMI and BWG ↕	Choubey et al., 2015
Anise, clove, and thyme EO	2 ml/head/day	*in vivo*	Shame goat	TMR	digestibility of ADF, OM, and ether extract ↑ ($P < 0.05$)	El-Essawy et al., 2021
Thyme leaf and celery seeds mixture 1:1	20 g/head/day	*in vivo*	Barki ewes	concentrate and fodder 60:40	digestibility and nutrient intake ↑ ($P < 0.05$)	Khattab et al., 2020
Rosemary and lemongrass	10 g of each separately/day/h	*in vivo*	Damascus goat	concentrate and berseem clover	NI ↕ ($P > 0.05$); OM and fibre digestion ↑ ($P < 0.05$)	Kholif et al., 2017
Oregano and carvacrol	50 mg/kg of DM each separately	*in vivo*	dairy cow	forage and concentrate 60:40	digestibility, N utilisation ↕	Benchaar, 2020
Garlic extract, coriander seed, mesquite pods and oregano	6 ml/head/day orally	*in vivo*	sheep	TMR	ingestive behaviour and NI ↕ ($P > 0.05$); ND ↑ ($P < 0.05$)	Da Silva et al., 2017
Black rice-purple maize extract 80:20	2-4-6% of diet	*in vivo*	male dairy cattle	TMR	intake of DM, OM, CP, NDF, ADG, and ADF ↕; EEI ↑ ($P < 0.05$)	Prommachart et al., 2021
Blend of *Echinacea*, garlic, thyme, caraway and liquorice	35, 20, 15, 15, and 15%, respectively	*in vivo*	Limousine bulls	roughage and concentrate	daily gain ↑ by 212 g/h/day while feed intake was ↓; protein and fat digestibility ↑ by 1.3 and 2.5%, respectively	Klebaniuk et al., 2016

EO – essential oil, TMR – total mixed ration, DM – dry matter, DMI – dry matter intake, LDG – live daily gain, FBW – final body weight, FCR – feed conversion ratio, NDF – neutral detergent fibre, NFC – non-fibre carbohydrate, BW – body weight, WG – weight gain, BBW – birth body weight, ADG – average daily gain, BWG – body weight gain, OM – organic matter, NI – nutrient intake, ND – nutrient digestibility, ADF – acid detergent fibre, EEI – ether extract intake; $P < 0.05$ indicates that there is significant effect of PFAs on the given parameters

nants (Simitzis, 2017). Supplementation of Holstein cow diets with tannin extract from *Acacia mearnsii* at up to 0.43% of DMI did not affect acetate levels. However, it caused a linear increase in the molar fraction of butyrate and a corresponding decrease in propionate in the ruminal fluid (Oliveira et al., 2023). Similarly, the addition of citral oil at 0.08, 0.16, or 0.24 ml per kg BW to Saanen goat diets resulted in a linear increase in butyrate proportion in the ruminal fluid. The ingestion of citral oil was shown to positively affect ruminal propionate and butyrate levels; nonetheless, it had a negative impact on the acetate ratio in goats (Canaes et al., 2017). Meanwhile, Muñoz-Cuautle et al. (2022) did not observe significant changes in ruminal parameters with the inclusion of 0.02 and 0.04% oregano essential oils in the lamb diet. Soltan and Patra (2020) reported that propolis improved rumen nitrogen metabolism and the formation of individual and total short-chain fatty acids, which benefits rumen microbial fermentation. Additionally, propolis can reduce methane production during ruminal fermentation. Similarly, Min and Solaiman (2018) found that diets rich in phytonutrient tannins could modify the microbiota and mitigate methane gas emissions. Studies have indicated that tannins can affect rumen fermentation and microbiota in both beneficial and detrimental ways. The effectiveness of tannins varies depending on their quantity, source, and the diet in which they are included. Rivera-Chacon et al. (2022) demonstrated that a phytogenic combination of clove powder (*Syzygium aromaticum*), mint oil (*Mentha arvensis*), thymol, and eugenol influenced rumen microbial populations and fermentation patterns. In an *in vitro* study, Faniyi et al. (2021) found that neem, drumstick, and scent (*Ocimum gratissimum*), along with spices like garlic, ginger, and onion leaves, could influence rumen fermentation and decrease sheep methane generation (Faniyi et al., 2021). Overall, depending on the additive and its concentration, different PFA, such as tannins and essential oils, can greatly improve fermentation and volatile fatty acid (VFA) production, while lowering methane emissions, although their efficacy varies greatly. Additional research is necessary to maximise these benefits for both ruminant health and environmental sustainability. PFA effects on rumen fermentation and VFA profile are presented in Table 2.

PFA effect on methane and ammonia emission

In addition to causing environmental pollution and intensifying the greenhouse effect, ruminal methane (CH_4) emissions also contribute to low production efficiency and animal energy losses. Therefore, it is crucial to develop strategies for reducing methane emissions from ruminants. Research has shown that feed additives such as plant extracts and nitrogen-containing compounds can significantly

Table 2. Effects of phytogenic feed additives (PFA) on rumen fermentation and volatile fatty acid (VFA) profile

PFA sources	Dosage	Study type	Animal species	Diet	Result	References
Bee propolis extract	3 g/head/day	*in vivo*	Santa Ines ewes	basal diet	total short-chain fatty acids and acetate/propionate proportion ↑ ($P < 0.05$)	Morsy et al., 2021
Boswellia sacra resin (BS)	2 and 4 g/head/day	*in vivo*	Nubian goats	basal diet	linear ↓ ($P < 0.01$) in acetate molar ratio. Linear ↓ ($P = 0.01$) in total short-chain fatty acids. linear ↑ ($P < 0.01$) in propionate molar proportions; and quadratically ↓ ($P < 0.05$) in branched-chain volatile fatty acids	Soltan et al., 2021
Oregano and cinnamon EO, turmeric extract, and tannic acid	300 mg – encapsulated oils/kg and 12.5 mg of curcumin/kg	*in vivo*	Holstein calves	concentrate	butyric acid, acetic acid, and propionic acid concentrations ↑	Brunetto et al., 2023
Red osier dogwood	0.3, 0.7 and 0.10% of diet	*in vivo*	beef heifers	high-grain diet	↕ rumen pH and total volatile fatty acid	Wei et al., 2019
CFE	50-100-150 g/day	*in vivo*	Holstein dairy calves	TMR	↑ total volatile fatty acid	Zhao et al., 2023
Oregano EO	0, 130 mg, and 260mg/day/h	*in vivo*	Pingliang red cattle	TMR	↑ propionate and butyrate's relative abundance in the high group	Zhang et al., 2021
TA	0.3, 0.9 and 2.7% dry matter	*in vivo*	Holstein bull	TMR	irrespective of dose TA ↓ ($P < 0.05$) valerate and isobutyrate; 0.9 and 2.7 % ↓ ($P < 0.05$) butyrate; acetate and acetate to propionate ratio ↑ ($P < 0.05$)	Wang et al., 2022
Rosemary and lemongrass	10 g of each separately/day/h	*in vivo*	Damascus goat	concentrate and berseem clover	the ruminal concentration of SCFA, propionate, total UFA, and linoleic acid ↑ ($P < 0.05$); total SFA ↓ ($P < 0.05$)	Kholif et al., 2017
PFA mixture	3 and 6 g/h/day	*in vivo*	Friesian cows	TMR	rumen pH, total VFA, propionate and acetate ↑ ($P < 0.05$)	Kholif et al., 2021
Oregano and carvacrol	50 mg/kg oDM each separately	*in vivo*	dairy cow	forage and concentrate 60:40	ammonia, pH, VFA, and protozoa count ↕	Benchaar, 2020
Dolichos biflorus seed, *Asparagus racemosus* root, *Amoora rohituk*a bark Homogeneous blend	10, 20, 30, and 40 g/kg substrate	*in vitro*	Beetal goat rumen fluids	green bajra + concentrate	VFA and ratio of propionate ↑ ($P < 0.001$); acetate's percentage and the ratio of acetate to propionate ↓	Shilwant et al., 2023

EO – essential oil, CFE – citrus flavonoid extract, TMR – total mixed ration, SCFA – short-chain fatty acids, UFA – unsaturated fatty acids, SFA – saturated fatty acids, TA – tannic acid; $P < 0.01$ indicates significant effect of PFA on the given parameters reduce ruminant methane emissions (Sun et al., 2021). These phytochemical additives reduce hyperammonia (NH_3-N) levels, suppress methanogenic and other harmful bacterial populations, increase VFA concentrations, and lower NH_3-N concentrations, leading to favourable alterations of rumen fermentation (Kholif and Olafadehan, 2021). Different combinations of phytogenic materials can lower the amount of CH_4 released by ruminants into the atmosphere. Methane is the second most significant greenhouse gas, and ruminants are a major source of its production (Karásková et al., 2015). Research indicates that hops or oak tannin extracts, used alone or in combination, do not affect the daily intestinal CH_4 production of cows (Focant et al., 2019). However, feeding Friesian lactating cows with 4% coriander per head per day significantly reduced ($P < 0.001$) ruminal ammonia-N content (Matloup et al., 2017). Legumes, which are high in tannins, can be used to increase dietary nitrogen content and improve pasture productivity. Tropical legumes like *Desmanthus* and *Leucaena leucocephala* have strong antimethanogenic properties and are considered a viable method for reducing intestinal CH_4 emission in cattle production (Almeida et al., 2021). In a study on Segurena sheep, olive cake treated with alkali was used to assess its effect on enteric methane emissions. These authors found that adding 400 g/kg of olive cake to the basal diet significantly decreased the production of enteric CH_4 (Aguilera et al., 2021). An *in vitro* work revealed that adding *Moringa oleifera* oil changed fermentation kinetics from acetate to propionate, thereby markedly reducing methane production in all mixed rations. Additionally, low and medium roughage feeds (30–50%) were shown to reduce the population of protozoa and methanogens (Ebeid et al., 2020). Buffalo calves were fed three distinct plant mixtures: Mix-1 (ajwain oil and lemon grass oil at a 1:1 ratio at 0.05% DMI), Mix-2 (garlic and soapnut at a 2:1 ratio at 2% of DMI), and Mix-3 (garlic, soapnut, harad, and ajwain at a 2:1 ratio at 1% of DMI). The result showed that feed conversion ratio was high (10.2%) in Mix-3, while methane emission was low up to 17.8% in Mix-1 (l/kg DMI and l/kg digestible DMI) (Samal et al., 2016). Methane production and ammonia emissions of beetal goats decreased linearly ($P < 0.05$) when a composite plant extract (*Dolichos biflorus* seed, *Asparagus racemosus* root, *Amoora rohituka* bark) was homogenously mixed and applied at levels of 10, 20, 30 and 40 g/kg free moisture substrate. The outcomes improved with increasing doses of the composite (Shilwant et al., 2023).

In both *in vivo* and *in vitro* studies, polyphenols from *Coleus amboinicus* lour (CAL) included at 20% in the lambs' diet significantly reduced ruminal methane production by suppressing the growth of methanogen bacterial communities. Additionally, CAL supplementation favourably affected the ruminal environment by balancing the development of ruminal microorganisms responsible for fatty acid fermentation and biohydrogenation (Yanza et al., 2022). Additionally, an *in vitro* study by Hundal et al. (2019) investigated the effects of various herbal feed additives on the nutritional value. The study found that a TMR supplemented with *Anethum sowa* at 2% of the substrate resulted in more effective fermentation compared to TMR with other herbal feed additives. This supplementation increased the production of total and individual VFA while reducing methane and ammonia emissions. Another *in vitro* research has shown that the combination of a low dose of eucalyptus oil (5 µl) with mulethi root extract (15 µl) can significantly reduce the rate of ruminal ammonia production ($P < 0.001$) without compromising feed digestion (Chanu et al., 2020). Feeding lactating cows a diet consisting of immature herbage and vine leaves has been shown to decrease methane emissions, as demonstrated for a ration comprising 69% legume-grass herbage, 13% grass hay, and 13% vine leaves (Birkinshaw et al., 2022). Adding green tea and oregano extract to dairy cow diets at concentrations of 0.056% and 0.028%, respectively, enhanced the digestible fraction of ingested DM and reduced methane emissions, measured in g per kg of digestible DMI (Kolling et al., 2018). The CH_4/VFA molar ratio decreased when hop pellets at the highest dose (475 mg/l) were combined with oak extracts, whereas the same additives applied separately exerted no significant effect. Additionally, oak extract, whether used alone at the highest dose (309 mg/l) or in combination with hop pellets, significantly reduced ammonia nitrogen concentrations (Quynh et al., 2018).

PFA effect on milk production and composition

The production of high-quality milk by dairy cattle is closely associated with optimal animal health (Yang et al., 2019). Understanding the nutritional value, technological properties, and traceability of milk requires a thorough examination of potential correlations between feeding systems and milk composition. Such insights could lead to the identification of new biomarker molecules (Li et al., 2020). Consequently, enhancing dairy performance may be achieved by incorporating appropriate feed additives into the diets of lactating animals (Focant et al., 2019). For instance, the addition of *Acacia mearnsii* tannin extract at up to 0.43% on a DM basis did not significantly affect milk yield or composition in Holstein cows, although it did result in a slight reduction in milk urea nitrogen (Oliveira et al., 2023). Canaes et al. (2017) reported no significant effects on milk production, fat-corrected milk (FCM), and fatty acid profile except for a linear reduction in milk fat production when citral oil was included in the diets of Saanen goats. Nubian goats receiving 2–4 g/day/animal of *Boswellia sacra* resin showed a linear ($P < 0.05$) increase in milk yield, energy-corrected milk (ECM), and net energy for lactation (Soltan et al., 2021). Adding a blend of green tea and curcuma extract (95:5) to the diet of lactating cows at 0.175 g resulted in a significant increase ($P < 0.05$) in energy-corrected milk yield (Winkler et al., 2015). Furthermore, including 10% ensiled olive cake in the diet of dairy cows (concentrate-to-roughage ratio of 64:36) led to an increase in milk fat yield, although the percentages of fat and protein, as well as protein yield, remained unchanged (Neofytou et al., 2020). Similarly, replacing maize silage with 60, 120, and 180 g of pomegranate by-product silage in a TMR diet for dairy cows resulted in improved digestibility of NDF and ADF at the levels of 60 and 120 g. While total milk production and ECM increased, milk protein and lactose content decreased at the 120 g level (Khorsandi et al., 2019). In conclusion, the impact of various PFA on milk production and composition varies considerably. Pomegranate by-product silage, green tea, curcuma extract, and *Boswellia sacra* resin have all shown promising effects, whereas tannin extract and citral oil have provided only modest benefits. Further research is necessary to fully realize the benefits of these supplements in enhancing dairy animal health and milk production. The effects of PFA on milk production and composition are summarised in Table 3.

PFA effect on reproductive performance

The unit cost of production in the cow-calf industry is determined by reproductive performance (Rasby and Funston, 2016). Increasing reproductive efficiency is critical for both commercial success and the long-term viability of livestock operations (Swelum et al., 2021). While, modern reproductive technologies have expanded the reproductive performance in various domestic cattle breeds, conventional procedures are also commonly applied to improve reproduction outcomes. Advances in biotechnologies have enabled detailed analysis and modification of reproductive processes both *in vitro* and *in vivo* (Mihaylova et al., 2020). Phytogenics, used as feed additives, serve multiple purposes, including reducing methane emissions and substituting antibiotics (Swelum et al., 2021). Among these, phytoestrogens – phenolic compounds found in plants – are particularly noteworthy for their estrogenic activity, either as agonists or antagonists in mammals (Hashem and Soltan, 2016). According to Swelum et al. (2021), PFA in fresh and conserved semen affected hormone profiles, sperm quality, and animal sexual behaviour. Azimi et al. (2020) studied the effects of purslane aqueous extract (PAE), purslane methanolic extract (PME), and purslane ethanolic extract (PEE) at concentrations of 25, 50, and 100 μm/ml on the quality of frozen-thawed goat spermatozoa. The results demonstrated that PAE at 50 μg/ml, PME at 50 μg/ml, and PEE at 50 μg/ml significantly reduced malondialdehyde (MDA) levels and improved total motility, viability, and mitochondrial activity ($P < 0.05$) compared to the control. Off all extracts studied, PME at 50 μg/ml produced the best results. Another study reported the effect of quercetin in tris citric acid extender at concentrations of 50, 100, 150, and 200 μM on the post-thaw quality and *in vivo* fertility of buffalo spermatozoa. The results showed a significant ($P < 0.05$) improvement in progressive motility (PM%), plasma membrane integrity (PMI%), supra vital plasma membrane integrity (SVPMI%), and acrosome integrity (ACR-1%) following treatment. After thawing, there was a significant increase in sperm SVPMI at 100 and 150 μM, as well as sperm PM and ACR-I at 150 and 200 μM (Ahmed et al., 2019). Similar results were obtained when 1.0% green tea extract (GTE) was added to the tris-citric acid extender. This addition enhanced total antioxidant capacity, increased *in vitro* longevity (%), and *in vivo* fertility, while reducing lipid peroxidation and DNA fragmentation in buffalo bull spermatozoa, following a freezing and thawing procedure (Ahmed et al., 2020). An *in vitro* study demonstrated that the addition of up to 100 μg/ml of *Moringa oleifera* leaf extract, along with reproductive hormones, increased the maturation rate of sheep oocytes. This treatment likely stimulated mRNA expression and the synthesis of essential proteins, such as maturation-promoting factor (MPF) (Barakat et al., 2015). In another *in vitro* study, the

Table 3. Effects of phytogenic feed additives (PFA) on milk production and composition

PFA sources	Dosage	Study type	Animal species	Diet	Result	References
Quercus robur 'oak tannin' (OT) *Humulus lupulus* 'hops' (HP)	169 g of OT; 56 g of HP.	*in vivo*	Holstein lactating cow	TMR	hops (HP) did not affect milk production and composition; OT-HP mixture enhanced the milk's fatty acid composition; α linoleic acid was increased by 17.5%	Focant et al., 2018
Lippia alba hay	30-60-90 g/kg of total DMI	*in vivo*	Alpine goat	TMR	MY, corrected MY$^{3.5\%}$, corrected solids, defatted dry extract, and milk contents ↑ ($P < 0.05$)	Da Silva et al., 2022
Anise, clove, and thyme EO	2 ml/head/day	*in vivo*	Shame goat	TMR	MY, protein, and lactose ↕. Fat yield and fat composition ↑ ($P < 0.05$); milk C12 and C8 FA ↓ ($P < 0.05$); composition of UFA and MUFA ↑ ($P < 0.05$). PUFA ↓ ($P < 0.05$)	El-Essawy et al., 2021
Thyme leaf and celery seeds mixture 1:1	20 g/head/day	*in vivo*	Barki ewes	concentrate and fodder 60:40	WG, ADG, MY, milk component yield, and feed efficiency ↑ ($P < 0.05$); milk composition ↕	Khattab et al., 2020
Capsicum oleoresin	250-500-1000 g/head	*in vivo*	Holstein cow	TMR	MY and energy corrected MY ↑; MF ↕	Oh et al., 2015
Rosemary and lemongrass	10 g of each separately/d/head	*in vivo*	Damascus goat	concentrate and berseem clover	MF and milk production ↑ ($P < 0.05$)	Kholif et al., 2017
PFA mixture	3 g and 6 g/head/d	*in vivo*	Friesian cows	TMR	milk rate, composition, total solids, fat, protein, and lactose ↑ at 3 g	Kholif et al., 2021
Coriander oil	4 g/head/d	*in vivo*	Friesian cow	concentrate and berseem clover	milk production, ECM, MF, milk efficiency ↑ ($P < 0.05$)	Matloup et al., 2017
Propolis	5 g/kg diet	*in vivo*	Barki ewes	concentrate and berseem hay	MY, MF, and milk total solid ↑ ($P < 0.05$)	Shedeed et al., 2019
Dolichos biflorus seed, *Asparagus racemosus* root, *Amoora rohituka* bark Homogeneous blend	20 g/kg of diet	*in vivo*	Beetal goat	Bajra and concentrate 60:40	MY ↑ ($P = 0.017$), lactose, and protein ↑ ($P = 0.045$); MF and solid ↕ ($P > 0.10$); the number of somatic cells ↓ ($P = 0.045$)	Shilwant et al., 2023
Mulberry leaf (flavonoid)	15, 30,45 g/day	*in vivo*	Murrah buffalo	TMR	daily MY ↑ ($P = 0{,}038$) in all levels; T3 and T4 in serum ↑ ($P < 0.05$), FCM, and milk protein ↑ by 45 g	Li et al., 2020
Grape seed and grape mark extract	1% of diet	*in vivo*	Holstein cow	TMR	MY and milk protein yield ↑	Gessner et al., 2015

TMR – total mixed ration, DMI – dry matter intake, FA – fatty acid, UFA – unsaturated fatty acid, MUFA – monounsaturated fatty acid, PUFA – polyunsaturated fatty acid, EO – essential oil, WG – weight gain, ADG – average daily gain, MY – milk yield, MF – milk fat, ECM – energy-corrected milk, FCM – fat-corrected milk, T3 – triiodothyronine, T4 – thyroxine; $P < 0.05$ indicates significant effect of PFA on the given parameters

application of quercetin at concentrations of 1, 10 and 100 ng/ml to cattle ovarian cells resulted in a reduction in proliferating cell nuclear antigen (PCNA) and Bax accumulation. Additionally, the release of progesterone (P4) from granulosa cells, and insulin-like growth factor I (IGF-I) secretion from the cattle cells were increased at the low dose (10 ng), but decreased at the high dose (100 ng) (Sirotkin et al., 2019). Similarly, Ardeshirnia et al. (2017) reported that quercetin concentrations of 5 and 10 μg/ml improved the quality of frozen-thawed ram epididymal spermatozoa.

PFA effect on blood profile

Blood metabolites are commonly applied to diagnose and predict disorders, as well as to assess normal physiology and well-being of animals. Waqas et al. (2023) reported increased blood urea nitrogen levels, and elevated serum globulin and total protein levels when the cows were fed a plant-based additive mixture. These results indicated optimal kidney function, improved nutritional status, increased microbial protein synthesis, and minimal protein catabolism (Waqas et al., 2023).

Weaned dairy heifer calves exposed to heat stress showed a negligible effect of PFA supplementation (Digestarom, DSM Nutritional Products Inc.) on feed intake, average daily gain (ADG), blood O_2 partial pressure, and blood levels of inflammation markers such as haptoglobin and lipopolysaccharide-binding protein (LBP). In all measurements, serum haptoglobin and plasma LBP concentrations were 44% and 38% lower, respectively, in PFA calves compared control calves (Wickramasinghe et al., 2023). Another study supplemented a mixture of cinnamon, turmeric, rosemary, and clove buds to the diet of heat-stress lambs, which resulted in a 1–2% increase in cholesterol but reduced creatinine levels (Hashemzadeh et al., 2022). Moreover, the addition of 250 g/head/day of anise seed powder to the diet of Holstein calves for 60 days did not significantly affect the content of total protein, albumin, glucose, cholesterol, aspartate aminotransferase (AST), gamma-glutamyl transferase (GGT), total antioxidant status (TAS), and total oxidant status (TOS) compared to control (Demirhan and Karafakioğlu, 2022). The effects of PFA on blood profile is presented in Table 4.

Effect of PFA as antioxidants in ruminants

Excessive levels of reactive oxygen species (ROS), such as hydroxyl radical (OH•), superoxide anion radical, or superoxide anion (O_2), are associated with various diseases, such as cancer and cardiovascular disorders (Aqeel et al., 2019). The antioxidant properties of a plant are typically related to its content of phenolic compounds, which generally act by inhibiting oxidation-reduction reactions or scavenging oxygen by donating hydrogen atoms (Amarowicz and Pegg, 2019). In line with this, Piao et al. (2023) have noted that antioxidant compounds in plants can suppress oxidative reactions by donating electrons to metal ions, with polyphenolic compounds demonstrating greater activity and effectiveness compared to vitamins E and C. Secondly, plant extracts, rich in hydroxyl groups similar to flavonoids, can provide more electrons, thereby enhancing antioxidant capacities. This process involves suppressing oxygen atoms and stimulating the production of antioxidant enzymes like glutathione peroxidase (GPx) and superoxide dismutase (SOD) (Purba and Paengkoum, 2022). Furthermore, Hrelia and Angeloni (2020)

Table 4. Effects of phytogenic feed additives (PFA) on blood profile

PFA sources	Dosage	Study type	Animal species	Diet	Result	References
Bee propolis extract	3 g/head/day	*in vivo*	Santa Ines ewes	basal diet	total protein, globulin, and glucose ↑ ($P < 0.05$); cortisol, triiodothyronine, and thyroxine ↓ ($P < 0.05$)	Morsy et al., 2021
Boswellia sacra resin (BS)	2 and 3 g/day/head	*in vivo*	Nubian goats	basal diet	blood plasma glucose, nonesterified free fatty acid, and β-hydroxybutyrate ↓ ($P < 0.01$)	Soltan et al., 2021
Oregano and cinnamon EO, turmeric EO, and tannic acid	300 mg EO/kg and 12.5 mg of turmeric/kg of diet	*in vivo*	Holstein's calves	concentrate	serum glucose ↓, globulin, and total protein ↑	Brunetto et al., 2023
Echinacea purpurea leaf	4-8-12 g/head/day	*in vivo*	Ossimi lambs	TMR	triglycerides, cholesterol and AST ↓.	Tantawi et al., 2023
Red osier dogwood	0.3,0.7 and 0.10% of diet	*in vivo*	beef heifers	high-grain diet	serum amyloid and haptoglobin of plasma ↑	Wei et al., 2019
Capsicum oleoresin	250-500-1000 g/head	*in vivo*	Holstein cow	TMR	blood serum β-hydroxybutyrate, neutrophils, eosinophils, and neutrophil-eosinophil ratio ↑	Oh et al., 2015
Coriander oil	4 g/head/day	*in vivo*	Friesian cow	concentrate and berseem clover	glucose concentration ↑ ($P = 0.013$); short-chain fatty acid ↕ ($P < 0,05$)	Matloup et al., 2017
Carvacrol and limonene	0.5 g/head/day	*in vivo*	Tzigai sheep	grass hay + concentrate	β-hydroxybutyrate ↓ ($P < 0.001$), triglycerides ↓ ($P = 0.014$); nonesterified fatty acid ↓ ($P = 0.021$); fructosamine ↓ ($P = 0.002$)	Varga-Visi et al., 2023
Black rice- purple corn extract 80:20	2, 4, 6% of diet	*in vivo*	male dairy cattle	TMR	glucose, urea, total cholesterol, AST, ALT, and protein carbonyl ↕, but MDA concentration ↑ ($P < 0.05$)	Prommachart et al., 2021

TMR – total mixed ration, EO – essential oil, AST – aspartate aminotransferase, ALT – alanine aminotransferase; $P < 0.05$ indicates significant effect of PFA on the given parameters have indicated that the mitochondria and chloroplasts of plant cells are associated with natural antioxidants, which can be transported to the mitochondria of animal cells when plants are ingested. This transfer can alter oxidative phosphorylation and electron transportation chain processes. The process of oxidation is a vital issue to consider from the first seconds of birth due to the sensitivity of animals to oxidative stress (Piao et al., 2023). This adverse conditions may occur when there is a deficiency of antioxidants, which can help prevent the spread of reactive oxygen species and mitigate their effects (Singh, 2015; Muñoz-Cuautle et al., 2022). Various intrinsic free radicals, and those originating from feed components can react with lipids in the animal body, making them unstable, reducing their nutritional value, and shortening the shelf life of meat (Singh, 2015). Plants and spices are well known as sources of antioxidants, and volatile oils extracted from plants of the family *Labiatae* are most attractive in this regard. Due to having phenolic and terpenoid compounds, rosemary, oregano, and thyme of the family *Labiatae*, as well as spices from the family *Zingiberaceae*, such as anise and coriander, are recognised for their significant antioxidant properties (Hussein et al., 2015). Plant polysaccharides also have scavenging properties that neutralise free radicals in the animal body and can prevent lipid peroxidation by altering the functional length chain of the lipid peroxidation reaction. Additionally, they stimulate the activation of antioxidant enzymes such as GPx and SOD (Hussein et al., 2015). Herbal extracts (HE) are widely used in animal nutrition to improve health status and immunity, and thus their incorporation into animal diets is recommended particularly in addressing oxidative stress (Piao et al., 2023). The findings of Manuelian et al. (2021) have shown that PFA can control oxidative reactions as effectively as synthetic antioxidants such as vitamins E and C. The latter authors argued that while research on PFA has primarily focused on poultry rather than ruminants, there is potential for PFA to serve as a unique alternative to synthetic growth promoters. Similarly, Yang et al. (2015) have argued that PFA can also be successfully substituted as a natural antioxidant with synthetic antioxidants like butylated hydroxytoluene and ethoxyquin. According to Pashtetsky et al. (2020), carvacrol and thymol SM may penetrate the cytoplasmic membrane, disrupt it and subsequently depolarise within the cytoplasm. According to Brunetto et al. (2023), incorporating a mixture of oregano and cinnamon EO with turmeric extract and tannin to the diet of Holstein steers led to a reduction in the levels of thiobarbituric acid reactive substance (TBARS) and ROS; in contrast, there was an increase in the activity of glutathione S-transferase and protein thiol levels. Similarly, Tantawi et al. (2023) reported that the inclusion of 4%, 8%, or 12% *Echinacea purpurea* leaf extract (EP) as a dietary supplement for lambs significantly increased ($P < 0.01$) SOD activity, glutathione levels, and total antioxidant capacity (TAC). Further, a blend of seeds and leaves (75:25) of three Bangladeshi traditional medicinal plants was used as a PFA in the daily feed in post-weaned bull calves, resulting in increased total antioxidant levels and activity of glutathione peroxidase (Bostami et al., 2021). OEO has been shown to act as a potent natural antioxidant, maintaining the stability of lamb meat at a high level (Muñoz-Cuautle et al., 2022). Supplementing lamb diet with a blend of rosemary, cinnamon, turmeric, and clove buds at 2% was shown to enhance total liver antioxidant capacity and reduced MDA levels in the liver (Hashemzadeh et al., 2022). Kumar et al. (2022) found that a mixed leaf meal of eucalyptus and poplar (*Populus deltoides*) (50 g/head/day) containing 0.71 g of condensed tannins, 2.30 g of tannin phenolics, and 3.19 g of phenolics, could positively alter the immune and antioxidant status of buffalo calves. HE have been widely recognised as alternatives to antibiotics due to their active properties. They can reduce oxidative stress in ruminants and positively affect animal meat quality and production (Huang et al., 2018). Supplementing buffalo cattle rations with 1% green tea extract and Tris citric acid extender as feed additives improved total antioxidant capacity (Ahmed et al., 2020). Similarly, a notable increase in antioxidant activities was observed when using PFA from three plant species (*Woodfordia fruticose, Solanum nigrum,* and *Trigonella foenum-graecum*) in the diet of adult goats (Choubey et al., 2015). Adding ethanolic saffron petal extract (SPE) to lamb diets reduced lipid oxidation and enhanced antioxidant status. The antioxidant level in lambs were similarly affected by SPE and vitamin E (Alipour et al., 2019). The antioxidant effects of selected PFA on ruminants are shown in Table 5.

PFA effect on the gut microbiota of ruminants

The antimicrobial properties of PFA have been well-documented in the published research (Skoufos et al., 2020). The active substances responsible for their antimicrobial effects include tannins (Huang et al., 2018) and phenolic compounds

Table 5. Antioxidant effects of selected phytogenic feed additives (PFA) on ruminants

Plant species/PSM	Plant part/ material	Dosage	Study type	Animal species	Diet/material	Result	References
Condensed tannin	–	1, 1.5, and 2%	*in vivo*	Lamb	FILM and wheat bran	G, SOD, and CAT activity, total thiol, protein thiol ($P < 0.05$) ↑, LPO ↓	Dey et al., 2015
PFAs *(Woodfordia fruticose-Solanum nigrum-Trigonella foenum-graecum)*	flowers, shoots, leaves -whole plant, seeds, respectively	2 and 3 %	*in vivo*	Goat	concentrate and roughage	GPx, C, and GST ↑ – non-enzymatic antioxidant ↕	Choubey et al., 2015
Oregano and green tea extract	extract	10 g/day/head-5g/day/head respectively	*in vivo*	Jersey cow	basal diet	oxidative stress biomarker of blood ↓	Vizzotto et al., 2021
Punica granatum PMG. *Caesalpinia spinosa* TA. *Castanea sativa* CH. *Uncaria gambir* GM.	extract	80 μg/ml	*in vitro*	Holstein dairy cow	bovin aortic endothelial cell	antioxidant activity was 63% ↓, 45% ↓, 51% ↓, and 27% ↓ for PMG, GM, CH, and TA, respectively;	Ciampi et al., 2020
Pomegranate	peel + seed	400 g seed + 400 g peels	*in vivo*	Holstein dairy cow	basal diet	PTAA ↑; MDA and blood SOD↕	Safari et al., 2018
Pomegranate peel	extract	0.1, 1.0 and 10 μg/ml	*in vitro*	Dairy cattle	bovine mammary epithelial cell	MDA ↓ (31.1%, $P < 0.001$)	Mastrogiovanni et al., 2020
Astragalus membranaceus	root	1%	*in vivo*	cashmere goat	basal diet	MDA ↓ ($P < 0.01$) – SOD and CAT ↑ ($P < 0.001$)	Luo et al., 2020
Grape	extract	670 mg/head/ day	*in vivo*	Holstein heifer	TMR	Total antioxidant capacity ↑ ($P < 0.05$)	Engler et al., 2022
Mulberry	leaf (flavonoid)	15 g, 30, 45 g/ day	*in vivo*	Murrah buffaloes	TMR	MDA, CAT ↓ ($P = 0.012$); GPx, HSP ↑ ($P < 0.01$); T-AOC ↓ ($P = 0.001$)	Li et al., 2020
Black rice- purple corn	extract	2-4-6% of diet	*in vivo*	male dairy cattle	TMR	MDA ↓ ($P < 0.05$)	Prommachart et al., 2021
Astragalus membranaceus	root	5,1 0, 15, 20, 30 r/kg of diet	*in vivo*	Ram lambs	basal diet	T-SOD, and T-AOC ↑ ($P \leq 0.018$). CAT and MDA ↑ ($P \leq 0.001$)	Hao et al., 2020
Green tea	extract	10 mg/kg/BW/d	*in vivo*	Holstein calves	colostrum and milk replacer	antioxidative status ↕	Maciej et al., 2016
Oregano	essential oil	0.02–0.04% of diet	*in vivo*	Hampshire lamb	basal diet (concentrate)	antioxidant activity ↑ ($P < 0.05$).	Muñoz-Cuautle et al., 2022;
Origanum vulgar, Citrus spp.*,* and *Echinacea* spp. *(*blend 1*) – Capsicum* spp.*, Cinnamomum* spp.*, Eugenia caryophyllata* spp. *(*blend 2*)* + an emulsifier each	extract	Blend 1 (0.11%). Bend 2 (0.0125%) of diet	*in vivo*	Ewes, rams	concentrate barley-based diet	GPx and T-SOD in blood remained unchanged ↕, TBARs ↓	Passetti et al., 2021
Propolis	extract	150-200-250 μl/ kg of BW/day	*in vivo*	lactating lamb	basal diet	↓ ($P = 0.01$) SOD activity, ↑ ($P = 0.01$) non-protein thiols and protein thiols concentration	Cécere et al., 2021
Propolis	extract	5 g/kg of diet	*in vivo*	Barki ewes	basal diet	↓ $P < 0.01$ hydrogen peroxide, nitric oxide, and SOD	Shedeed et al., 2019
Curcuma longa 'Curcumin'	extract	100 mg–200 mg/kg for 30 days	*in vivo*	Nursing lambs	concentrate	↑antioxidant ability of serum against peroxyl radicals ↓ lipoperoxidation	Molosse et al., 2019
Orange peel	essential oils (OPEO)	150 mg-300 mg-450 mg/kg concentrate	*in vivo*	Chios ewes	concentrate and alfalfa hay	blood plasma GPx, GR, and SOD – activities of milk lactoperoxidase ↑ ($P < 0.05$).	Kotsampasi et al., 2018
Woodfordia fruticose, Solanum nigrum, and *Trigonella*	(flowers, shoots, and leaves), (whole plant) and (seeds), respectively	2 and 3% of diet	*in vivo*	Jamunapari goats	concentrate and roughage	↑ ($P < 0.05$) GPx, CAT, and glutathione-S-transferase at 3%; ↕ non-enzymatic antioxidant indices	Choubey et al., 2015

PSM – plant secondary metabolite, FILM – *Ficus infertoria* leaf meal, G – glutathione, SOD – superoxide dismutase, CAT – catalase, LPO – lipid peroxidation, GPx – glutathione peroxidase, GST – glutathione-S-transferase, PTAA – plasma total antioxidant activity, MDA – malondialdehyde, TMR – total mixed ration, HSP – heat shock protein, T-AOC – total antioxidant capacity, T-SOD – total superoxide dismutase; TBARs – thiobarbituric acid reactive substances; OPEO – orange peel essential oil; GR – glutathione reductase, PMG – pomegranate, GM – gambier, CH – chestnut; $P < 0.01$ indicates significant effect of PFA on the given parameters

(Skoufos et al., 2020). Plants such as oregano thyme and sage, which belong to the family *Labiatae* are among the most commonly used for this purpose. The mechanism of action of antimicrobials can be associated with hydrophobic essential oils in these plants, which strongly penetrate microbial cell membranes, fragmenting them, leading to ion leakage. *Sanguinaria canadensis* has also been reported to exhibit remarkable antimicrobial activity (Hussein et al., 2015). Plants contain hydrophobic EO that can penetrate the lipid layers of bacterial cell walls and mitochondria, leading to the accumulation of these oils in the lipid layer. This accumulation disrupts ion transport, compromises membrane integrity, and alters the osmotic pressure of the cell. The decrease in ATP synthesis and increased hydrolysis indicate a rapid dissipation of H+ and K+ ion gradients, which serve as proton-motive sources. This leads to the depletion of the intracellular ATP pool slowing bacterial growth due to reduced transmembrane electric potential and increased membrane proton permeability. Cell death occurs when the loss of vital molecules and ions surpasses the bacterial tolerance threshold (Simitzis, 2017). The result of Álvarez-Martínez et al. (2021) demonstrated that membrane disruption is the main mechanism of action of terpenes, flavones, flavonols, certain alkaloids, and phenylpropanoids, which showed promising antibacterial activity, either alone or in combination with extracts. The potent antimicrobial properties of EO enable them to combat various food-borne and pathogenic bacterial strains, including *Salmonella typhimurium, Escherichia coli, Shigella dysenteria, Bacillus cereus, Pseudomonas aeruginosa, Campylobacter, Listeria monocytogenes,* and *L. innocua* (Stevanović et al., 2018). Researchers have reported significant antimicrobial potential of some plants and substances obtained from them. Clove, cinnamon, and caraway have shown considerable activity (Wickramasinghe et al., 2023), as have turmeric, oregano, thyme, and rosemary (Karásková et al., 2015). Additionally, thymol and thyme (Salehi et al., 2018), carvacrol and thymol (Memar et al., 2017), and OEO have also demonstrated substantial antimicrobial effects (Leyva-López et al., 2017). Red-osier dogwood exhibited the potential to penetrate the membranes of the rumen microbiota (Erinle et al., 2023). Furthermore, the phytochemicals in propolis phytochemicals, also known for their antibacterial properties, can improve ruminal fermentation, and thus provide nutritional benefits for ruminants (Soltan and Patra, 2020). Gilling et al. (2019) reported that the active ingredients in lemongrass, cinnamon, and oregano essential oils – citral, cinnamaldehyde, and carvacrol, respectively – as well as extracts from grape seeds, olive oil, green tea, and allspice buds, can be administered individually, in combination, or in combination with fast-acting antibiotics to produce persistent residues. However, Ye et al. (2018) observed that the addition of monensin or cinnamaldehyde did not significantly reduce protozoan population or methane production under the conditions of their study. Zhou et al. (2020) demonstrated *in vitro* that using different levels of OEO (13 mg/l, 52 mg/l, 91 mg/l, and 130 mg/l) slightly increased the relative abundance of *Prevotella* and *Dialister* bacteria as the concentration of OEO increased. When EO incorporation rates increased, certain bacteria showed distinct polynomial responses, while other reacted in similar patterns. Ashraf et al. (2023) investigated the effectiveness of *Zingiber officinale* (ginger) and *Curcuma longa* (turmeric) against coccidia in sheep. The authors found that administering 300 mg/kg BW of turmeric reduced the number of oocytes by 44.92%, 54.32%, 64.21%, and 61.95% in a 4-week test, respectively. For the same dosage of ginger, the reductions were 39.65%, 54.81%, 57.18%, and 58.22% after 4 weeks, respectively. Additionally, the agar well diffusion method was employed to assess the antimicrobial activity of *Halexylon salicornicum* aqueous and solvent extracts against a range of animal pathogens, including *Salmonella typhimurium*, *Pseudomonas aerogenes*, *Streptococcus pyogenes*, *Escherichia coli*, *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Bacillus cereus*, *Shigella flexneri*, and *Enterococcus faecium*. The extract demonstrated antimicrobial activity against all tested strains of animal pathogens (El-Desoukey et al., 2022). Chan et al. (2018) evaluated the effectiveness of several plant species – *Cinnamomum burmannii, Origanum vulgare* L.*, Syzygium aromaticum* L.*, Cinnamomum cassia Presl, Fallopia japonica Houtt,* and *Punica granatum* L. – against five lactic acid bacteria (LAB) and five food-borne pathogenic bacteria (FBPB). Overall, the findings revealed that phenolic-rich extracts had significant antibacterial activity against FBPB but were less effective against LAB. In another study, 143 different essential oils were tested for their effect on *Staphylococcus aureus* during the stationary phase (Xiao et al., 2020). These authors identified 10 EO as particularly effective against *Staphylococcus aureus* in both the growth and stationary phases (Xiao et al., 2020).

Another study found an effect of residues of 36 plant species on the anaerobic fermentation of alfalfa. Interestingly, species such as *Myristica houtt*, *Elsholtzia ciliata*, *Agastache rusgosa*, *Citrus aurantium*, *Citrus reticulata*, *Atractylodes lancea* T., *Codonopsis pilosula* F., and *Syzygium aromaticum* L., relatively decreased drug resistance, especially in *Salmonella* and *E. coli* strains. Additionally, a reduction in pathogenic bacterial counts was also observed. Increasing the concentration of citrus flavonoid extract (CFE) positively correlated with higher levels of beneficial bacteria, such as *Bifidobacterium* spp., the *Clostridium coccoides-Eubacterium rectale* group, and *Faecalibacterium* in faeces. Conversely, the count of *Ruminococcus torques* and *Rosburia* was reduced after CFE addition, while increasing counts of *Bacteroides* and *Phascolarctobacterium* were recorded (Li et al., 2022). Kholif and Olafadehan (2021) found that high doses of PSM as feed additives inhibited the growth and activity of cellulolytic bacteria in the rumen, while low and moderate doses did not significantly affect bacterial activity. *Halexylon salicornicum* (Moq.) Bunge ex Boiss has been identified as a natural prophylactic antimicrobial and growth promoter, especially beneficial for chicken and cattle farms. It serves as a preferable alternative to chemical antimicrobials in animal feed, with no adverse effects or residues in animal products (El-Desoukey et al., 2022). The effects of selected PFA on ruminant microbial species are illustrated in Table 6.

PFA effects on the immunological status of ruminants

PFA are used in animal nutrition primarily for their potential to enhance the immune system of ruminants (Karásková et al., 2015). According to recent research, plant nutrients exert physiological influence on host animals through receptor-mediated mechanisms, affecting insulin regulation, oxidative stress, and immune responses (Oh et al., 2017). Liu et al. (2020) studied the effects of a combination of essential oils (carvacrol, caryophyllene, p-cymene, cineole, terpinene, and thymol) and prebiotics (arabinogalactans and cobalt lactate at 44.1 ppm) added to the starter diet of newborn Holstein calves. The results demonstrated increased concentrations of IgG, IgM, IgA, and total serum protein in the blood. Similarly, a diet including essential oils of oregano and cinnamon, along with turmeric extract, was fed to Holstein calves. This diet resulted in a reduction in lymphocytes and heavy-chain immunoglobulins, while levels of IgA and ceruloplasmin increased. Brunetto et al. (2023) administered 1.5 g/head/day of *Tribulus terrestris* extract (TTE) in feed and 0.5–1 µl in peripheral blood mononuclear cells demonstrated both *in vivo* and *in vitro* that TTE may modulate immunological responses and induce lymphocyte transformation in rams. This effect occurs by inhibiting lymphocyte DNA degradation and promoting their blastogenic capacity through antioxidant activity, which implies their ability to produce cytokines (Abdelrazek et al., 2018). In another study, curcumin (0.9 mg/kg BW) and a phytogenic blend of thymol, carvacrol, and cinnamaldehyde (2.7 mg/kg BW) were used as an alternative to monensin and flavomycin antibiotics in the diet of Holstein calves. Results revealed that the curcumin and phytogenic blend combination significantly reduced ($P = 0.05$) monocyte and lymphocyte counts, while higher IgA and IgG titres were observed in the curcumin group (Molosse et al., 2022). *Terminalia bellirica* Gaertn. Roxb., *Emblica officinalis* Gaertn., and *Terminalia chebula* Retz. were included in the diet of post-weaned bull calves at a 75:25 ratio of seed to bark for each plant, with 0.5% of each plant used in the ration. All three treatments resulted in a decrease in IGF level, enhanced ($P < 0.05$) lymphocytic proliferation, and increased IgG levels (Bostami et al., 2021). Moreover, propolis supplementation in Barki ewes at 5 g/kg diet resulted in a significant increase ($P < 0.05$) in white blood cell (WBC) counts and IgA titre, while the value of mean corpuscular haemoglobin (MCH) decreased ($P < 0.05$); however, no effect was observed for IgM and IgG titres (Shedeed et al., 2019). Additionally, supplementation with 4.5% licorice extract to a cottonseed hull-based diet for karakul sheep improved IgA and IgG concentrations and elevated total antioxidant capacity (Guo et al., 2019).

Meat composition and carcass quality

Meat is vital to a healthy and well-balanced diet as it is a source of protein, iron, zinc, essential fatty acids, and B vitamins (Wood, 2017) reference. The fatty acid (FA) composition has an impact on the nutritional quality of meat. On the other hand, consumption of excessive amounts of meat has been associated with pathophysiology of cancer and heart failure, with saturated fatty acids (SFA) identified as significant contributors. In contrast, polyunsaturated fatty acid (PUFA), particularly n-3 PUFA, has been recognised for their positive impact on health, including reduced risk of thrombosis and coronary heart disease in humans (Smeti et al., 2018).

Table 6. Effects of selected phytogenic feed additives (PFA) on ruminant microbial species

Plant species/ PSM	Plant part/ material	Dosage	Study type	Animal species	Diet/material	Result	References
Oregano	EO	130 mg/day/head 260 mg/day/head	*in vivo*	Pingliang red cattle	TMR	↑ *Parabacteroides distasonis* and *Bacteroides thetaiotaomicron* counts	Zhang et al., 2021
Oregano	EO	4–7 g/day	*in vivo*	Merino sheep	basal diet	↑ ruminal fungi count at 7 g ↓ ruminal protozoa count; ↕ total ruminal bacteria count; ↑ *R. flavefaciens, R. albus,* and *F. succinogenes* at 4 g	Zhou et al., 2019
Aloe vera	Extract	3% of total ration	*in vivo*	Rathi calve	TMR	↓ protozoal counts and ruminal ammonia-N	Bhati et al., 2017
Enterolobium cyclocarpum (Jacq) Griseb. and *Gliricidia sepium* (Jacq.) Steud	Foliage and pods	15-30-45%	*in vivo*	Heifer	basal diet (*Brachiaria brizantha* "Hochst; ex A; rich; " Stapf)	↕ methanogenic archaea, total protozoa, and total bacteria in the rumen population	Molina-Botero et al., 2019
Propolis	Extract	150-200-250 µl/kg of BW/day	*in vivo*	lactating lamb	basal diet	↓ ($P = 0.01$) counts of *Escherichia coli* and total coliform counts in faeces	Cécere et al., 2021
Cymbopogon citratus (lemongrass)	EO	–	*in vitro*	Agar well diffusion method	–	generated inhibition zone against *Staphylococcus aureus, Bacillus subtilis* and *Bacillus cereus*, was 32.0 ± 0.75, 48.0 ± 1.05 and 21.0 ± 0.64 mm respectively; the inhibition zone against *Proteus vulgaris* was 23.0 ± 0.73 mm; and no inhibition zone for *Pseudomonas aeruginosa* and *E. coli* were detected	Shendurse et al., 2021
Thymol, cinnamaldehyde, and eugenol	EOM	1 g/kg of diet 2 g/kg of diet	*in vitro*	strained rumen fluid	–	↑ *ruminococcus albus* and *Selenomonas ruminantium* $P < 0.001$ and $P < 0.005$ ↑ *Ruminococcus flavefaciens, Butyrivibrio fibrisolvens*, and fungi $P < 0.001$	Kim et al., 2019
Oregano ORO, garlic GAO, peppermint PEO	EO	0.50 g/l	*in vitro*	rumen fluid	–	ORO and GAO ↓ *Firmicutes* phylum counts- PEO ↑ *Firmicutes* phylum counts ORO and PEO ↑ *Bacteroidetes* phylum counts all EOs ↓ *Butyrivibrio* genus; 67 single OTUs, (operational taxonomic units)," exhibit substantial differences ($P \leq 0.05$)	Patra and Yu, 2015
PPC	feed additive	mixture of alfalfa and PPC in a ratio of 40:60 (DM basis)	*in vivo*	lamb	fresh forage	*E. coli* O157:H7 faecal shedding ↓	Huang et al., 2015
Carvacrol and limonene	extract	0.5 g/head/day	*in vivo*	Tzigai sheep	grass hay + concentrate	number of nematode eggs in faeces ↓ ($P = 0.02$); *Haemonchus contortus* nematodes in abomasum ↕	Varga-Visi et al., 2023
Eucalyptus camaldulensis	leaf meal	40,80 and 120 g/h/day	*in vivo*	Swamp buffalo	concentrate and rice straw.	protozoa and proteolytic bacteria were ↓ ($P < 0.05$); fungal zoospores, total viable bacteria, amylolytic, cellulolytic ↕	Thao et al., 2015

EO – essential oil, EOM – essential oil mixture, PPC – purple prairie clove, TMR – total mixed ration, DM –dry matter; $P < 0.01$ indicates significant effect of PFA on the given parameters

Table 7. Effects of selected phytogenic feed additives (PFA) on meat characteristics

PFA sources	Dosage	Study type	Animal species	Diet	Result	References
Mesquite pods (*Prosopis juliflora*) extract	6 ml/day/each group	*in vivo*	Santa Ines × Dorper F1 crossbred lambs	pasture and supplementation	performance, exterior carcass measurements, leg weight, femoral muscles, carcass weight, and commercial cuts ↓ ($P < 0.05$)	Coelho et al., 2020
Foeniculum vulgare seed powder	0.75 and 1.5% of diet	*in vivo*	Male lambs	forage-concentrate 40:60	Weights of both warm and cold carcass, lean meat, testicles, gallbladder, loin, and eye muscle area ↑ ($P < 0.05$) at 1.5% than control.	Hajalizadeh et al., 2019
REO	0.3 and 0.6 ml/head/day	*in vivo*	lamb	oat-hay and concentrate	Acceptability and flavour ↑ ($P < 0.05$). Total PUFA ↑. Omega-6, PUFA/SFA and n-6/n-3 percentages ↑.	Smeti et al., 2018
Blend of essential oils of (oregano, garlic, lemon, rosemary, thyme, eucalyptus and sweet orange)	3.5 g and 7 g/head/day	*in vivo*	crossbred young bull	sugarcane: concentrate 10:90	Meat colour, chemical and FA composition and WHC ↕. LO ↓ at 3.5 g. 7g resulted to pro-oxidant effects.	Guerrero et al., 2014

REO – rosemary essential oils, PUFA – poly unsaturated fatty acid, SFA – saturated fatty acid, WHC – water holding capacity, LO – lipid oxidation, FA – fatty acids; $P < 0.05$ indicates significant effect of PFA on the given parameters

A meta-analysis examining the effects of EO as a replacement for monensin in beef cattle diets showed improved parameters of the ribeye area (weighted mean differences (WMD) = 0.82 cm^2; $P < 0.0001$), subcutaneous fat thickness (WMD = 0.56 mm; $P < 0.0001$), and carcass dressing percentage (WMD = 0.38%; $P = 0.03$) (Torres et al., 2021). Meanwhile, Piran Filho et al. (2021) found that a PFA mixture containing cinnamon, caraway, licorice, and vanilla increased the carcass weight and DMI of F1 Angus × Nellore bulls. Adding daily a blend of oregano oil and cobalt (4 g and 7 g) to the basal diet of Suffolk lambs improved carcass weight and dressing percentages ($P < 0.01$) (7 g) compared to other treatments;. head width was also greater ($P > 0.01$) at 7 g, while rump width increased ($P > 0.01$) in lambs fed both doses of the blend (Piran Filho et al., 2021). The addition of rosemary and clove EO and an active principal blend (eugenol, thymol, and vanillin) to a concentrated diet of Nellore heifers (up to 4 g/head/day), alone or in combination, had no effects ($P > 0.05$) on fat thickness, marbling, pH, muscle area, thawing, and drip loss; however, colour, texture lipid oxidation, and cooking loss ($P < 0.05$) were affected by the EO treatments, in comparison to the control diet, EO and the active principle blend decreased lipid oxidation, cooking loss, and color loss (de Oliveira Monteschio et al., 2017). The effects of selected PFA on meat quality parameters are shown in Table 7.

Conclusions

Continuous efforts are being made to produce high-quality products that benefit human health and are central to animal nutrition science. This review emphasised the benefits, as well as nutritional and medicinal properties of plants used as feed additives in ruminants. Interest in phytogenic feed additives is increasing due to the unique ability of ruminants to efficiently utilise plants and their by-products. Commonly used plants such as oregano, rosemary, thyme, coriander, garlic, eucalyptus, anise, clove, peppermint, cinnamon, turmeric, or drumstick have shown satisfactory results, particularly as antioxidant and growth promoters. Additionally, fruit extracts such as mulberry, pomegranate, and grape seed have been shown to positively impact performance, digestibility, milk production, immunity, and antioxidant status. However, the use of plant extracts faces several challenges, including limited production, underdeveloped extraction technologies, unclear dosing guidelines based on species, weight, and age, high cost and inconsistent effects. Additionally, there have been relatively few animal feeding studies and limited research on the mechanisms of action of many plant extracts. To address these challenges, further research is needed to elucidate the mechanisms of various phytogenic feed additives and their practical applications in ruminant nutrition.

Conflict of interest

The Authors declare that there is no conflict of interest.

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