Animal Reports
An open access peer reviewed journal
https://animalreportsjournal.com/
Animal reports, 2025, 1: 41-59

Modern nutritional approaches to mitigating enteric methane emissions in ruminants: A review

Sabrin Abdalrahman Morshedy [1,*]

1. Fish and Animal Production Department, Faculty of Agriculture (Saba Basha), Alexandria University, Alexandria, Egypt

Corresponding author(s): Morshedy, S. A.; Sabrin_morshedy@alexu.edu.eg

Article Info.
Submitted*: 1/5/2025*
Revised*: 23/5/2025*
Accepted*:25/5/2025*
Online*: 27/5/2025*
Doi: pending
Cite as: Morshedy, S. A. (2025) Modern nutritional approaches to mitigating enteric methane emissions in ruminants: A review. Animal Reports, 1: 41-59.

Abstract: Sustainable livestock production increased public concern towards reducing greenhouse gases. The emission of enteric methane from ruminants, if not well managed, contributes to a significant loss of energy consumed and a marked environmental challenge. Methane has <80 times higher global warming potential than CO_2. Enteric methane contributes by >40% of agricultural emissions and 13-19% of global methane emissions. Furthermore, the increased demand for animal protein sources, especially in developing countries, highlights the pressure on greenhouse gas emissions. Therefore, the search for a methane mitigating strategy is a continuous series and a hot topic in animal nutrition laboratories. There are several mitigating nutritional strategies with varying mitigating potentials from 10 to 90% associated with or without digestion or growth complications. These solutions include the use of new ingredients such as insect meal, modulating the quality of food, the inclusion of lipids, and increased concentrate: roughage ration, which decreased CH_4 approximately by 18%, 30%, 6% and 50% in the best situations. Furthermore, feed additives have considerable effects on CH4 emissions by inhibiting methanogenesis or competing with substrates for methanogens, such as nanoengineered or nanoencapsulated materials, CH_4 inhibitors (statins, bromochloromethan, and 3-NOP) that could inhibit CH4 production by 90%. Several phytobiotic feed additives, including tannins, saponins, and essential oils, have moderate CH4 inhibition effect up to 30%. Seaweed was reported to have nearly complete inhibition of CH4 of the Asparagopsis, Ascophyllum, Dictyota and Rhodophyta genes in vitro or in vivo evaluation. However, the application of these solutions still faces some barriers, including cost, availability, efficacy across production systems, and potential impacts on animal productivity. This review evaluates the mechanisms, effectiveness, and nutritional implications of these nutritional strategies, with particular attention to their applicability in different ruminant production systems (in vivo and in vitro models) for more sustainable production.

Keywords: Enteric CH_4; nutritional strategies; CH_4 inhibitors; insect meal; nanotechnology; feed additives.

1 Introduction

With the growth of the population and increased nutritional awareness, the demand for animal protein products (meat, milk, and processed animal products) is increasing. This increase is associated with serious environmental impacts and triggers public health and environmental concerns related to greenhouse gases produced by ruminants (Ban & Guan, 2021). Worldwide efforts have been paid of trying to control the increase in greenhouse gas production and increased atmospheric temperature above 1.5 ℃ by 20250 to maintain global warming at a safe level (Reisinger et al., 2025). This commitment needs to reach zero greenhouse gases emissions globally by 2050, which means an equilibrium between emitted gases and the recovery of these gases by the environment (Matthews & Wynes, 2022).

Ruminants have a unique digestive system that adapts to utilized low quality feed and forage and digests complex fiber sources during fermentation process to produce easy digested substrates and new nutrients, including volatile fatty acids (VFA), vitamins, proteins, ….. etc. (Owens & Basalan, 2016). This process performed by a group of anerobic microbes in a complex ecosystem including bacteria, protozoa, and fungi that have adaptability, interactions, and symbiotic relationship (Castillo-González et al., 2014). The rumen is a suitable environment for these microorganisms to grow and reproduce and get energy from the animal feed, at the same time it facilitates roughage and low-quality grass digestion and conversion to highly nutrients in their microbial body mass that can be used by the host finally (Wanapat et al., 2013). On the other hand, the fermentation process produces some by-products, such as carbon dioxide and H_2, with the latter used by Methanogens to produce CH_4 (Owens & Basalan, 2016).

Ruminants consider the main CH_4 producer in the agriculture sectors, whereas they contribute by >40% of CH_4 emission from agriculture greenhouse gases (Dillon et al., 2021) and 13-19% of the global CH_4 emissions (Liu & WB., 2008). CH_4 has 86 times global warming potential that of CO_2 during the last 20 years (IPCC, 2021). Furthermore, CH_4 causes a significant energy loss averaged 8-12% of total consumed feed, which consequently causes significant economic loss (Johnson KA & DE., 1995). CH_4 emissions also represent part of energy losses during ruminant farming. On average, approximately 8 to 12% of the energy consumed in feed is wasted in the form of CH_4 emissions (Johnson & Johnson, 1995). Few numbers of the largest meat and dairy companies (35) produced 14% of total livestock greenhouse gases emissions and currently they have to acquire the possible strategies to decrease this emissions (Leahy et al., 2020). Figure 1 showed the contribution of different main sectors to CH_4 emission. It showed that the agriculture sector represents the second source of CH_4 after the energy sector.

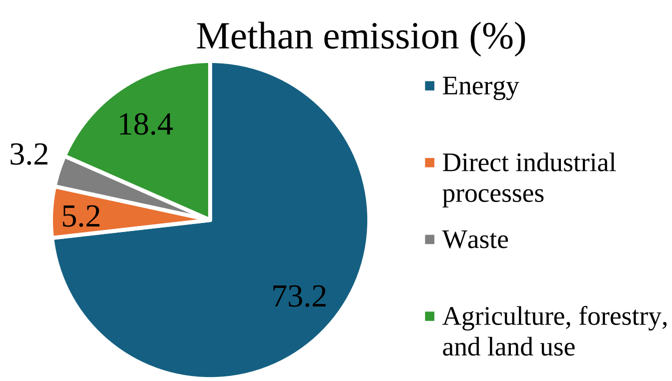

Fig. (1) Contribution of the main sectors to CH_4 (%) emission (Ritchie, 2020; Dillon et al., 2021).

The attempts to reduce CH_4 emission from ruminants are the worldwide focus of animal nutrition scientists. Hundreds of attempts have been conducted, including management, genetics, and nutritional strategies (chemical and antimicrobial compounds) to modify the microbial structure or the fermentation process to reduce CH_4 production and enhance energetic efficiency (Owens & Basalan, 2016). The review aims to provide a comprehensive resource for researchers, nutritionists, and policymakers seeking novel nutritional-based solutions to alleviate or mitigate CH_4 emission from livestock and overcome these sustainability challenges.

2 Methane production in the rumen and Methanogenesis

Understanding CH_4 production in ruminants requires examination of the rumen's complex microbial ecosystem (Patra et al., 2017). The responsible microorganisms for CH_4 production in rumen is methanogens, which are several species of anaerobic organisms (120 species) that can utilize carbon dioxide and hydrogen to produce CH_4. The methanogens usually grow at pH range of 6.0–8.0 and can utilized hydrogen, formate, methanol, methylamine, acetate, etc. as a substrate (Sirohi et al., 2010; Cersosimo & Wright, 2015). The rumen methanogens community structure differs from ruminant species to others and also feed type, in *Mandya* sheep fed on straw and concentrate diet *Bacteroidetes* and *Firmicutes* represent 82% of the bacterial community and *Methanobacteriales* constituted of 13% of the community, while Archaea acount 2.5% of the ruminal microbiota (Malik et al., 2022).

The CH_4 production process begins in the rumen by breaking down plant polysaccharides by fiber-digesting bacteria (e.g., *Ruminococcus* spp.) producing H_2 as a byproduct (Gleason, 2021). This H_2 is then utilized by methanogenic archaea (primarily *methanobrevibacter* spp.) to reduce CO_2 to CH_4 through the hydrogenotrophic pathway (Liu et al., 2017). In addition, rumen ciliate protozoa play a crucial role by hosting Methanogens in symbiotic relationships, accounting for up to 37% of total Methanogenesis (Gleason, 2021).

Several dietary factors significantly influence the CH_4 production process, high-fiber diets promote acetate production (a major H_2 source), while starch-rich diets favor propionate formation, which acts as an H_2 sink (Li et al., 2022; Chiariotti, 2023). Animal-related factors also contribute, with breed differences and the production stage affecting emission rates (Ghassemi Nejad et al., 2024; Muetzel et al., 2024). Recent advances in microbial genomics have revealed substantial diversity in rumen methanogen populations, suggesting potential for targeted microbial interventions (Ghassemi Nejad et al., 2024). The ratio of acetate to propionate in rumen fermentation serves as a key indicator of CH_4 production potential, with higher acetate: propionate ratios typically associated with greater CH_4 emissions (Morgavi et al., 2010; Vanhatalo & Halmemies-Beauchet-Filleau, 2020).

3 Dietary Strategies for CH_4 Mitigation

3.1 Insects as novel feed ingredients

Recently, the use of edible insects as a feedstuff is increasing, where it introducing nutritious and cost-efficient feed ingredients (Hong & Kim, 2022). Its impacts on rumen fermentation and CH_4 production need to be extensively addressed. Ahmed et al. (2021) reported that substitution of 25% of soyabean with *Gryllus bimaculatus* and *Brachytrupes portentosus* meal significantly decreased CH_4 production by 18% and 16%, respectively.

In addition, in male beef cattle, cricket (*G. bimaculatus*) meal using as a 100% substitution levels of soyabean meal significant increased VFA, and propionate concentrations, with significant decrease of CH_4 production and protozoal populations (Phesatcha et al., 2023). Eight full-fat insect meals were examined in comparison with conventional plant protein sources by *in vitro* experiment. The used insect meal markedly reduced total gas production, CH_4 emission, total VFA, ammonia level, and organic matter disappearance compared to plant proteins (Renna et al., 2022).

Black soldier fly larva oil has been used in *in vitro* study up to 6% in 40:60 roughage to concentrate ratio. The results indicated that 4% is the suitable addition level with significant low level CH_4 production and suitable digestibility coefficients (Prachumchai & Cherdthong, 2023). The modulation effects of insect meal or oil on ruminal fermentation could be attributed to its chitin, fat, and protein contents, and the high level of unsaturated fatty acids that could inhibit rumen fermentation (Renna et al., 2022).

3.2 Forage quality and management

One of the main strategies to mitigate CH_4 production is considering the quality of dietary forage. Legumes like alfalfa and clover typically produce 15-20% lower CH_4 yields (g CH_4/kg DMI) than grasses due to their lower fiber content and faster rumen passage rates (Hatew, 2015). Bannink et al. (2016) reported that CH_4 emission intensity changed in dairy cattle fed grass herbage and grass silage by 5.6% to 7.3% of gross energy intake and 27.4 to 36.9 g CH_4/kg digested OM, and 19.7 to 24.6 g CH_4/kg dry matter, respectively. Sheep (Romney ewe hoggets) fed alfalfa silage substituted with increasing levels of corn silage (25, 50, 75 or 100%) or corn grain (25, 50 or 65% rolled corn grain) on a DM basis at a fixed DMI level (2% of BW). The results revealed that emission of CH_4/DMI increased with increasing substitution levels up to 50% with both corn silage and corn grain then decreased gradually but not than that of 100% alfalfa silage (Jonker et al., 2016).

In growing beef cattle, the effect of vegetative and mature fresh pasture forage and supplementation with maize silage or palm kernel expeller on CH_4 production (g/day) and yield (g/kg dry matter intake; DMI) was studied in growing beef cattle. No clear differences were observed in CH_4 production between feeding of vegetative or mature pasture. However, using 100% maize silage increased the CH_4 yield by 23.80%. Also, supplementation with maize silage increased CH_4 production by 10% than cattle fed mature pasture only or supplemented with palm kernel expeller (Jonker et al., 2015). These studies revealed that improving forage quality represents one of the most accessible CH_4 mitigation strategies for pasture-based systems (Bannink et al., 2016; Jonker et al., 2016; Macome et al., 2017).

Furthermore, pasture management could also affect CH_4 production. Feeding dairy cows with whole-plant corn silage at different maturity levels (25-40% dry matter) showed that increasing harvest maturity level reduced CH_4 production linearly without negatively affecting cow performance (Hatew et al., 2016). In another study, forage maturity at harvest significantly impacts CH_4 emission potential, with early cutting forages (vegetative stage) reducing emissions by up to 30% compared to mature forages (Ramin & Huhtanen, 2013). Therefore, strategic grazing management, including rotational systems that maintain forage at optimal growth stages, can further enhance these benefits while improving overall system productivity. Furthermore, increasing starch levels in the diet affect CH_4 production in cows fed diets total mixed ration of (60% grass silage and 40% concentrate on DM basis). *In situ* incubation of starch showed that CH_4 production was decreased in fast than slow and in high starch–based diets than low starch-based diet (Hatew, Podesta, et al., 2015). However, trade-offs exist, as higher-quality forages may require more intensive management and potentially higher production costs. In tropical systems, the introduction of tannin-rich legumes like Leucaena leucocephala has shown particular promise, reducing CH_4 by 22% while improving protein supply (Animut et al., 2008).

3.3 Lipid supplementation

Lipid supplementation reduces enteric CH_4 emissions primarily through the biohydrogenation of unsaturated fatty acids (UFAs) in the rumen (Bayat & Shingfield, 2012). The mechanism by which UFAs (linoleic acid (C18:2) or linolenic acid (C18:3)) can control CH_4 emission is the ability of rumen bacteria to convert them into saturated fatty acids (SFAs) by incorporating hydrogen (H_2) into their carbon chains (Yang et al., 2024). This process competitively reduces the availability of H_2 for Methanogenic archaea, thereby suppressing CH_4 (CH_4) production (Caro et al., 2016). Furthermore, this mechanism differs depending on fat source, in steers grazing tallgrass-prairie alone or supplemented with whole cottonseed, bypass fat, or a supplement containing soybean oil. All fat supplemented groups had lower CH_4 production than the control group. This effect may have resulted from reduced ADF digestibility (Beck et al., 2019). Also, in grazing steers fed 1% linseed oil supplementation reduced CH_4 emissions by 38% when expressed in mg/d/kg BW (Carvalho et al., 2016). Additionally, certain lipids (e.g., medium-chain fatty acids like lauric acid, C12:0) exhibit direct antimicrobial effects on Methanogens by disrupting their cell membranes (Soliva et al., 2004). Studies indicate that for every 1% increase in dietary lipid content (up to 6–7% of dry matter intake, DMI), CH_4 yield (g CH_4/kg DMI) decreases by 5.6% on average (Martin et al., 2010). On the other hand, Cross-bred Aberdeen Angus steers feed increasing oil levels only tended to reduce in CH_4. However, the combination with nitrate supplementation could enhance the decrease of CH_4 production (Duthie et al., 2018).

In sheep, supplementation with fat had high suppression effects on CH_4 production based on meta analysis (Patra, 2014). Dietary increasing levels of macadamia cake (4.5%, 8.5%, and 14% on a dry matter basis) as a high nutritional value ingredients with reach source of lipids reducing daily production of enteric CH_4 without negatively affect the nutrient digestibility and ruminal fermentation up to inclusion levels of 14% (Takahashi et al., 2024). However, fat can be possible mitigation methods to CH_4 emission, some implication could be experienced with high fat inclusion rate, including reduce microbial attachment, altering fibrolytic bacteria, fiber degradation (Toral et al., 2009; Shinkai et al., 2012).

3.4 Concentrate feeding and starch-rich diets

Rumen microorganisms enable to digest the cellulose rich feed stuff (roughage) to VFA that can be used by the animal as a source of energy and finally converted to meat and milk, however a by-products of this process were elaborated, including hydrogen and CO2 which can be utilized by Methanogens to produces CH_4 (Nadeem & Sufyan, 2005). Several previous studies evaluated the potential of manipulating the roughage-to-concentrate ratio to reduce the formation of gases. However, increasing non-fiber roughage or concentrate (starch) directed the rumen fermentation process toward propionate production rather than acetate (Wang et al., 2018). Propionate considers electron acceptors, in another words, acts as a hydrogen sink and competing with methanogens for available hydrogen (Wang et al., 2023).

The level of starch inclusion, fermentation rate (slow, medium, and rapid) or its form (native and gelatinized) significantly affect CH_4 production in cow or *in vivo* studies. Whereas high inclusion rate, rapid and gelatinized starch reduced CH_4 production (Hatew, Cone, et al., 2015).

The effect could also be due to the bypass of 30% of starch to the small intestine without fermentation avoiding methanogenesis in the rumen (Harmon et al., 2004).

Wang et al. (2018) reported in an *in vitro* experiment that reducing neutral detergent fiber content from 24.0 to 15.8% with maintaining other dietary ingredients at the same ration causes a 14.06% decrease in CH_4 production. In another study, increasing starch in cows diets increased total rumen VFA levels, decreased acetate production without differences in rumen pH, or ruminal CH_4 production (Darabighane et al., 2021).

Furthermore, forage-to-concentrate ratio positively affects the fermentation process in ruminants and subsequent CH_4 emissions. The increase in forage: concentrate from 68:32 to 39:61 respectively, significantly reduced CH_4 emissions by 27.2 and13.8% in Holsteins cows and Jerseys cows, respectively (Olijhoek et al., 2018). In grazing Jersey cows on ryegrass pasture, increasing concentrate supplementation levels (0, 4, and 8 kg/cow/day) linearly decreased enteric CH_4 production without affecting VFA concentrations and ruminal pH (Van Wyngaard et al., 2018). In *in vitro* study using rumen fluid inoculum grazing cows feed on Italian rye grass and different concentrate levels (2, 5, and 8 kg/animal/day). The use of a high concentrate level increased total gas and propionate with decreased CH_4 production (Kim et al., 2018). CH_4 emission decreased by 48% in Holestine cows fed a diet with 91% concentrate (Olijhoek et al., 2022). Recently, the effect of using agriculture by-products, including spent mushroom, hempseed cake, red and green apple pomace, coffee by-products, and distiller's dried grains with soluble at a level of 100, 200 and 300 g kg^{-1}, the *in vitro* results revealed a linear decrease of gas production and CH_4 emissions. The maximum percent of CH_4 production was 33.6% with inclusion of 300 g kg^{-1} (Xue et al., 2025).

The increasing in concentrate or starch percent in the ruminal diet represents promising mitigation approaches to CH_4 production, meanwhile this process could have some trade-offs such as ruminal acidosis (Elmhadi et al., 2022). Lambs fed diets with 25% starch or higher decreased blood pH and HCO_3 values with the potential risk of subacute acidosis (Şevket & KARSLI, 2024). Starch infusion in cow acclimated to high fiber diet decreased fecal pH as an indication of hindgut acidosis (Abeyta et al., 2023). Ruminal acidosis could be associated with ruminal microbial modulation and several heath complications, including rumenitis, milk fat depression, inflammation, laminitis, and liver abscesses (Elmhadi et al., 2022).

4 Feed Additives

Feed additives are widely used in commercial ruminants production systems not only improving animal health and production performance, but also to modulate ruminal microbiota to low CH_4 emissions (Newbold & Rode, 2006). Several pathways were identified for controlling CH_4 production by feed additives including suppressing of methanogenesis or competing with substrate for methanogens (Honan et al., 2021; Sun et al., 2021). Fig. 2 illustrated complications and mitigation strategies of methane production in rumen.

4.1 Nono-feed additives

Nanotechnology is a cutting-edge technique for mitigating CH_4 emissions from ruminants. Nanoengineered materials have enhanced properties depending on the type, size, and synthesize methods, including absorption, adsorption, and cation exchange capacity (Mahler et al., 2012). These properties could increase the potential of using nano-substances in controlling enteric CH_4 emissions. Zn-nanoparticles reduced the microbial population, CH_4 production and hydrogen sulfide in automated gas production system during 72 hours at 500 and 1000 μg g^{-1} (Sarker et al., 2018). Furthermore, *in vitro* gas production model, the addition of Zn oxide and nano-Zn at increasing levels (20, 40, and 60 mg Zn/kg DM) significantly decreased CH_4 emissions and protozoa count at level of 20 mg normal or nano-Zn form. The increase in Zn levels (40, and 60 mg Zn/kg DM) did not add any positive effects (Riazi et al., 2019). Green-synthesized CuO and ZnO nanoparticles have been added to rumen fluid up to 20 mg/ml with using alfalfa (*Medicago sativa*) hay as the main substrate. Both nanoparticle significantly decreased CH_4 emission, protozoa colonization, *in vitro* gas production, however CuO negatively affect ruminal fermentation (Palangi et al., 2024).

The nanomodified natural adsorbents also showed a high efficiency of CH_4 mitigation. The use of nano-montmorillonite (MNM) coated with cetyltrimethylammonium bromide at a dose of 0.5 g / kg of DM significantly reduced CH_4 emission and improved in vitro nutrient digestion (Soltan et al., 2021). Nano-zeolite was tested compared to natural zeolite *in vitro* and *in vivo* using goats on rumen fermentation. The *in vitro* experiment indicated that both forms of zeolite have affected CH_4 emission in a linear model. In the *in vivo* experiment, both zeolite forms increased total short-chain fatty acids and butyrate concentrations and significantly decreased ammonia levels (El-Nile et al., 2021). Recently, urea-impregnated nano-zeolite was added to sheep diet, which significantly reduced CH_4 emissions in its heat activated form and significantly increased the production of acetate, propionate, butyrate, and total VFA (Kardaya et al., 2025).

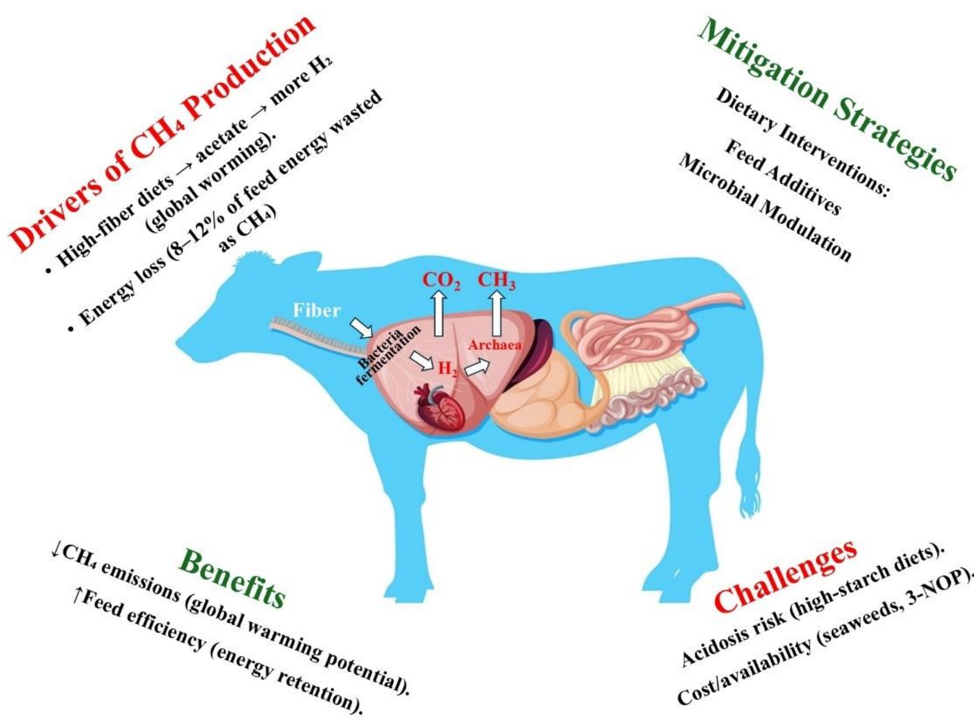

Fig. Methane production complication and dietary mitigation strategies.

Nano-encapsulation technique is widely used in the field of animal nutrition to enhance animal performance, taste and texture of the diet, protecting active components and reducing wastes (Garba & Fırıncıoğlu, 2023). Furthermore, nano-encapsulated *Yucca schidigera* extract (0.25, 0.5, and 1 mL/g DM) was used *in vitro* experiments using bulls' ruminal fluid. All supplementation significantly increased gas production and decreased CH_4, CH_4 conversion efficiency, CO, and H_2S emissions (Botia-Carreño et al., 2024). The nano-encapsulated threonine, methionine, tryptophan, and lysine were tested on *in vitro* gas production experiment. The use of nano-encapsulated methionine recorded the lowest significant CH_4 production and the highest metabolizable energy, while nano-encapsulated threonine reported the lowest (De Jesús et al., 2024).

4.2 CH_4 inhibitors

Several statin compounds (simvastatin, atorvastatin, and rosuvastatin) were used as a CH_4 inhibitor in an *in vitro* experiment at levels starting from 1: 100 mg/L. All tested level reduced CH_4 production and the highest effective was simvastatin and the lowest was rosuvastatin (Joch et al., 2022). The metabolites of *Monascus ruber* (mainly lovastatin) were tested as anti-methanogenic and showed a linear decreasing effect on CH_4 production (Boudra et al., 2024). Furthermore, lovastatin was examined using the rumen inoculum of sheep, goats, and cows. It showed a marked lowering effect on CH_4 emission, especially in sheep rumen, more than other tested rumen. Total VFA was not affected, but acetate and valerate were decreased (Ábrego-García et al., 2024).

3-nitrooxypropanol (3-NOP) inclusion in dairy cow total mixed ration at dose of 60 mg/kg for 15 days decreased CH_4 emission (26%), emission yield (27%), and emission intensity (29%), without any negative effects on feed efficiency or productive performance (Melgar et al., 2021). Van Wesemael et al. (2019) determined the effect of 3-NOP supplantation methods in dairy cows and found that inclusion in roughage or concentrates efficiently reduced CH_4 production by 28 and 23%, respectively.

A 1-year 3-NOP supplementation experiment was conducted using Holstein-Friesian dairy cows to identify the long-term effects of 69.8 mg of 3-NOP / kg of DM on milk production and CH_4 emission. The results indicated an overall reduction of 21% in CH_4 production; however, the effect of 3-NOP decreased over time. The yields of energy and fat and protein corrected milk increased by 6.5% compared to the control (van Gastelen et al., 2024). 3-NOP is a highly specific CH_4 inhibitor that inhibits the nickel enzyme methyl-coenzyme M reductase and disrupts CH_4 synthesis in the rumen methanogens (Duin et al., 2016).

BromochloroCH_4-cyclodextrin was also used as a dietary supplementation in steers rumen and induced an absence of Methanogenic archaeal with 4.5-times higher *Lachnospiraceae* (Matsui et al., 2020). A combination of chloroform and 9,10-anthraquinone was used as CH_4 inhibitor in the solid diets of the young calves during the first 12 weeks and was monitored for 49 weeks of rearing. The treated animal showed nearly CH_4 inhibition (90% reduction) with increasing H2 emissions also the acetate: propionate ratio decreased, meanwhile the microbial community was not affected by treatment which means that treatment affected the microbial metabolic pathways (Cristobal-Carballo et al., 2021).

Furthermore, the addition of active carbon at a level of 0.5% reduced 30-40% of CH_4 emissions and 10% of CO_2 production associated with decreased of Methanogenic flora by 30% and increased the nonmethanogenic species (Al-Azzawi et al., 2021). A novel activated carbon-rich mineral supplement was used to mitigate at 0 - 6% DM level *in vitro* experiments using Rhodes grass hay substrate and rumen fluid from Holstein-Friesian steers. The treatment inhibits

CH_4 production up to 29.32% without negative effects on total VFA production and DM digestibility (Tahery et al., 2025).

4.3 Phytobiotic compounds

Secondary metabolites from plants could be used to mitigate gas production. The rumen-cannulated *Merino wethers* fed encapsulating *Acacia mearnsii* tannin extract showed a reduction in CH_4 production of 19% and 30% with encapsulating and crude tannin extract, respectively (Adejoro et al., 2019). The increasing in tannin in the cattle diet to 12.5 g/kg DM by including of green tea by-product significantly reduced CH_4 emission without compromising animal performance (Khoa et al., 2018). In Nellore (*Bos indicus*) and Holstein (*Bos taurus*) cows fed tannin extract at increasing levels of 0. 0.5, 1, 1.5% of dry matter. The threshold for suppression of CH_4 emissions was 0.72% of tannin supplementation, and the effect was significantly increased with increasing supplementation levels (Perna Junior et al., 2023).

The effect of tannin extract from different forage species was tested compared to rutin on gas and CH_4 production at increasing levels (10, 20, and 30 g/kg DM). The results showed that tannin causes 15% CH_4 reduction at the highest level of supplementation, while rutin did not affect its production (Verma et al., 2024). The mixture of tannin from quebracho and chestnut in individual or in combination with essential oil (EO) blends were used *in vitro*. The addition of tannin induced a reduction of ammonia production by 31% and CH_4 emission by 15% (Foggi et al., 2022).

Effect of three essential oils (sage, pine, and clove) supplementation with increasing levels (300, 600, and 900 mg/L) on *vitro* ruminal fermentation characteristics was evaluated using rumen inoculum from three mature ewes. The gas and CH_4 production were significantly reduced with all essential oil and the best effect was reported with clove oil (Bokharaeian et al., 2023). Furthermore, garlic, thyme, clove, orange peel, mint, and cinnamon significantly reduced CH_4 and gas production *in vitro* at a level of 300 ppm (Rofiq et al., 2021). In non-pregnant female ewes fed dietary supplementation with essential oils blend (essential oils and polyphenols), bioflavonoids and chestnut tannins had lower CH_4 production by 13% than control animals (Atzori et al., 2023). Moreover, using *Pinus koraiensis* cone essential oil (PEO) at a level of 1g/kg diet reduced CH_4 production by 67% *in vitro* model based on 50:50 roughage to concentrate ratio (Choi et al., 2023).

Dietary saponin alone or in combination with nitrate and sulphate at level of 1.5% of concentrate feed significantly reduced CH_4 production in calves by 11.84, 26.78, and 38% with nitrate and sulphate, or nitrate and saponin or combination with nitrate, sulphate and saponin, respectively (Yadav et al., 2021). The saponins reach *Sesbania graniflora* pods meal extract was used in at increasing level (0, 0.2, 0.4, and 0.6%). The results indicated a significant reduction in decreased protozoal population, CH_4 emission in a dose-dependent manner (Unnawong et al., 2021). Lactating Beetal goats fed plant extract (CPE) rich in polyphenolics and saponins experienced a higher proportion of VFA and propionate with lower concentrations of acetate, CH_4 and ammonia. This effect is associated with higher production performance and animal health (Shilwant et al., 2023).

4.4 Seaweeds and algae

Algae and algae extracts were investigated to control CH_4 emission *in vivo* and *in vitro* models with suppression levels reaching 91% of emission. Total gas and CH_4 production were significantly reduced phlorotannins extracted from seaweed *Ascophyllum nodosum* in a dose-dependent manner (Wang et al., 2008). An *in vitro* experiment was carried out to evaluate the effect of 20 tropical marine and freshwater macroalgae on gas and CH_4 production using rumen fluid from cattle fed low-quality roughage. The results indicate that all examined macroalgae induced significant reduction in gas and CH_4 production and the highest effective species are *Dictyota* and *Asparagopsis* with suppression of gas production by 53.2% and 61.8%, and CH_4 production by 92.2% and 98.9% after 72 h, respectively (Machado et al., 2014).

Increasing dietary levels of *A. taxiformis* in the sheep diet reduced total VFA production and acetate levels with increasing propionate concentrations. Therefore, it was associated by 80% reduction in CH_4 emission after 72 days of experiment (Maia et al., 2016). Using rumen fluid cannulated Holstein cows and supplanted with 0.5% *Rhodophyta* sp. extracts increased cumulative gas production with decreased CH_4 production and ciliate-associated methanogens , and improved acetate/propionate ratio (Lee et al., 2017).

In dairy cattle, red seaweeds, *A. armata*, was used as a feed additive to mitigate CH_4 production at levels of 0.5 to 1%. CH_4 production was decreased by 26.4% and 67.2% at 0.5% and 1% *A. armata* supplementation level respectively (Breanna M Roque et al., 2019). *In vitro* evaluation showed a marked reduction in CH_4 production by tropical macroalgae, *A. taxiformis*, from 38.7 mL/g DM in the control to 0.20 mL/g DM in 2% algal supplemented treatment, that represent 90% suppression effectiveness (Chagas et al., 2019). The use of red macroalgae *A. taxiformis* at dose of 0.5% significantly reduced CH_4 production in a semi-continuous *in vitro* rumen system by 95% without any negative effect on other fermentation parameters. The same study suggested that *A. taxiformis* CH_4 suppression effect could attributed to rapid metabolic alteration in rumen Methanogens to inhibit CH_4 production and extended decline in methanogen abundance (Breanna Michell Roque et al., 2019). The main mode of action of seaweeds CH_4 inhibition is due to the presence of bromoform compound which disrupts vitamin B_{12}-dependent enzymes in Methanogens , and blocking the final step of CH_4 synthesis (Glasson et al., 2022).

5 Conclusion

This review highlighted the potential of different modern nutritional strategies to mitigate enteric methane emission. Among the reviewed strategies, insect meal as a novel feedstuff has potential methane mitigating effects. However, methane inhibitors that include feed additives (nanomaterials, statins, bromochloromethan, 3-NOP, photobiotics, and seaweed) have a promising effect in somewhat blocking methane production. As the world seeks sustainable production of animal protein, the reduction of methane could be of prime importance for producers, scientists, and policymakers to achieve the SDGs goals. Integrated approaches that combine feeding management, customized feed additives and precision feeding may offer sustainable pathways for CH_4 reduction without compromising animal performance.

Authors Contribution:

Sabrin A. Morshedy: Conceptualization, Investigation, Software, Methodology, Validation, Formal analysis, Writing-Original Draft, Writing-Review & Editing

Ethical approval:

Not applicable.

Informed consent:

Not applicable.

Conflict of interest statement

The authors declare no conflict of interest.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

6 References

Abeyta, M., Horst, E., Goetz, B., Rodriguez-Jimenez, S., Mayorga, E., Al-Qaisi, M., & Baumgard, L. (2023). Effects of hindgut acidosis on inflammation, metabolism, and productivity in lactating dairy cows fed a high-fiber diet. *Journal of dairy Science*, *106*(4), 2879-2889. https://doi.org/10.3168/jds.2022-22680.

Ábrego-García, A., Medina-Mendoza, G. G., & Miranda-Romero, L. A. (2024). The Anti-Methanogenic Activity of Lovastatin in Batch Cultures Using Rumen Inoculum from Sheep, Goats, and Cows. *Fermentation*, *10*(8), 393. https://doi.org/10.3390/fermentation10080393.

Adejoro, F. A., Hassen, A., & Akanmu, A. M. (2019). Effect of lipid-encapsulated acacia tannin extract on feed intake, nutrient digestibility and methane emission in sheep. *Animals*, *9*(11), 863. https://doi.org/10.3390/ani9110863.

Ahmed, E., Fukuma, N., Hanada, M., & Nishida, T. (2021). Insects as novel ruminant feed and a potential mitigation strategy for methane emissions. *Animals*, *11*(9), 2648. https://doi.org/10.3390/ani11092648.

Al-Azzawi, M., Bowtell, L., Hancock, K., & Preston, S. (2021). Addition of activated carbon into a cattle diet to mitigate GHG emissions and improve production. *Sustainability*, *13*(15), 8254. https://doi.org/10.3390/su13158254.

Animut, G., Puchala, R., Goetsch, A., Patra, A., Sahlu, T., Varel, V., & Wells, J. (2008). Methane emission by goats consuming diets with different levels of condensed tannins from lespedeza. *Animal Feed Science and Technology*, *144*(3-4), 212-227. https://doi.org/10.1016/j.anifeedsci.2007.10.014.

Atzori, A., Porcu, M., Fulghesu, F., Ledda, A., & Correddu, F. (2023). Evaluation of a dietary blend of essential oils and polyphenols on methane emission by ewes. *Animal Production Science*, *63*(15), 1483-1493. https://doi.org/10.1071/AN23070.

Ban, Y., & Guan, L. L. (2021). Implication and challenges of direct-fed microbial supplementation to improve ruminant production and health. *Journal of animal science and biotechnology*, *12*(1), 109. https://doi.org/10.1186/s40104-021-00630-x.

Bannink, A., Warner, D., Hatew, B., Ellis, J., & Dijkstra, J. (2016). Quantifying effects of grassland management on enteric methane emission. *Animal Production Science*, *56*(3), 409-416. https://doi.org/10.1071/AN15594.

Bayat, A., & Shingfield, K. J. (2012). Overview of nutritional strategies to lower enteric methane emissions in ruminants. *Suomen Maataloustieteellisen Seuran Tiedote*(28), 1-7. https://doi.org/10.33354/smst.75433.

Beck, M., Thompson, L., Williams, G., Place, S., Gunter, S., & Reuter, R. (2019). Fat supplements differing in physical form improve performance but divergently influence methane emissions of grazing beef cattle. *Animal Feed Science and Technology*, *254*, 114210. https://doi.org/10.1016/j.anifeedsci.2019.114210.

Bokharaeian, M., Ghoorchi, T., Toghdory, A., & Esfahani, I. J. (2023). The dose-dependent role of sage, clove, and pine essential oils in modulating ruminal fermentation and biohydrogenation of polyunsaturated fatty acids: a promising strategy to reduce methane emissions and enhance the nutritional profile of ruminant products. *Applied Sciences*, *13*(20), 11605. https://doi.org/10.3390/app132011605.

Botia-Carreño, E. O., Elghandour, M. M., Khusro, A., Velazquez, D. R., Kreuzer-Redmer, S., & Salem, A. Z. (2024). Nano-encapsulated Yucca extract as feed additives: Ruminal greenhouse gas emissions of three forages. *AMB Express*, *14*(1), 142-158. https://doi.org/10.1186/s13568-024-01803-3.

Boudra, H., Rathahao-Paris, E., Hohenester, U., Traikia, M., Gauthier, M., & Morgavi, D. (2024). Antimethanogenic activity of Monascus metabolites in the rumen revealed by the concentration of statins, their diversity and the presence of acid forms. *Animal Feed Science and Technology*, *314*, 116013. https://doi.org/10.1016/j.anifeedsci.2024.116013.

Caro, D., Kebreab, E., & Mitloehner, F. M. (2016). Mitigation of enteric methane emissions from global livestock systems through nutrition strategies. *Climatic Change*, *137*, 467-480. https://doi.org/10.1007/s10584-016-1686-1.

Carvalho, I. P. C. d., Fiorentini, G., Berndt, A., Castagnino, P. d. S., Messana, J. D., Frighetto, R. T. S., Reis, R. A., & Berchielli, T. T. (2016). Performance and methane emissions of Nellore steers grazing tropical pasture supplemented with lipid sources. *Revista Brasileira de Zootecnia*, *45*(12), 760-767. https://doi.org/10.1590/S1806-92902016001200005.

Castillo-González, A., Burrola-Barraza, M. E., Domínguez-Viveros, J., & Chavez-Martinez, A. (2014). Rumen microorganisms and fermentation. *Archivos de medicina veterinaria*, *46*(3), 349-361.

Cersosimo, L. M., & Wright, A.-D. G. (2015). Rumen methanogens. In A. K. Puniya, R. Singh, & D. N. Kamra (Eds.), *Rumen microbiology: From evolution to revolution* (pp. 143-150). Springer.

Chagas, J. C., Ramin, M., & Krizsan, S. J. (2019). *In vitro* evaluation of different dietary methane mitigation strategies. *Animals*, *9*(12), 1120. https://doi.org/10.3390/ani9121120.

Chiariotti, A. (2023). Rumen environmental and nutritional strategies to mitigate emissions from livestock. *Cuban Journal of Agricultural Science*, *57*. https://orcid.org/0000-0003-0828-4610.

Choi, Y., Lee, S. J., Kim, H. S., Eom, J. S., Jo, S. U., Guan, L. L., Seo, J., Lee, Y., Song, T., & Lee, S. S. (2023). Assessment of the Pinus koraiensis cone essential oil on methane production and microbial abundance using in vitro evaluation system. *Animal Feed Science and Technology*, *299*, 115640. https://doi.org/10.1016/j.anifeedsci.2023.115640.

Cristobal-Carballo, O., McCoard, S. A., Cookson, A. L., Ganesh, S., Lowe, K., Laven, R. A., & Muetzel, S. (2021). Effect of methane inhibitors on ruminal microbiota during early life and its relationship with ruminal metabolism and growth in calves. *Frontiers in microbiology*, *12*, 710914. https://doi.org/10.3389/fmicb.2021.710914.

Darabighane, B., Tapio, I., Ventto, L., Kairenius, P., Stefański, T., Leskinen, H., Shingfield, K. J., Vilkki, J., & Bayat, A.-R. (2021). Effects of starch level and a mixture of sunflower and fish oils on nutrient intake and digestibility, rumen fermentation, and ruminal methane emissions in dairy cows. *Animals*, *11*(5), 1310. https://doi.org/10.3390/ani11051310.

De Jesús, J. A. C., Elghandour, M. M. M. Y., Adegbeye, M. J., Aguirre, D. L., Roque-Jimenez, J. A., Lackner, M., & Salem, A. Z. M. (2024). Nano-encapsulation of essential amino acids: ruminal methane, carbon monoxide, hydrogen sulfide and fermentation. *AMB Express*, *14*(1), 109. https://doi.org/10.1186/s13568-024-01767-4.

Dillon, J. A., Stackhouse-Lawson, K. R., Thoma, G. J., Gunter, S. A., Rotz, C. A., Kebreab, E., Riley, D. G., Tedeschi, L. O., Villalba, J., & Mitloehner, F. (2021). Current state of enteric methane and the carbon footprint of beef and dairy cattle in the United States. *Animal Frontiers*, *11*(4), 57-68. https://doi.org/10.1093/af/vfab043.

Duin, E. C., Wagner, T., Shima, S., Prakash, D., Cronin, B., Yáñez-Ruiz, D. R., Duval, S., Rümbeli, R., Stemmler, R. T., & Thauer, R. K. (2016). Mode of action uncovered for the specific reduction of methane emissions from ruminants by the small molecule 3-nitrooxypropanol. *Proceedings of the National Academy of Sciences*, *113*(22), 6172-6177. https://doi.org/10.1073/pnas.1600298113.

Duthie, C., Troy, S., Hyslop, J., Ross, D., Roehe, R., & Rooke, J. (2018). The effect of dietary addition of nitrate or increase in lipid concentrations, alone or in combination, on performance and methane emissions of beef cattle. *animal*, *12*, 280-287. https://doi.org/10.1017/S175173111700146X.

El-Nile, A., Elazab, M., El-Zaiat, H., El-Azrak, K. E.-D., Elkomy, A., Sallam, S., & Soltan, Y. (2021). *In vitro* and *in vivo* assessment of dietary supplementation of both natural or nano-zeolite in goat diets: Effects on ruminal fermentation and nutrients digestibility. *Animals*, *11*(8), 2215. https://doi.org/10.3390/ani11082215.

Elmhadi, M. E., Ali, D. K., Khogali, M. K., & Wang, H. (2022). Subacute ruminal acidosis in dairy herds: Microbiological and nutritional causes, consequences, and prevention strategies. *Animal Nutrition*, *10*, 148-155. https://doi.org/10.1016/j.aninu.2021.12.008.

Foggi, G., Terranova, M., Conte, G., Mantino, A., Amelchanka, S. L., Kreuzer, M., & Mele, M. (2022). In vitro screening of the ruminal methane and ammonia mitigating potential of mixtures of either chestnut or quebracho tannins with blends of essential oils as feed additives. *Italian Journal of Animal Science*, *21*(1), 1520-1532. https://doi.org/10.1080/1828051X.2022.2130832.

Garba, A. M., & Fırıncıoğlu, S. Y. (2023). Role of Encapsulation Nutrients for Improvement of Ruminant Performance and Ruminant Derived–Products. *Eurasian Journal of Agricultural Research*, *7*(2), 109-126.

Ghassemi Nejad, J., Ju, M.-S., Jo, J.-H., Oh, K.-H., Lee, Y.-S., Lee, S.-D., Kim, E.-J., Roh, S., & Lee, H.-G. (2024). Advances in methane emission estimation in livestock: A review of data collection methods, model development and the role of AI technologies. *Animals*, *14*(3), 435. https://doi.org/10.3390/ani14030435.

Glasson, C. R., Kinley, R. D., de Nys, R., King, N., Adams, S. L., Packer, M. A., Svenson, J., Eason, C. T., & Magnusson, M. (2022). Benefits and risks of including the bromoform containing seaweed Asparagopsis in feed for the reduction of methane production from ruminants. *Algal Research*, *64*, 102673. https://doi.org/10.1016/j.algal.2022.102673.

Gleason, C. B. (2021). *Improving the Understanding of Factors Driving Rumen Fermentation* Institute and State University]. Blacksburg, Virginia.

Harmon, D., Yamka, R., & Elam, N. (2004). Factors affecting intestinal starch digestion in ruminants: A review. *Canadian Journal of Animal Science*, *84*(3), 309-318. https://doi.org/10.4141/A03-077.

Hatew, B. (2015). *Low emission feed: opportunities to mitigate enteric methane production of dairy cows* Wageningen University and Research].

Hatew, B., Bannink, A., Van Laar, H., De Jonge, L., & Dijkstra, J. (2016). Increasing harvest maturity of whole-plant corn silage reduces methane emission of lactating dairy cows. *Journal of dairy Science*, *99*(1), 354-368. https://doi.org/10.3168/jds.2015-10047.

Hatew, B., Cone, J., Pellikaan, W., Podesta, S., Bannink, A., Hendriks, W., & Dijkstra, J. (2015). Relationship between in vitro and in vivo methane production measured simultaneously with different dietary starch sources and starch levels in dairy cattle. *Animal Feed Science and Technology*, *202*, 20-31. https://doi.org/10.1016/j.anifeedsci.2015.01.012.

Hatew, B., Podesta, S., Van Laar, H., Pellikaan, W., Ellis, J., Dijkstra, J., & Bannink, A. (2015). Effects of dietary starch content and rate of fermentation on methane production in lactating dairy cows. *Journal of dairy Science*, *98*(1), 486-499. https://doi.org/10.3168/jds.2014-8427.

Honan, M., Feng, X., Tricarico, J., & Kebreab, E. (2021). Feed additives as a strategic approach to reduce enteric methane production in cattle: Modes of action, effectiveness and safety. *Animal Production Science*, *62*, 14. https://doi.org/10.1071/AN20295.

Hong, J., & Kim, Y. Y. (2022). Insect as feed ingredients for pigs. *Animal bioscience*, *35*(2), 347. https://doi.org/10.5713/ab.21.0475.

IPCC. (2021). *Summary for policymakers," in Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Joch, M., Vadroňová, M., Výborná, A., & Jochová, K. (2022). Inhibition of *in vitro* rumen methane production by three statins. *Annals of Animal Science*, *22*(1), 271-282. https://doi.org/10.2478/aoas-2021-0022.

Johnson KA, & DE., J. (1995). Methane emissions from cattle. *Journal of Animal Science*, *73*, 2483-2492. https://doi.org/10.2527/1995.7382483x.

Jonker, A., Lowe, K., Kittelmann, S., Janssen, P., Ledgard, S., & Pacheco, D. (2016). Methane emissions changed nonlinearly with graded substitution of alfalfa silage with corn silage and corn grain in the diet of sheep and relation with rumen fermentation characteristics in vivo and *in vitro*. *Journal of Animal Science*, *94*(8), 3464-3475. https://doi.org/10.2527/jas.2015-9912.

Jonker, A., Muetzel, S., Molano, G., & Pacheco, D. (2015). Effect of fresh pasture forage quality, feeding level and supplementation on methane emissions from growing beef cattle. *Animal Production Science*, *56*(10), 1714-1721. https://doi.org/10.1071/AN15022.

Kardaya, D., Sudrajat, D., Wahyuni, D., Gopar, R., & Pramartaa, I. (2025). Rumen metrics in sheep fed diets enriched with urea-impregnated nano-zeolites. *J. Anim. Health Prod*, *13*(2), 223-234. https://dx.doi.org/10.17582/journal.jahp/2025/13.2.223.234.

Khoa, M., Quang, N., Thang, T., Phung, T., & Kien, T. (2018). Effect of tannin in green tea by-product in combination with bio-char supplemented into basal beef cattle diet on nutrient digestibility, methane production and animal performance. *Open Journal of Animal Sciences*, *8*(03), 206. https://doi.org/Open10.4236/ojas.2018.83015.

Kim, S.-H., Mamuad, L. L., Kim, E.-J., Sung, H.-G., Bae, G.-S., Cho, K.-K., Lee, C., & Lee, S.-S. (2018). Effect of different concentrate diet levels on rumen fluid inoculum used for determination of in vitro rumen fermentation, methane concentration, and methanogen abundance and diversity. *Italian Journal of Animal Science*, *17*(2), 359-367. https://doi.org/10.1080/1828051X.2017.1394170.

Leahy, S., Clark, H., & Reisinger, A. (2020). Challenges and prospects for agricultural greenhouse gas mitigation pathways consistent with the Paris agreement. *Front. Sustain. Food Syst.*, *4*, 69. https:/doi.org/10.3389/fsufs.2020.00069.

Lee, S. J., Shin, N. H., Jeong, J. S., Kim, E. T., Lee, S. K., & Lee, S. S. (2017). Effect of Rhodophyta extracts on in vitro ruminal fermentation characteristics, methanogenesis and microbial populations. *Asian-Australasian journal of animal sciences*, *31*(1), 54-62. https://doi.org/0.5713/ajas.17.0620.

Li, Q. S., Wang, R., Ma, Z. Y., Zhang, X. M., Jiao, J. Z., Zhang, Z. G., Ungerfeld, E. M., Le Yi, K., Zhang, B. Z., & Long, L. (2022). Dietary selection of metabolically distinct microorganisms drives hydrogen metabolism in ruminants. *The ISME Journal*, *16*(11), 2535-2546. https://doi.org/10.1038/s41396-022-01294-9.

Liu, C., Meng, Q., Chen, Y., Xu, M., Shen, M., Gao, R., & Gan, S. (2017). Role of age-related shifts in rumen bacteria and methanogens in methane production in cattle. *Frontiers in microbiology*, *8*, 1563. https://doi.org/10.3389/fmicb.2017.01563.

Liu, Y., & WB., W. (2008). Metabolic phylogenetic and ecological diversity of the methanogenic archaea. *Annals of the New York Academy of Sciences*, *1125*, 171-189. https://doi.org/10.1196/annals.1419.019.

Machado, L., Magnusson, M., Paul, N. A., de Nys, R., & Tomkins, N. (2014). Effects of marine and freshwater macroalgae on in vitro total gas and methane production. *PLoS One*, *9*(1), e85289. https://doi.org/10.1371/journal.pone.0085289.

Macome, F., Pellikaan, W. F., Hendriks, W., Dijkstra, J., Hatew, B., Schonewille, J., & Cone, J. W. (2017). In vitro gas and methane production of silages from whole-plant corn harvested at 4 different stages of maturity and a comparison with in vivo methane production. *Journal of dairy Science*, *100*(11), 8895-8905. https://doi.org/10.3168/jds.2017-12953.

Mahler, G. J., Esch, M. B., Tako, E., Southard, T. L., Archer, S. D., Glahn, R. P., & Shuler, M. L. (2012). Oral exposure to polystyrene nanoparticles affects iron absorption. *Nature nanotechnology*, *7*(4), 264-271. https://doi.org/10.1038/nnano.2012.3.

Maia, M., Fonseca, A., Oliveira, H., Mendonça, C., & Cabrita, A. (2016). The potential role of seaweeds in the natural manipulation of rumen fermentation and methane production. *Sci. Rep.*, *6*, 32321. https://doi.org/10.1038/srep32321.

Malik, P., Trivedi, S., Kolte, A., Sejian, V., Bhatta, R., & Rahman, H. (2022). Diversity of rumen microbiota using metagenome sequencing and methane yield in Indian sheep fed on straw and concentrate diet. *Saudi Journal of Biological Sciences*, *29*(8), 103345. https://doi.org/10.1016/j.sjbs.2022.103345.

Martin, C., Morgavi, D. P., & Doreau, M. (2010). Methane mitigation in ruminants: from microbe to the farm scale. *animal*, *4*(3), 351-365. https://doi.org/10.1017/S1751731109990620.

Matsui, H., Tajima, K., & Itabashi, H. (2020). Diversity of prokaryotes in the rumen of steers fed a diet supplemented with or without bromochloromethane, an anti-methanogenic compound. *Japan Agricultural Research Quarterly: JARQ*, *54*(2), 179-183. https://doi.org/10.6090/jarq.54.179.

Matthews, H. D., & Wynes, S. (2022). Current global efforts are insufficient to limit warming to 1.5 C. *Science*, *376*(6600), 1404-1409. https://doi.org/10.1126/science.abo3378.

Melgar, A., Lage, C., Nedelkov, K., Räisänen, S., Stefenoni, H., Fetter, M., Chen, X., Oh, J., Duval, S., & Kindermann, M. (2021). Enteric methane emission, milk production, and composition of dairy cows fed 3-nitrooxypropanol. *Journal of dairy Science*, *104*(1), 357-366. https://doi.org/10.3168/jds.2020-18908.

Morgavi, D. P., Forano, E., Martin, C., & Newbold, C. J. (2010). Microbial ecosystem and methanogenesis in ruminants. *animal*, *4*(7), 1024-1036. https://doi.org/10.1017/S1751731110000546.

Muetzel, S., Hannaford, R., & Jonker, A. (2024). Effect of animal and diet parameters on methane emissions for pasture-fed cattle. *Animal Production Science*, *64*(3), AN23049. https://doi.org/10.1071/AN23049.

Nadeem, A., & Sufyan, A. (2005). Partial replacement of forage fiber with non-forage fiber in ruminant ration: a review. *Pakistan Journal of Vetrinary Science*, *25*(2), 92-97.

Newbold, C. J., & Rode, L. (2006). Dietary additives to control methanogenesis in the rumen. International congress series, https://doi.org/10.1016/j.ics.2006.03.047.

Olijhoek, D., Hellwing, A. L. F., Noel, S. J., Lund, P., Larsen, M., Weisbjerg, M. R., & Børsting, C. F. (2022). Feeding up to 91% concentrate to Holstein and Jersey dairy cows: Effects on enteric methane emission, rumen fermentation and bacterial community, digestibility, production, and feeding behavior. *Journal of dairy Science*, *105*(12), 9523-9541. https://doi.org/10.3168/jds.2021-21676.

Olijhoek, D., Løvendahl, P., Lassen, J., Hellwing, A., Höglund, J., Weisbjerg, M., Noel, S., McLean, F., Højberg, O., & Lund, P. (2018). Methane production, rumen fermentation, and diet digestibility of Holstein and Jersey dairy cows being divergent in residual feed intake and fed at 2 forage-to-concentrate ratios. *Journal of dairy Science*, *101*(11), 9926-9940. https://doi.org/10.3168/jds.2017-14278.

Owens, F. N., & Basalan, M. (2016). Ruminal fermentation. In D. Millen, M. De Beni Arrigoni, & R. Lauritano Pacheco (Eds.), *Rumenology* (pp. 63-102). Springer Nature. https://doi.org/10.1007/978-3-319-30533-2_3.

Palangi, V., Macit, M., Nadaroglu, H., & Taghizadeh, A. (2024). Effects of green-synthesized CuO and ZnO nanoparticles on ruminal mitigation of methane emission to the enhancement of the cleaner environment. *Biomass Conversion and Biorefinery*, *14*(4), 5447-5455. https://doi.org/10.1007/s13399-022-02775-9.

Patra, A., Park, T., Kim, M., & Yu, Z. (2017). Rumen methanogens and mitigation of methane emission by anti-methanogenic compounds and substances. *Journal of animal science and biotechnology*, *8*, 1-18. https://doi.org/10.1186/s40104-017-0145-9.

Patra, A. K. (2014). A meta-analysis of the effect of dietary fat on enteric methane production, digestibility and rumen fermentation in sheep, and a comparison of these responses between cattle and sheep. *Livestock Science*, *162*, 97-103. https://doi.org/10.1016/j.livsci.2014.01.007.

Perna Junior, F., Galbiatti Sandoval Nogueira, R., Ferreira Carvalho, R., Cuellar Orlandi Cassiano, E., & Mazza Rodrigues, P. H. (2023). Use of tannin extract as a strategy to reduce methane in Nellore and Holstein cattle and its effect on intake, digestibility, microbial efficiency and ruminal fermentation. *Journal of Animal Physiology and Animal Nutrition*, *107*(1), 89-102. https://doi.org/10.1111/jpn.13702.

Phesatcha, B., Phesatcha, K., Matra, M., & Wanapat, M. (2023). Cricket (*Gryllus bimaculatus*) meal pellets as a protein supplement to improve feed efficiency, ruminal fermentation and microbial protein synthesis in Thai native beef cattle. *Animal bioscience*, *36*(9), 1384. https://doi.org/10.5713/ab.23.0107.

Prachumchai, R., & Cherdthong, A. (2023). Black soldier fly larva oil in diets with roughage to concentrate ratios on fermentation characteristics, degradability, and methane generation. *Animals*, *13*(15), 2416. https://doi.org/10.3390/ani13152416.

Ramin, M., & Huhtanen, P. (2013). Development of equations for predicting methane emissions from ruminants. *Journal of dairy Science*, *96*(4), 2476-2493. https://doi.org/10.3168/jds.2012-6095.

Reisinger, A., Fuglestvedt, J. S., Pirani, A., Geden, O., Jones, C. D., Maharaj, S., Poloczanska, E. S., Morelli, A., Johansen, T. G., & Adler, C. (2025). Overshoot: A Conceptual Review of Exceeding and Returning to Global Warming of 1.5° C. *Annual Review of Environment and Resources*, *50*. https://doi.org/10.1146/annurev-environ-111523-102029.

Renna, M., Coppa, M., Lussiana, C., Le Morvan, A., Gasco, L., & Maxin, G. (2022). Full-fat insect meals in ruminant nutrition: in vitro rumen fermentation characteristics and lipid biohydrogenation. *Journal of animal science and biotechnology*, *13*(1), 138. https://doi.org/10.1186/s40104-022-00792-2.

Riazi, H., Rezaei, J., & Rouzbehan, Y. (2019). Effects of supplementary nano-ZnO on in vitro ruminal fermentation, methane release, antioxidants, and microbial biomass. *Turkish Journal of Veterinary & Animal Sciences*, *43*(6), 737-746. https://doi.org/10.3906/vet-1905-48.

Ritchie, H. (2020). *Sector by sector: where do global greenhouse gas emissions come from?*

Rofiq, M., Negara, W., Martono, S., Gopar, R., & Boga, M. (2021). Potential effect of some essential oils on rumen methane reduction and digestibility by in vitro incubation technique. IOP Conference Series: Earth and Environmental Science,

Roque, B. M., Brooke, C. G., Ladau, J., Polley, T., Marsh, L. J., Najafi, N., Pandey, P., Singh, L., Kinley, R., & Salwen, J. K. (2019). Effect of the macroalgae *Asparagopsis taxiformis* on methane production and rumen microbiome assemblage. *Animal Microbiome*, *1*, 1-14. https://doi.org/10.1186/s42523-019-0004-4.

Roque, B. M., Salwen, J. K., Kinley, R., & Kebreab, E. (2019). Inclusion of Asparagopsis armata in lactating dairy cows' diet reduces enteric methane emission by over 50 percent. *Journal of Cleaner Production*, *234*, 132-138. https://doi.org/10.1016/j.jclepro.2019.06.193.

Sarker, N. C., Keomanivong, F., Borhan, M., Rahman, S., & Swanson, K. (2018). In vitro evaluation of nano zinc oxide (nZnO) on mitigation of gaseous emissions. *Journal of Animal Science and Technology*, *60*, 1-8. https://doi.org/10.1186/s40781-018-0185-5.

Şevket, E., & KARSLI, M. A. (2024). Determinating the relationship between starch level and acidosis in high starch containing diets in lambs. *Large Animal Review*, *30*(3), 137-144. https://orcid.org/0000-0002-3081-9450.

Shilwant, S., Hundal, J. S., Singla, M., & Patra, A. K. (2023). Ruminal fermentation and methane production *in vitro,* milk production, nutrient utilization, blood profile, and immune responses of lactating goats fed polyphenolic and saponin-rich plant extracts. *Environmental Science and Pollution Research*, *30*(4), 10901-10913. https://doi.org/10.1007/s11356-022-22931-y.

Shinkai, T., Enishi, O., Mitsumori, M., Higuchi, K., Kobayashi, Y., Takenaka, A., Nagashima, K., & Mochizuki, M. (2012). Mitigation of methane production from cattle by feeding cashew nut shell liquid. *Journal of dairy Science*, *95*(9), 5308-5316. https://doi.org/10.3168/jds.2012-5554.

Sirohi, S., Pandey, N., Singh, B., & Puniya, A. (2010). Rumen methanogens: a review. *Indian journal of microbiology*, *50*, 253-262. https://doi.org/10.1007/s12088-010-0061-6.

Soliva, C. R., Meile, L., Cieślak, A., Kreuzer, M., & Machmüller, A. (2004). Rumen simulation technique study on the interactions of dietary lauric and myristic acid supplementation in suppressing ruminal methanogenesis. *British Journal of Nutrition*, *92*(4), 689-700. https://doi.org/10.1079/BJN20041250.

Soltan, Y., Morsy, A., Hashem, N., Elazab, M., Sultan, M., Marey, H., Lail, G. A. E., El-Desoky, N., Hosny, N., & Mahdy, A. (2021). Modified nano-montmorillonite and monensin modulate in vitro ruminal fermentation, nutrient degradability, and methanogenesis differently. *Animals*, *11*(10), 3005. Modified Nano-Montmorillonite and Monensin Modulate *In Vitro* Ruminal Fermentation, Nutrient Degradability, and Methanogenesis Differently.

Sun, K., Liu, H., Fan, H., Liu, T., & Zheng, C. (2021). Research progress on the application of feed additives in ruminal methane emission reduction: a review. *PeerJ*, *9*, e11151. https://doi.org/10.7717/peerj.11151.

Tahery, S., Parra, M. C., Munroe, P., Mitchell, D. R., Meale, S. J., & Joseph, S. (2025). Developing an activated biochar-mineral supplement for reducing methane formation in anaerobic fermentation. *Biochar*, *7*(1), 26. https://doi.org/10.1007/s42773-024-00403-5.

Takahashi, L. S., Sanches, T. P., Issakowicz, J., Bueno, M. S., Bompadre, T. F. V., de Paz, C. C. P., Abdalla, A. L., & da Costa, R. L. D. (2024). Lipid supplementation with macadamia by-product reduces methane emissions by sheep. *Small Ruminant Research*, *231*, 107174. https://doi.org/10.1016/j.smallrumres.2023.107174.

Toral, P. G., Belenguer, A., Frutos, P., & Hervás, G. (2009). Effect of the supplementation of a high-concentrate diet with sunflower and fish oils on ruminal fermentation in sheep. *Small Ruminant Research*, *81*(2-3), 119-125. https://doi.org/10.1016/j.smallrumres.2008.12.009.

Unnawong, N., Cherdthong, A., & So, S. (2021). Crude saponin extract from *Sesbania grandiflora* (L.) Pers pod meal could modulate ruminal fermentation, and protein utilization, as well as mitigate methane production. *Tropical Animal Health and Production*, *53*, 1-9. https://doi.org/10.1007/s11250-021-02644-z.

van Gastelen, S., Burgers, E. E., Dijkstra, J., de Mol, R., Muizelaar, W., Walker, N., & Bannink, A. (2024). Long-term effects of 3-nitrooxypropanol on methane emission and milk production characteristics in Holstein-Friesian dairy cows. *Journal of dairy Science*, *107*(8), 5556-5573. https://doi.org/10.3168/jds.2023-24198.

Van Wesemael, D., Vandaele, L., Ampe, B., Cattrysse, H., Duval, S., Kindermann, M., Fievez, V., De Campeneere, S., & Peiren, N. (2019). Reducing enteric methane emissions from dairy cattle: Two ways to supplement 3-nitrooxypropanol. *Journal of dairy Science*, *102*(2), 1780-1787. https://doi.org/10.3168/jds.2018-14534.

Van Wyngaard, J., Meeske, R., & Erasmus, L. (2018). Effect of concentrate feeding level on methane emissions, production performance and rumen fermentation of Jersey cows grazing ryegrass pasture during spring. *Animal Feed Science and Technology*, *241*, 121-132. https://doi.org/10.1016/j.anifeedsci.2018.04.025.

Vanhatalo, A., & Halmemies-Beauchet-Filleau, A. (2020). Optimising ruminal function: the role of silage and concentrate in dairy cow nutrition to improve feed efficiency and reduce methane and nitrogen emissions. In C. McSweeney & R. Mackie (Eds.), *Improving rumen function* (pp. 651-692). Burleigh Dodds Science Publishing.

Verma, S., Akpensuen, T. T., Wolffram, S., Salminen, J.-P., Taube, F., Blank, R., Kluß, C., & Malisch, C. S. (2024). Investigating the efficacy of purified tannin extracts from underutilized temperate forages in reducing enteric methane emissions *in vitro*. *Scientific Reports*, *14*(1), 12578. https://doi.org/10.1038/s41598-024-63434-9.

Wanapat, M., Kang, S., & Polyorach, S. (2013). Development of feeding systems and strategies of supplementation to enhance rumen fermentation and ruminant production in the tropics. *Journal of animal science and biotechnology*, *4*, 1-11. https://doi.org/10.1186/2049-1891-4-32.

Wang, K., Nan, X., Chu, K., Tong, J., Yang, L., & Zheng, S. (2018). Shifts of hydrogen metabolism from methanogenesis to propionate production in response to replacement of forage fiber with non-forage fiber sources in diets *in vitro*. *Front Microbiol*, *9*, 2764. https://doi.org/10.3389/fmicb.2018.02764.

Wang, K., Xiong, B., & Zhao, X. (2023). Could propionate formation be used to reduce enteric methane emission in ruminants? *Science of the Total Environment*, *855*, 158867. https://doi.org/10.1016/j.scitotenv.2022.158867.

Wang, Y., Xu, Z., Bach, S., & McAllister, T. (2008). Effects of phlorotannins from *Ascophyllum nodosum* (brown seaweed) on in vitro ruminal digestion of mixed forage or barley grain. *Animal Feed Science and Technology*, *145*(1-4), 375-395. https://doi.org/10.1016/j.anifeedsci.2007.03.013.

Xue, B., Thompson, J. P., Yan, T., Stergiadis, S., Smith, L., & Theodoridou, K. (2025). Dose–response effects of dietary inclusion of agro-industrial by-products on *in vitro* ruminal fermentation and methane production. *Journal of the Science of Food and Agriculture*. https://doi.org/10.1002/jsfa.14263.

Yadav, R. D., Mohini, M., Singh, D., & Chugh, R. (2021). Dietary effect of combination of nitrate, sulphate and saponin on growth rate and methane mitigation on crossbred calves. *The Pharma Innovation Journal*, *10*, 540-544.

Yang, Z., Zheng, Y., Liu, S., Xie, T., Wang, Q., Wang, Z., Li, S., & Wang, W. (2024). Rumen metagenome reveals the mechanism of mitigation methane emissions by unsaturated fatty acid while maintaining the performance of dairy cows. *Animal Nutrition*, *18*, 296-308. https://doi.org/10.1016/j.aninu.2024.06.003.