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REVIEW

Reduction of Methane Emission in Ruminants via Modern Feeding

Mohammed A. Amean[1], Nuha Hameed Albasssam[2], Basim S. A. Al Sulivany[3], Muhammad Owais[4*]

[1]*Animal Production Department, College of Agriculture, Tikrit University, Tikrit, Iraq.*
[2]*Department of Animal Production, College of Agriculture, University of Tikrit, Salah Al-deen, Iraq*
[3]*Department of Biology, College of Science, University of Zakho, Zakho, 42002, Duhok, Kurdistan Region, Iraq.*
[4]*Department of Zoology, Ghazi University, Dera Ghazi Khan, Punjab, Pakistan.*

ABSTRACT

This review examines approaches used in ruminants and discusses the mechanisms of action, effectiveness, and practical applications for mitigating enteric methane production. Methane emissions contribute to greenhouse gas accumulation from ruminant animals and are documented as a significant challenge for sustainable livestock production because it decreases the effectiveness of feed utilization. The ruminal fermentation process helps to maintain rumen function by converting the hydrogen and carbon dioxide into methane due to the methanogenic archaea. The developing feeding strategies due to the continuous change in the climate focused to diminish methane emissions without disturbing the animal performance. The lipid supplementation, nitrate incorporation, tannin-containing feeds, essential oils, ionophores, seaweed-based additives, and 3-nitrooxypropanol are evaluated in this study with the feed processing techniques and precision feeding systems. Dietary lipids at 15–25% are reported to decrease methane emissions, while nitrate can reduce emissions by 20–40%. The moderate reductions were reported with the tannins and other plant-derived compounds, while the red seaweed *Asparagopsis taxiformis* recorded high mitigation potential with 80% reduction in some studies. Similarly, 3-NOP demonstrated considerable suppression of methane without major adverse effects on animal productivity. The current study's evidence suggested that the combination of multiple mitigation approaches can give more sustained reductions than depending on a single intervention. Therefore, there is a need for careful attention to the important factors such as feed cost, animal health, product quality, regulatory approval, and producer acceptance.

Keywords: *Methane; Enteric Fermentation; Ruminant Nutrition; Feed Additives*

Corresponding Author: Muhammad Owais, Department of Zoology
E-mail: **owaisgulmuhammad@gmail.com**
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INTRODUCTION

The global climate transformation and its significant effects on atmospheric chemistry have become among the most pressing environmental challenges facing modern society (Singh *et al.,* 2022). Global warming has become a threat to agricultural livestock production due to greenhouse gases such as ethane (CH_4), which have a significant impact on global warming potential (Yang *et al.,* 2023). While methane persists in the atmosphere for a shorter duration than carbon dioxide (CO_2), its warming potential is approximately 28 times greater than that of CO_2. Agriculture is a major source of anthropogenic methane emissions, which produce a substantial proportion of global agricultural greenhouse gas outputs (Huang *et al.,* 2023). Livestock production contributes 14–18% of anthropogenic greenhouse gas emissions, including ruminant animals including cattle, sheep, goats, and buffalo, due to the unique microbial fermentation processes occurring within the rumen (Zhang *et al.,* 2025). These animals are responsible for the enteric methane emission and fermentation, which is a natural by-product of feed digestion and is released chiefly through eructation (Mellouki *et al.,* 2015).

The rumen is a complex microbial ecosystem consisting of bacteria, archaea, protozoa, fungi, and viruses, which is extremely important for specialized anaerobic fermentation and represents the largest single source within the sector (Paswan *et al.,* 2022). However, fermentation maintains microbial metabolic activity and also generates large quantities of metabolic hydrogen (H_2). During fermentation, microbes break down structural and non-structural carbohydrates into unstable fatty acids (VFAs), bacterial protein, gases, and other metabolites (Yu *et al.,* 2025). The unstable fatty acids (VFAs) provide the majority of the host animal's energy necessities, which include acetate, propionate, and butyrate (Sanjorjo *et al*., 2023). Methanogenic archaea employ hydrogen and carbon dioxide to yield methane, thus it helping as a chief hydrogen sink within the rumen ecology (Qi *et al*., 2023).

Methane production plays a significant role in maintaining rumen fermentation balance and represents a significant loss of dietary energy, which is estimated between 2% and 12% of gross energy intake (Min *et al.,* 2022). It depends on the loss of methane, diet composition, animal species, and production system, reducing methane emissions, enlightening feed conversion effectiveness, and prolific performance (Garg *et al.,* 2013). Consequently, it offers a twin advantage by reducing the environmental footprint of livestock production. The mitigate in greenhouse gas emissions is progressively stimulated to implement practices that reduce emissions without compromising food security (Garg *et al*., 2014). Livestock producers have developed strategies for assessing and reducing livestock-related greenhouse gas emissions, which involve nutritional approaches and are regarded as having emerged as among the most practical and directly deployable mitigation options accessible to producers (Goopy *et al*., 2020).

The nutritional management is conventionally intensive, chiefly on exploiting growth, milk production, reproductive performance, and feed efficiency. However, modern feeding methods progressively integrate ecological sustainability (Cuervo *et al*., 2025). These developments have facilitated precision nutrition, rumen microbiology, molecular biology, and metagenomics, thereby enhancing understanding of the microbial communication involved in methane production (Króliczewska *et al*., 2023). These modern targeted dietary strategies improve rumen fermentation management and reduce methane emissions (Shinkai *et al*., 2023). Many of these approaches include dietary lipid supplementation, nitrate feeding, and tannin-containing feeds. Additionally, it also includes essential oils, seaweed-derived compounds, ionophores, and novel inhibitors such as 3-nitrooxypropanol (3-NOP). Modern methane mitigation approaches involve enhancements in fodder quality, feed processing skills, and precision nutrition systems (Mackie *et al*., 2023). It is also involved in reducing methane emissions through enhanced nutrient utilization and feed management. Reducing hydrogen production and redirecting hydrogen toward alternative metabolic pathways involves the conquering of methanogenic microorganisms, which directly inhibit enzymes involved in methane synthesis (Lu *et al*., 2019).

Responses often vary according to diet composition, animal species, physiological status, management practices, and environmental conditions. Moreover, some mitigation methods may destructively disturb the fiber digestion, feed intake, nutrient utilization, animal health, and product quality (Tyler *et al*., 2020). The recent potential of microbiome-targeted interventions in the rumen microbiome also highlighted advances in metagenomics and microbial ecology in animals. It also revealed substantial variation in methanogen populations, which include microbial manipulation and genetic changes (Karasov *et al*., 2011). Despite significant progress, no single mitigation strategy has demonstrated general operability across all production systems. The Precision feeding technologies among individual animals can improve mitigation potential by optimizing nutrient supply according to individual animal necessities, and reducing excess fermentation losses (Kassahn *et al*., 2009).

Therefore, a complete assessment of available feeding strategies is required to recognize practical solutions capable of reducing methane emissions while sustaining productive effectiveness. This review about rumen methanogenesis observes modern dietary approaches with their mechanisms of action, efficiency, restrictions, and diagnoses for sustainable ruminant production. This study aims to study the reduction of methane emissions in ruminants via modern feeding strategies required to recognize practical solutions capable of reducing methane emissions.

Rumen Methanogenesis: Mechanism and Microbial Basis

The rumen microbial community is involved in the degradation of dietary carbohydrates, proteins, and lipids. The rumen functions consist of billions of microorganisms that enable ruminants to use fibrous plant materials unavailable to monogastric animals (Mutungwazi *et al*., 2021). Fermentation of feed substrates produces microbial biomass, volatile fatty acids, carbon dioxide, and hydrogen, which collectively support animal efficiency while simultaneously producing conditions promising for methane formation (Ungerfeld *et al*., 2023). *Ruminococcus albus*, *Ruminococcus flavefaciens*, and *Fibrobacter succinogenes* play a chief role as cellulolytic bacteria for decomposing structural carbohydrates (Karasov *et al*., 2011). During cellulose and hemicellulose fermentation, the accretion of hydrogen within the rumen contributes considerably to hydrogen production in the anaerobic fungi and ruminal protozoa (Söllinger *et al*., 2018). It can inhibit microbial metabolism because many fermentation pathways depend on sustaining a low hydrogen partial pressure. The significant quantities of hydrogen that are released also contribute significantly to hydrogen production (De la Fuente *et al*., 2019).

The *Methanobrevibacter*, *Methanosphaera*, *Methanomicrobium*, and *Methanobacterium* are the dominant methanogenic genera, which provide an important ecological function and are commonly identified in the rumen of animals (Kharitonov *et al*., 2021). Among these groups, *Methanobrevibacter* species are involved in removing the excess hydrogen and are generally considered the most plentiful and metabolically important methanogens in cattle and sheep (Misiukiewicz *et al*., 2021). Methanogenic archaea, commonly responsible for methane formation, undergo hydrogenotrophic methanogenesis; the principal biochemical pathway is given below.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

This reaction designates carbon dioxide as the electron acceptor, whereas hydrogen acts as the electron donor (Bueno de Mesquita *et al*., 2023). This mechanism permits the methanogens to produce metabolic energy while avoiding hydrogen accretion within the rumen atmosphere. Numerous methanogens play an important role in methane production, and it serves as the interspecies hydrogen transfer in close association with ruminal protozoa (Choudhury *et al*., 2022). Protozoa residing internally in the ruminants and produce hydrogen during carbohydrate fermentation, which enhances methane production efficiency and is immediately utilized by neighboring methanogens (Mackie *et al*., 2023). This symbiotic relationship is particularly involved in the protozoal suppression, which reduces methane emissions (Kharitonov *et al*., 2021).

Adetunji *et al*. (2022) demonstrated the strong influence of methane output due to the interactions between bacteria, protozoa, fungi, and methanogens. This process strongly advances the metagenomic sequencing of the protozoa and reveals substantial diversity among methanogenic communities, emphasizing associations between microbial alignment and methane emissions. The phenomenon of variations in microbial populations attached to their surfaces contributes substantially to differences in methane production among individual animals. In this response, methanogenesis is regarded as the dominant hydrogen disposal pathway and is known as an alternative hydrogen sink. In the rumen, there is also another pathway, which involves propionate formation and states that during propionate synthesis, hydrogen is combined into metabolic intermediates rather than being transformed into methane. The important dietary strategies promote propionate production and usually reduce methane emissions. Consequently, propionate production has been further regarded as the most energetically favorable pathway for decreasing methane emissions (Kassahn *et al*., 2009).

Reductive acetogenesis, nitrate reduction, and fumarate reduction are alternative processes, and in the intermediate nitrite production process, nitrate is reduced to ammonia using hydrogen (Egas *et al*., 2024). This route can successfully compete with methanogens for available hydrogen and is thermodynamically advantageous. Similar to this, fumarate reduction produces precursors for succinate and propionate while consuming hydrogen (Yang *et al*., 2023). Methane synthesis is a significant diversion of metabolic hydrogen from an energy standpoint. The methane is used for metabolic activities that increase animal production, and effective dietary techniques require processes behind ruminal methanogenesis (Jeyanathan *et al*., 2014). Therefore, methanogenesis is regarded as the energetically advantageous route and a key component of methane mitigation efforts (Li *et al*., 2024). Developing modern feeding techniques preserves rumen function and focuses on particular microbial populations while lowering the energy and costs associated with the environment related to enteric methane production. Its enzymatic mechanisms contribute to the production of methane (Choi *et al*., 2026).

MODERN FEEDING STRATEGIES FOR METHANE MITIGATION

1-Lipids and Oils

The nutritional approach in ruminants to depressing enteric methane emissions with the source of dietary lipid has drawn a lot of attention to methane generation; in contrast, some complementary methods related to feed additives also targeted the individual microbial groups (Lileikis *et al*., 2023). Additionally, biohydrogenation, unsaturated fatty acids function as substitute hydrogen sinks dropping the amount of fermentable organic ingredients that rumen microorganisms (Beauchemin *et al*., 2009). The amount of hydrogen available for methanogenesis is decreased during this reaction as rumen microbes consume hydrogen to saturate double bonds in fatty acids (Honan *et al*., 2021). Less substrate is available for microbial fermentation when dietary lipids moderately substitute carbs in the ration, which decreases the formation of hydrogen and consequent methane synthesis (Frederick *et al*., 2024). Sun *et al*. (2022) demonstrated that Lipids on methanogenic archaea and ruminal protozoa exert direct inhibitory effects to suppress protozoal populations. The medium-chain fatty acids, such as lauric acid and myristic acid, are frequently involved in lower methane emissions. Antimicrobial properties found in coconut oil selectively influence microbial communities involved in hydrogen production. Because many methanogens are associated with some unsaturated fatty acids through interspecies hydrogen transfer, decreases in protozoal numbers. Furthermore, various lipid sources were also evaluated for methane mitigation. Vegetable oils demonstrated varying degrees of effectiveness, including the coconut, canola, soybean, sunflower, and linseed oils. Oilseeds, particularly flaxseed, cottonseed, and sunflower seed, have also been investigated and provide a substitute means of cumulative dietary lipid concentration, while supplying additional nutrients. Animal fats have also been used due to consumer preferences and market regulations and have been investigated as a source of supplementary nutrients. Andersen *et al*. (2023) described the effectiveness of lipid supplementation, which provides a balance between methane reduction and rumen function and is closely related to the dietary inclusion level of dry matter between 4 and 8%. The dietary supplementation studies described that the exceeding inclusion level of dry matter damages fiber digestion by destructively affecting cellulolytic bacteria attachment rates, subsequent in reduced feed intake and animal performance. Subsequently, the excessive lipid supplementation.

Toral *et al*. (2018) concluded methane reductions ranging from 15 to 25% under commercial conditions and reported different responses depending on diet composition and animal species. Lipid supplementation, one of the most consistent nutritional approaches, has been reported to incorporate unsaturated fatty acids strategically into ruminant diets. Despite its effectiveness, economic attention and potential impacts are generally not recommended, particularly due to the nutrient digestibility. Numerous studies evaluated the lipid supplementation, and responses vary for methane mitigation.

2-Nitrates

Yang *et al*. (2016) concluded that the nitrate supplementation directly participates with methanogens for accessible hydrogen in the rumen and appears as a promising approach for reducing enteric methane emissions. The nitrate reduction strategy is based on the principle which thermodynamically used for methane formation, and it is more favorable than methanogenesis, which allows nitrate-utilizing microorganisms to capture hydrogen. The resulting ammonia within the rumen undergoes a sequential reduction process that can then be utilized by ruminal microorganisms for microbial protein synthesis. First, nitrate is reduced to nitrite, which is subsequently converted to ammonia. Because these decrease reactions consume hydrogen, less hydrogen remains accessible for methanogenic archaea. The methane mitigation of 10 and 20 g nitrate per kilogram of dietary dry matter has consistently demonstrated reductions ranging from 20 to 40%, depending on dietary composition, adaptation period, and supplementation level (Lileikis *et al*., 2023). Some studies have reported potential of nitrate is substantial, and even greater reductions occur when nitrate is combined with other methane mitigation strategies. Despite their efficiency and effectiveness, the nitrate supplements also present safety challenges due to their different inclusion rates (Olijhoek *et al*., 2016). Absorbed nitrite in the methemoglobin enters the bloodstream and converts hemoglobin to methemoglobin, which can reduce the oxygen transport capacity and can accumulate in the rumen. It causes the toxicity nitrate reduction to exceed the rate of nitrite conversion (Vargas *et al*., 2022). Proper ration formulation and management practices can decrease the risk of respiratory distress, reduced feed intake, weakness, and allow the ruminal microbial community to slow down for safe implementation (Sejian *et al*., 2015). Animals with nitrate supplementation decrease these risks, and gradual adaptation is essential to develop efficient nitrate-reducing populations (Sharifi *et al*., 2022). However, methane mitigation in ruminant production systems remains one of the most effective hydrogen-diverting strategies (Cottle *et al*., 2011). However, implementation remains inadequate in some regions due to concerns about handling, safety, and producer acceptance (Lileikis *et al*., 2023).

3-Tannins

Bule *et al*. (2020) described that the tannins are naturally classified into two major groups: condensed tannins and hydrolysable tannins, which are polyphenolic compounds found in numerous trees, shrubs, legumes, and forage plants. Tannins are generally used as methane mitigation agents; their effects on methane production are associated with modifications in ruminal microbial activity, nutrient degradation, and hydrogen availability. It has increased noticeably because they are a natural and consequent substitute for synthetic feed additives. Condensed tannins and hydrolysable tannins commonly occur in species including chestnut and oak. The biological activity of tannins depends on their chemical structure, molecular weight, and dietary attention, which are also commonly found in plants such as quebracho, sainfoin, birdsfoot trefoil, and mimosa. Tannins can directly inhibit methanogenic archaea and ruminal protozoa, thereby reducing methane formation, and some mechanisms contribute to methane reduction. In addition, fiber degradation commonly decreases hydrogen production, indirectly limiting methane synthesis (Versari *et al*., 2013). Hoque *et al*. (2025) reported that the proteins, carbohydrates, and microbial enzymes alter fermentation patterns within the rumen and described the methane decreases, fluctuating from 10 to 20%, when tannins are included at restrained dietary levels. 20 and 40 g/kg dietary dry matter are regarded as the effective supplementation rates, but optimal concentrations vary according to tannin source and animal species. The condensed tannins as compared to hydrolysable tannins display better methane mitigation potential than under similar conditions.

Cosme *et al*. (2025) demonstrated that the tannins can enhance protein utilization and improve nitrogen utilization efficiency in some production systems. It can also enhance the low of undegraded dietary protein to the small intestine and decrease the ruminal protein degradation. High levels of tannins can lower productivity due to the decrease in nutrient digestibility, feed intake, and microbial activity. The extreme tannin concentrations may affect animal performance; therefore, the proper selection of tannin-containing feeds and inclusion rates are essential for the advantages and to diminish the adverse effects.

4-Seaweeds (*Asparagopsis taxiformis*)

Wheeler *et al*. (2021) conducted a study on Seaweed (*Asparagopsis taxiformis*) and described that it is primarily attributed to red seaweeds and has generated considerable scientific and commercial interest. Its supplementation demonstrated exceptional methane-reducing potential in both laboratory and animal studies. Among the emerging methane mitigation technologies, the presence of halogenated compounds within the rumen directly inhibits methanogenic activity including the effectiveness of bromoform. In particular, methane formation in archaea involves the reduction of methyl-coenzyme M to methane, which depends on a series of enzymatic reactions. Bromoform interferes with this process by disrupting enzymes that are involved in the final stages of methanogenesis. The methanogenic archaea depend on losing their capacity to utilize hydrogen proficiently, which leads to substantial reductions in methane production. In vitro studies conclude that methane reductions exceeding 90% under controlled experimental conditions. As a result, in vivo experiments have shown 30 to 80% reductions in dairy and beef cattle, which generally depend on supplementation rate, feeding system, and diet composition. Meng *et al*. (2025) reported that effective enclosure levels are typically between 0.2 and 0.5% of dietary dry matter, indicating relatively low inclusion rates, making seaweed supplementation attractive for reducing methane emissions and appealing from a nutritional perspective because minimal dietary modification is required. In addition, several studies have reported the developments in feed conversion efficiency due to reduced energy losses associated with methanogenesis. However, responses in animal performance vary across the production systems; it has also been observed that there are neutral effects on feed intake and productivity, while others have described slight decreases in intake at higher supplementation levels. Despite the promising efficacy of seaweeds, it is attractive, which may affect storage stability and consistency of supplementation in the highly volatile bromoform, and several practical limitations currently restrict large-scale adoption (Shang *et al*., 2026). The seaweeds' large-scale cultivation has also been elevated regarding potential residues in milk and meat products. Furthermore, some experiments have shown that processing, transportation, and quality control of seaweed biomass remain significant challenges (Bačėninaitė *et al*., 2022). Rotter *et al*. (2021) described the low residual level of the seaweed when it is used appropriately at a higher level. The *Asparagopsis taxiformis* is widely observed as one of the most capable biological tools presented for methane mitigation. Consequently, it is regarded as another important consideration for the economic feasibility. Current production costs remain comparatively high with these seaweed cultivation technologies and are associated with conventional feed additives, restraining the extensive commercial use. Nevertheless, continued advances in and cumulative demand for low-carbon livestock products may improve the economic feasibility of this method in the future.

5-Nitrooxypropanol (3-NOP)

Black *et al*. (2021) documented that the most significant breakthroughs in methane mitigation are the development of 3-nitrooxypropanol (3-NOP), which represents one of the research areas during the past decade specifically designed to suppress methanogenesis without harmfully distressing rumen fermentation and animal productivity. The commercially marketed 3-Nitrooxypropanol, commonly known as 3-NOP targeted methane inhibitor that is highly reduced with the dietary interventions, which indirectly reduce methane production and directly affect the biochemical pathway responsible for methane synthesis. The past studies demonstrated the substantial methane reductions with the dairy and beef cattle and specifically involved inhibiting the methyl-coenzyme M reductase, the terminal enzyme complex in methane formation by methanogenic archaea. Castaneda *et al*. (2025) described that in dairy systems, the final step of methanogenesis allows most other ruminal fermentation processes to continue normally, and enzymes catalyze the inhibition, effectively preventing methane production, while 3-NOP acts have consistently demonstrated. Responses are commonly dose-dependent because the reductions commonly range from 25 to 35%, whereas decreases approaching 40% have been reported in beef cattle receiving high-concentrate diets. It's recommended that inclusion rates commonly range from 60 to 80 mg/kg of dietary dry matter. Compared with many natural additives, the 3-NOP has produced relatively stable methane reductions across numerous studies and production environments, and its effectiveness varies according to diet composition and microbial adaptation. The studies involved the major advantages of 3-NOP and also the adverse effects on animal health, milk production, growth performance, reproductive efficiency, and feed intake, and no evidence has been found for the extensive safety assessments.

Nevertheless, 3-NOP requires unremitting supplementation because methane emissions commonly return to baseline levels after treatment cessation and currently characterizes one of the most scientifically validated and commercially progressive methane mitigation technologies obtainable for ruminant production (Brady *et al*., 2024). Another important benefit is the absence of detectable remains in edible animal products, and it was concluded that the compound is rapidly metabolized and does not accumulate in tissues or milk (Marco-Contelles, 2023). Consequently, economic considerations were conducted in several regions, including several European nations and parts of Latin America, and described that the feed additives are more difficult to deliver consistently. Additionally, commercial use has expanded in various countries, and its effectiveness remains important in extensive grazing systems (Duin *et al*., 2016).

6-Essential Oils and Plant Secondary Metabolites

Plant-derived secondary metabolites are capable of fermentation pathways and are involved in modifying ruminal microbial populations, which are extracted from the herbs and spices that contain bioactive compounds (Yáñez-Ruiz *et al*., 2020). Essential oils as natural alternatives to synthetic feed additives can change cell membrane penetrability, which prevents enzyme activity and suppresses populations of methanogens and protozoa (Faniyi *et al.*, 2016). Most examples comprise garlic oil, eugenol from clove, thymol from thyme, and cinnamaldehyde from cinnamon, and numerous saponins, which encompass plant extracts such as Yucca and Quillaja. The methane-reducing effects of these compounds are chiefly related to their antimicrobial properties (Odhaib *et al*., 2021). Variability is influenced by additive composition, dosage, diet type, and animal species, which indirectly decreases methane production by disrupting the interspecies hydrogen transfer between protozoa and methanogens (Vizzarri *et al*., 2026). Saponins, in particular, have demonstrated anti-protozoal activity, and reported methane reductions generally range from 5 to 15%. One of the main limitations of essential oils is microbial variation, which may allow the ruminal microorganisms to develop tolerance, which subsequent in lessened efficiency over time (Christaki *et al*., 2012). Lillehoj *et al*. (2018) focused on classifying the combinations of bioactive compounds that are capable of creating more consistent and determined methane mitigation effects. The potential compatibility with organic production responses varies considerably among studies. Despite these limitations, plant secondary metabolites remain attractive because of their natural origin, and consumer acceptance may allow systems that indirectly decrease methane production

7-Enumerate ionophores

Ionophores are antimicrobial compounds most extensively studied and widely used in ruminant nutrition to improve feed efficiency. Monensin is the ionophore with respect to methane mitigation, which is also involved in reducing the risk of ruminal disorders (Seema *et al*., 2025). Although methane reduction selectively inhibits gram-positive bacteria that produce hydrogen and acetate, monensin can influence ruminal fermentation in ways that indirectly decrease methane production (Azzaz *et al*., 2015). Additionally, ionophores promote greater propionate production and reduce protozoal populations, which act as an alternative hydrogen sink. This microbial shift limits hydrogen availability for methanogens, which is considered a secondary benefit, and methane reductions associated with monensin supplementation typically range from 5 to 10% (Callaway *et al*., 2003). However, long-term responses are often inconsistent, and it is widely used in many countries because ruminal microbial populations may adapt to the additive over time. (Tedeschi *et al*., 2003). The practical contribution to methane mitigation strategies worldwide varies internationally, and their use as growth promoters has been prohibited in the European Union (Prusty *et al*., 2025).

8-Feed Processing and Physical Form

The methane mitigation potential of feed processing can influence ruminal fermentation characteristics. Feed processing techniques and methane production by altering nutrient availability and passage rate through the digestive tract (Van Der Poel *et al*., 2020). Processing generally increases the digestibility of starch-rich feeds. The common processing methods include grinding, pelleting, steam flaking, rolling, and extrusion (Getachew *et al*., 2005). Improved starch utilization often promotes propionate formation and accelerates ruminal passage, dropping the time available for methane-producing fermentation. Nevertheless, processing technologies are generally modest, thereby reducing hydrogen availability for methanogens (Dey *et al*., 2025). While decreasing acetate production is already integrated into many livestock production systems, it may contribute, commonly ranging from 5 to 10%, meaningfully when combined with other mitigation strategies (Eugène *et al*., 2021).

9-Precision Feeding and Forage Quality

Empel *et al*. (2016) described that precision feeding plays a critical role in determining methane production. It aims to provide nutrients according to the specific requirements of individual animals or production groups. High-quality forages are generally characterized by greater digestibility, and these feeds promote faster ruminal passage and greater animal productivity, including slower fiber concentration and improved nutrient availability. Diets containing greater proportions of starch-rich ingredients, such as corn silage, improve feed utilization efficiency, and precision feeding can indirectly reduce methane emissions per unit of animal product. By minimizing nutrient oversupply, forage quality can reduce methane emissions and frequently produce less methane than diets dominated by highly fibrous grass silages. Similarly, inclusion of legumes comprising moderate concentrations of condensed tannins may concurrently improve the forage quality and reduce methane production (González *et al*., 2018). Precision feeding technologies are playing an increasingly important role in sustainable methane mitigation programs (Sonea *et al*., 2023). The livestock systems approach is technologically advanced to maximize productivity and minimize greenhouse gas emissions. It includes the utilization of sensors, automated feeding systems, and analytical nutritional models to enhance the ration formulation and minimize nutrient waste (Mixtajová *et al*., 2026).

PRACTICAL IMPLEMENTATION OF METHANE EMISSION REDUCTION STRATEGIES

Although numerous nutritional interventions have demonstrated the capability to decrease enteric methane emissions, combining complementary approaches has become a significant focus of current methane mitigation research (Kebreab *et al*., 2026). Their practical application under commercial conditions requires a comprehensive and integrated approach influenced by microbial adaptation, dietary composition, management practices, and animal-specific factors (Caro *et al*., 2016). Consequently, commercial production systems designate that individual mitigation strategies rarely achieve extreme efficiency when applied in isolation. Furthermore, the long-term persistence of methane reduction highlights the importance of combined mitigation programs that target multiple pathways involved in methanogenesis rather than relying on a single mode of action (Tricarico *et al*., 2022). One of the main challenges associated with single-feed additives has shown relatively stable long-term responses and the tendency of the rumen microbial ecosystem to adapt over time. Some additives, such as 3-nitrooxypropanol (3-NOP), display declining effectiveness after prolonged use (Malyugina *et al*., 2025). It also includes essential oils and ionophores. Several studies have demonstrated additive or synergistic effects, for example, lipid supplementation as an alternative hydrogen sink may reduce hydrogen production while tannins simultaneously suppress methanogens and protozoa (Nisbet *et al*., 2020). Similarly, combinations of nitrate and 3-NOP directly inhibit the enzymatic machinery responsible for methane synthesis and have attracted considerable interest because they target different stages of hydrogen utilization (Martin *et al*., 2010). Different methane mitigation approaches may provide greater methane reductions. Such combinations minimize potential negative effects associated with high inclusion rates of individual additives (Reisinger *et al*., 2021).

The effectiveness of methane mitigation strategies promotes propionate production and reduces ruminal pH and is strongly influenced by the basal diet. High-concentrate diets, impaired fiber digestion, and metabolic disorders generally produce less methane than forage-based diets (Lileikis *et al*., 2023). Therefore, methane mitigation should complement rather than compromise overall ration quality (Stolaroff *et al*., 2012). Combining nutritional interventions represents another important consideration, as genetic development may provide cumulative benefits for long-term methane reduction (Nisbet *et al*., 2020). Animal-to-animal variation shows that methane emissions can differ by as much as 20–30% among animals, and these differences are associated with variations in feed intake, rumen function, microbial populations, and host genetics (Kebreab *et al*., 2026). Such findings have encouraged interest in genetic selection programs intended to breed animals with characteristically lower methane emissions (Paramesh *et al*., 2023). Symeon *et al*. (2025) described that the measurement of methane emissions under commercial conditions is essential for evaluating mitigation strategies and quantifying methane production and is often considered the reference standard for research studies. Alternative approaches, such as the sulfur hexafluoride (SF_6) tracer technique, GreenFeed systems, portable laser methane detectors, and automated sensor technologies, enable the assessment of mitigation approaches under the applied production surroundings and provide valuable data for emission records. Respiration chambers, opportunities for on-farm methane, remain the most accurate method despite the high cost and limited capacity.

Vineis *et al*. (2024) demonstrated that the cost of feed additives, delivery systems, labor requirements, and potential effects ultimately determines whether methane mitigation technologies can be adopted widely by livestock producers. Increasingly, economic assessments must be considered alongside environmental benefits, being expressed in terms of economic feasibility and productivity. Technologies improve feed efficiency and reduce methane emissions, which provide both environmental and economic returns. As carbon markets and sustainability incentives become operative, the methane mitigation strategies may progressively become profitable for producers.

The successful methane mitigation in ruminant production systems is generally more attractive depending on a single intervention and continues to develop in terms of carbon dioxide equivalent (CO_2-e) abated (Lean *et al*., 2021). Instead, integrated programs provide the most sustainable and economically viable pathway toward substantial reductions in livestock greenhouse gas emissions. It combines nutritional management, feed additives, forage improvement, precision feeding, genetic selection, and accurate monitoring systems (Jebari *et al*., 2024).

CHALLENGES AND RESEARCH GAPS

While many feed additives and dietary interventions have demonstrated promising efficiency and consistency, under commercial farming systems remain areas of active investigation (Ntsongota *et al*., 2025). Despite substantial progress in the development of nutritional strategies for methane mitigation, the economic challenges continue to limit their widespread implementation. One of the primary concerns under controlled experimental conditions involves the long-term safety and sustainability of methane mitigation technologies. Several scientific nitrate-based products and halogenated compounds derived from seaweeds and needed to be assessed under diverse production conditions. It generally indicates acceptable safety profiles when recommended inclusion rates are followed; additional long-term investigations require careful evaluation to ensure that prolonged use does not negatively affect animal health, reproductive performance, or product safety (Jawla *et al.*, 2025).

Consequently, further research is compulsory to assess the residue dynamics in livestock products produced using methane mitigation technologies, and is needed to establish regulatory guidelines and maintain public confidence. Another important challenge of additive-derived compounds or metabolites in milk and meat products increasingly depends on assurances regarding food safety and product quality. Microbial adaptation within the rumen is highly resilient and capable of adjusting to environmental changes and represents a significant biological limitation. The rumen ecosystem may progressively adjust to feed additives, dropping their efficiency over time (Haldar *et al*., 2022). Understanding the mechanisms of fundamental microbial variation remains a critical research priority for attaining continued methane decreases.

Many additives need specialized storage conditions, precise mixing procedures, or daily supplementation to preserve efficiency. Practical implementation at the farm level also presents challenges (Kebreab *et al*., 2026). Therefore, the progress of technologies suitable for pasture-based making systems remains an important objective (Ahmedsham *et al*., 2018). More region-specific research is needed to identify mitigation strategies that are operative under varied climatic and management conditions. Another major limitation is the lack of consistent methodologies for measuring and reporting methane emissions.

CONCLUSION

Enteric methane emissions remain a major challenge for ruminant production because they contribute to greenhouse gas emissions and reduce feed energy efficiency. Recent advances in nutrition and rumen microbiology have led to the development of several mitigation strategies, including 3-NOP, nitrates, seaweeds, lipids, tannins, essential oils, and improved forage management. The greatest methane-reduction potential was recorded with the *Asparagopsis taxiformis* 3-NOP and nitrate supplementation under all production conditions. The methane mitigation depends on diet composition, animal type, management practices, and economic feasibility factors. Therefore, combining multiple nutritional strategies with precision feeding offers the most practical long-term solution with enhanced forage utilization. Future research should focus on rumen microbial manipulation, innovative feed additives, and cost-effective technologies that support more sustainable livestock production systems.

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