https://doi.org/10.61308/UXZR9566

Effects of dietary lipid supplementation on enteric methane emissions and feed efficiency in ruminants: A review

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Citation: Abdullateef, A. I., Ariya, A. A., Hafsat, O. O. & Gbadamosi, N. O. (2026). Effects of dietary lipid supplementation on enteric methane emissions and feed efficiency in ruminants: A review. *Bulgarian Journal of Animal Husbandry, 63*(4), 56-66

Abstract: Enteric methane emissions from ruminant livestock represent a major environmental challenge and a significant loss of dietary energy, thereby reducing feed efficiency and animal productivity. This review examines the effects of dietary lipid supplementation on enteric methane production and feed efficiency in ruminants. Methane formation is closely linked to rumen fermentation processes, hydrogen availability, and the activity of methanogenic archaea. Dietary lipids influence these processes through multiple mechanisms, including reduction of fermentable organic matter, biohydrogenation of unsaturated fatty acids, suppression of rumen protozoa and methanogens, and shifts in volatile fatty acid profiles toward increased propionate production. In addition to mitigating methane emissions, lipid supplementation increases dietary energy density, which can enhance feed utilization efficiency and animal performance when appropriately managed. However, excessive lipid inclusion may negatively affect dry matter intake, fiber digestibility, and rumen microbial activity. The review highlights that the effectiveness of lipid supplementation depends on lipid type, inclusion level, and production system. Overall, dietary lipid supplementation presents a viable nutritional strategy for reducing enteric methane emissions while improving feed efficiency, provided that its limitations are carefully addressed through balanced diet formulation.

Keywords: enteric methane; dietary lipids; rumen fermentation; feed efficiency; ruminants

INTRODUCTION

Enteric methane (CH_4) emissions from ruminants constitutes a significant global environmental challenge, contributing majorly to anthropogenic greenhouse gas (GHG) emissions. Methane has a global warming potential approximately 27 - 30 times greater than carbon dioxide (CO_2) over a 100-year time horizon, making it a critical target for climate change mitigation strategies (IPCC, 2021). The livestock sector, particularly ruminants such as goats, sheep and cattle accounts for a significant amount of global methane emissions due to microbial fermentation processes occurring in the rumen. As the demand for animal-source foods continues to increase globally, reducing methane emissions without compromising animal productivity has become a major priority for sustainability of livestock production systems. Beyond its environmental impact, methane production in ruminants represents a direct loss of dietary energy, typically amounting to approximately 2 - 12% of gross energy intake, which reduces feed efficiency and overall animal productivity (Beauchemin et al., 2020).

Nutrition plays an important role in maintaining enteric methane production in ruminants. Methane formation is closely linked to rumen fermentation patterns, feed composition, feed intake level, and the structure of the rumen microbial ecosystem. Dietary manipulation has therefore emerged as one of the most practical and imme-

diately applicable approaches to mitigate methane emissions at the farm level. By altering the supply of fermentable substrates and modulating the composition and activity of rumen microbial populations, nutritional strategies can substantially influence hydrogen production, utilization pathways, and its subsequent conversion to methane (Beauchemin et al., 2020).

Among the various dietary interventions investigated, dietary lipid supplementation has received multiple attention as an optimistic methane mitigation strategy. Lipids are known to suppress methanogenesis through different mechanisms, including reduced hydrogen production, direct inhibition of methanogenic archaea, and decreased rumen protozoal populations. Dietary supplementation with lipids, particularly polyunsaturated fatty acids, has been shown to reduce enteric methane emissions by altering rumen fermentation, reducing methanogenic microbial activity, and increasing the utilization of metabolic hydrogen via biohydrogenation pathways (Sun et al., 2022).

Although dietary lipid supplementation can reduce enteric methane emissions, high levels of supplemental lipids have been associated with reduced dry matter intake and altered nutrient digestibility, which can negatively affect rumen fermentation and production performance (Bales et al., 2025). Although lipid supplementation can be implemented immediately on commercial farms, overall, it has low to moderate scope for CH_4 mitigation due to cost and potential negative effects on animal production and product quality. Additionally, lipids increase dietary energy density, which may improve feed efficiency and animal performance when appropriately incorporated into ruminant diets.

The objective of this article is to review the effects of dietary lipid supplementation on enteric methane emissions and feed efficiency in ruminants. Particularly, the review examines the biological basis of methane production, the role of lipids in ruminant nutrition, and the mechanisms through which dietary lipids influence rumen fermentation, methane output, and feed utilization efficiency.

ENTERIC METHANE EMISSION IN RUMINANTS

Rumen fermentation and methanogenesis

Ruminants possess a specialized forestomach, the rumen, which houses a diverse and complex microbial ecosystem comprised of bacteria, protozoa, archaea, and fungi. These microorganisms permit the digestion of fibrous plant materials that are indigestible to monogastric animals. During rumen fermentation, carbohydrates are degraded into volatile fatty acids (VFAs), primarily acetate, propionate, and butyrate, which serve as the main source of energy for the host animal. However, this process also generates metabolic hydrogen (H_2) as a by-product.

Methanogenesis is a process of CH_4 production in the rumen, where H_2 reduced the CO_2 with the help of methanogenic archaea. This is a dynamic process, in which methanogens strongly influence the metabolism of fermentative and acetogenic bacteria via interspecies hydrogen transfer. This process plays a crucial role in maintaining a low partial pressure of hydrogen in the rumen, thereby allowing fermentation to proceed efficiently. Methane produced in the rumen is expelled mainly through eructation, representing a direct loss of dietary energy to the animal.

Biological pathways of hydrogen transfer to methane

The principal pathway of methane formation in the rumen is hydrogenotrophic methanogenesis, in which methanogens convert carbon dioxide and hydrogen into methane and water. Alternative pathways, such as methylotrophic methanogenesis, play a lesser role under typical rumen conditions. Hydrogen availability is a key determinant of methane production, as it is produced during the formation of acetate and butyrate, while propionate formation acts as a competitive hydrogen sink. Consequently, diets that favor propionate production are generally associated with reduced methane emissions. Interactions among rumen microbes also influence hydrogen flow. Rumen protozoa, for example, are significant producers of hydrogen and often harbor methanogens either

on their surface or internally, facilitating efficient hydrogen transfer to methane. Thus, changes in microbial population dynamics can markedly affect methane output.

Contribution of methane to global greenhouse gas emissions

Enteric fermentation in ruminant livestock is a major source of methane emissions within the agricultural sector, contributing a substantial share of methane released into the atmosphere and thereby playing an important role in global greenhouse gas emissions and climate change mitigation challenges (Morgavi et al., 2023). Enteric methane from ruminants constitutes a major share of agricultural GHG emissions worldwide. Livestock production is estimated to contribute approximately 14 - 18% of total anthropogenic GHG emissions, with methane accounting for a substantial proportion of this figure. Enteric fermentation alone represents the largest source of methane emissions within the agricultural sector, particularly in developing regions where extensive ruminant production systems predominate.

Ruminant animals, including cattle, sheep, and goats, contribute significantly to greenhouse gas emissions with CH_4 and CO_2. Ruminants produce methane during their digestive process through fermentation, which is primarily expelling via eructation (belching). Additionally, the decomposition of ruminant manure further contributes to greenhouse gas emissions by producing CH_4 and N_2O. Emissions intensities are defined as the GHG emissions per unit weight of product (kg CO_2eq/kg product). Monogastric animals have far lower emissions than ruminants. For example, for pork, it is around 2 kg CO_2eq/kg, and for chicken, it is less than 1 kg CO_2eq/kg, while for beef, it is 32 kg CO_2eq/kg. This high value is due to methane production through ruminant fermentation). It is reported that ruminant animals are responsible for threequarters of the total CO_2 equivalent (CO_2-eq) emissions from the livestock sector. It is estimated that cattle farming accounts for approximately 4% of global greenhouse gas emissions through methane production.

Methane emissions from enteric fermentation – ruminant animals (cattle, buffalo, sheep and goat) produce CH4 as part of their digestive process. In their rumen (stomach), microbial fermentation breaks down carbohydrates into simple molecules that can be digested by the animals. Methane is a by-product of this process. Poorly digestible (i.e. fibrous) rations cause higher CH_4 emissions per unit of ingested energy. Methane and N_2O emissions from manure management – manure contains two chemical components that can lead to GHG emissions during storage and processing: organic matter that can be converted into CH_4 and N that leads to nitrous oxide emissions. Methane is released from the anaerobic decomposition of organic material. This occurs mostly when manure is managed in liquid form, such as in deep lagoons or holding tanks. During storage and processing, nitrogen is mostly released in the atmosphere as ammonia (NH_3) that can be later transformed into N_2O (indirect emissions).

Factors affecting methane yield

Several physiological and dietary factors influence enteric methane yield in ruminants, including feed composition and quality, rumen fermentation characteristics (such as pH and volatile fatty acid profiles), digesta retention time, and the structure of the rumen microbial ecosystem, all of which vary with animal species and management conditions (Thacharodi et al., 2024). Rumen pH plays a key role in the activity of fiber-degrading microbes and fermentation characteristics; pH values close to neutral (around 6.3 - 6.8) are generally associated with more active cellulolytic bacteria and efficient fiber digestion, while prolonged deviations below this range inhibit fiber-degrading microbial activity and can alter fermentation end-products relevant to methane formation (Li et al., 2021). Diet composition, particularly the type and fermentability of carbohydrates consumed, plays a critical role in shaping rumen fermentation patterns and volatile fatty acid profiles, which in turn influence enteric methane emissions in ruminants (Sun et al., 2022). Different carbohydrate sources

and forage-to-concentrate ratios influence rumen fermentation pathways and methane production, with diets higher in readily fermentable carbohydrates generally shifting fermentation toward pathways (e.g., propionate) that are associated with lower methane emissions compared with high-fiber, forage-based diets (Sun et al., 2022). Increasing the proportion of concentrate relative to forage in ruminant diets tends to decrease enteric methane emissions per unit of feed intake or product output, as higher concentrate levels alter rumen fermentation toward pathways (e.g., propionate) that are associated with reduced hydrogen availability for methanogenesis compared with high-forage diets (Purba and Sangsawad, 2025). Feeding ruminants a high-concentrate diet has been shown to reduce the abundance of ruminal methanogens and cellulolytic bacteria compared with higher roughage diets, as shifts in substrate availability and fermentation conditions alter the microbial community composition and function (Zhang et al., 2022).

Microbial population structure is another critical determinant. The abundance of methanogens and protozoa, as well as the activity of fiber-degrading bacteria, directly influences hydrogen availability and methane formation. Nutritional interventions that modify these microbial populations can therefore be effective in mitigating enteric methane emissions.

DIETARY LIPIDS AND THEIR ROLE IN RUMINANT NUTRITION

Types and sources of dietary lipids

Ruminant diets can include lipids from multiple origins - such as plant-derived oils (e.g., sunflower, linseed, olive), oilseeds, and other high-fat feed components - and these lipid sources vary in their fatty acid profiles and degrees of saturation, which can influence rumen fermentation characteristics, microbial populations, and methane production (Vargas et al., 2020). Plant-based lipids, particularly those rich in unsaturated fatty acids, have been extensively studied for their potential to reduce methane emissions. The choice of lipid source and inclusion level is critical, as excessive lipid supplementation can negatively affect fiber digestion and the performance of animals.

Nutritional functions of lipids in ruminant diets

Lipids represent a group of organic compounds including fatty acids or their derivatives and are insoluble in water but soluble in organic solvents. They are mainly made of carbon and hydrogen and, in a lesser extent, oxygen. Their primary function is storing energy (such as triglycerides) since they have a high energy content (9 Kcal / g). Comparatively, carbohydrates and proteins provide only 4 Kcal / g once metabolized. In addition, when stored anhydrously (without water), unlike carbohydrates and proteins, they constitute an extremely concentrated source of energy.

Lipids serve several important nutritional functions in ruminant diets. They are a concentrated source of energy, providing approximately 2.25 times more energy than carbohydrates. Lipids also supply essential fatty acids required for normal physiological functions, reproduction, and product quality, such as milk fat composition (Palmquist and Jenkins, 2017). In addition to their energy contribution, dietary lipids influence rumen fermentation patterns. By partially replacing fermentable carbohydrates, lipids can reduce overall hydrogen production in the rumen. Moreover, certain fatty acids exert toxic effects on specific rumen microorganisms, thereby altering microbial activity and fermentation end-products.

Mechanisms through which lipids alter fermentation and nutrient utilization

Dietary lipids reduce enteric methane emissions through different mechanisms. Inclusion of dietary lipids can reduce the pool of fermentable organic matter in the rumen, which in turn alters hydrogen production and availability for methanogenesis, ultimately contributing to lower enteric methane emissions (Beauchemin et al., 2020). Also, unsaturated fatty acids act as alternative hydrogen sinks through biohydrogenation, thereby competing with methanogenesis for available hydrogen (Vargas et al., 2020). Supplementation

of unsaturated lipids in ruminant diets has been shown to suppress rumen protozoal populations and exert inhibitory effects on methanogenic archaea, contributing to reductions in enteric methane production (Palangi et al., 2022).

From a feed efficiency perspective, lipid supplementation increases dietary energy density, which can improve animal performance when intake is not constrained. However, excessive lipid inclusion may impair fiber digestion by inhibiting cellulolytic bacteria, highlighting the need for balanced formulation. When optimally applied, dietary lipids offer a strategic means of simultaneously reducing methane emissions and enhancing feed efficiency in ruminant production systems.

MECHANISMS OF METHANE MITIGATION BY LIPID SUPPLEMENTATION

Biohydrogenation: How unsaturated fatty acids capture hydrogen

Dietary fat in the rumen undergoes two processes: fat hydrolysis and biohydrogenation. Fat is hydrolyzed in the rumen to produce FAs, which are rapidly hydrogenated (Dewanckele et al., 2020). A study revealed that the rumen fermentation reduces by approximately 50% when the fat content in the diet is over 10%, especially when more unsaturated fatty acids (UFA) (Luo et al., 2022). This phenomenon could be attributed to the fact that numerous FAs adhere to the feed surface, which hinders the microbes from being able to hydrolyse the feed substrate (Luo et al., 2022). Most methanogens rely on the coupling of methanogenesis with membrane potential generation for ATP production (Downing and Nayak, 2025). However, FAs can potentially disrupt the electron transport chain by binding to electron carriers or altering membrane integrity, while also interfering with oxidative phosphorylation by decreasing membrane potential and the proton gradient (Yoon et al., 2018), meanwhile, UFA undergo biohydrogenation in the rumen, resulting in hydrogen consumption (Toral et al., 2018). Therefore, these two factors may be the reason UFA reduce CH_4 emissions from the rumen.

Defaunation: Suppression of rumen protozoa and methanogens

Rumen protozoa produce both formate and H_2, but ruminal formate metabolism is poorly understood compared with interspecies H_2 transfer (Tapio et al., 2017). The production of CH_4 pulls release of H_2 into the rumen via hydrogenases in bacteria, protozoa, and fungi. This interspecies H_2 transfer to methanogens is integrally linked in ruminal VFA metabolism; these 2 processes are readily studied in continuous culture, because net (after recycling) VFA production can be measured without absorption or end-product feedback, and headspace CH_4 and H_2(aq) can be directly measured rather than estimated (Wenner et al., 2017).

Reduced fiber digestion: Less fermentable substrate for methane formation

The rumen provides an ideal habitat for protozoa, whose concentration can reach 10^5 - 10^6 cells/mL. In return, protozoa function as ecosystem engineers in the rumen microbial community, exerting regulatory control through predation on bacteria and fungi, competition for nutrients, and symbiotic associations with methanogens (Solomon et al., 2022). Protozoa prey on bacterial and fungal spores, but are preferentially retained in the rumen, thus reducing the postruminal microbial protein supply (Millen et al., 2016). Protozoa compete with amylolytic bacteria for dietary starch, which is mostly fermented into acetate by protozoa (Yu et al., 2024), while mostly into propionate by amylolytic bacteria (Yu et al., 2024; Millen et al., 2016).

Shift in fermentation pattern: Increased propionate formation reduces hydrogen

The balance between propionate formation and acetate and butyrate formation has a key role in determining H_2, available in rumen for utilization by methanogenic archaea. Wang et al. (2023) demonstrated that increases in propionate formation are strongly associated with decreases

in CH_4 production. In a meta-analysis, Wang et al. (2023) found that inhibiting CH_4 production in batch cultures resulted in redirection of metabolic hydrogen toward propionate and H_2, but not butyrate. In addition, propionate is predominantly used as a glucose precursor in ruminants, and more propionate formation would likely result in a more efficient utilization of feed energy. Maximizing the flow of metabolic hydrogen in the rumen away from CH_4 and toward VFA (mainly propionate) would increase the efficiency of ruminant production and decrease its environmental impact (Wang et al., 2023). Therefore, modifying the dietary formulation with NFFS may be an effective measure to shift the hydrogen flow toward alternative electron acceptors such as propionate.

EFFECTS OF LIPID SUPPLEMENTATION ON FEED EFFICIENCY

Relationship between lipid inclusion and feed intake / digestibility

In intensive dairy sheep production, feeding systems have moved away from pasture-based to high-concentrate diets, which may affect the nutritional value of milk fat, decreasing the concentration of potentially health-promoting fatty acids (FA), such as *cis*-9 *trans*-11 conjugated linoleic acid (CLA), *trans*-11 18:1, or 18:3n-3 (Hervás et al., 2021; Nudda et al., 2020; Gómez-Cortés et al., 2020). In these production systems, diet supplementation with lipids is also widespread to increase the energy density of the ration and therefore production level (Palmquist and Jenkins, 2017). Furthermore, this nutritional strategy has proven to be very useful to improve milk FA profile by modifying the content of bioactive FA (Toral et al., 2020; Carreño et al., 2016; Vargas-Bello-Pérez et al., 2021). Supplements rich in palmitic acid (mainly as calcium soaps, palm oil, and fractionated FA) are frequently recommended and used by dairy nutritionists, as they seem to offer the best productive responses.

Effects on rumen microbial activity and volatile fatty acid profiles

The volatile fatty acids (VFA) produced by microbial fermentation in the rumen are the main source of energy absorbed by the digestive tract of ruminants. The amount and profile of VFA formed in the rumen has consequences for the efficiency of energy utilization, production of methane, risks of ruminal acidosis and composition of animal products. Using an empirical approach, the **NDS Ruminal pH sub-model** provides a quantitative review on VFA yield in the rumen, based on several dietary parameters (Beckett et al., 2021).

Impacts on growth rate, milk yield, or feed conversion efficiency

Economic impact

• Feed accounts for 60-70% of total production costs in cattle farming.

• Improved FCE reduces feed expenses, increasing profitability.

• Efficient cattle reach market weight faster, reducing overhead costs.

Growth performance

• Cattle with better FCE grow faster due to optimal nutrient utilization.

• Efficient feed conversion leads to higher average daily gain (ADG).

• Well-managed FCE ensures consistent muscle development and carcass quality.

Environmental sustainability

• Lower FCR means less feed production, reducing land, water, and energy use.

• Decreased methane emissions from digestion contribute to lower greenhouse gas outputs.

• Sustainable cattle farming practices rely on optimizing FCE.

Limitations: Lipid level thresholds and possible depression in fiber digestibility

One of the most obvious differences in fiber digestibility and utilization among forage species is between legumes and grasses. Legumes are typically more digestible than grasses, because

they contain less fiber, not because legume fiber is more digestible. In fact, legume fiber is more lignified and less digestible than that of grasses. Similarly, the major factor lowering digestibility of forages, as their mature is the higher fiber and lower cell-soluble concentrations of mature forages. Grass leaves develop a lignified midrib to provide mechanical support, which contributes to the high fiber concentration of grass leaf blades. Because the fiber concentration of grass leaf blades is twice that of legume leaves, grass leaf blades are often less digestible than those of legumes. The difference is not as great as suggested by the large difference in NDF concentration, however, because the NDF of grasses is more digestible.

ENVIRONMENTAL AND ECONOMIC IMPLICATIONS

Methane mitigation potential of various lipid sources

The amount of methane emitted is strongly related to feed intake and diet composition. Thus, reductions in GHG from ruminants of up to 60% can be achieved just by dietary intervention, with a number of nutritional strategies proposed to reduce methane emissions (Beauchemin et al., 2022; Ugbogu et al., 2022; Almeida et al., 2021). One of these strategies is the supplementation of feed with plant oils (Bayat et al., 2018; Knapp et al., 2014). The inclusion of fats in ruminant diets is considered a promising approach to manipulate the rumen microbial community to reduce methane emissions. Consequently, feed digestion (ruminal and total tract) may be adversely affected by the addition of lipids at levels exceeding 5 - 6% of dietary dry matter, primarily due to the toxic effects of long-chain unsaturated fatty acids on rumen fibrolytic microorganisms (Ponnampalam et al., 2024; Martínez Marín et al., 2011; Weld and Armentano, 2017). There are some studies on the effects of dietary plant oil supplementation on specific rumen parameters, but there is a paucity of work considering both the effects on the metabolic products, and the likely microbial mechanisms that drive them, integrating these phenomena as a whole(Edwards et al., 2008).

Lifecycle or carbon footprint benefits of lipid feeding

Integrating lipids into livestock diets serves as a potent strategy for methane mitigation, as specific fatty acids inhibit the activity of methanogenic archaea within the rumen environment, leading to a significant decrease in enteric greenhouse gas output (Beauchemin et al., 2022). This shift not only reduces the direct carbon footprint of the animal but also improves the overall lifecycle assessment by lowering the emission intensity per kilogram of meat or milk produced (Arndt et al., 2019). From an economic perspective, the high caloric density of lipids allows for a more compact and efficient ration, which can significantly reduce total feed costs and improve the feed conversion ratio across various production stages. Furthermore, the use of lipid supplements can enhance reproductive performance and animal health, thereby reducing the overhead costs associated with herd turnover and veterinary interventions (Kokčić et al., 2024). Ultimately, the adoption of lipid-based feeding strategies aligns animal productivity with global sustainability goals by optimizing nutrient utilization and reducing waste across the entire production chain (Almeida et al., 2021). These dual benefits make lipid supplementation a cornerstone of modern precision nutrition, balancing the need for increased food security with the necessity of reducing the agricultural sector's environmental impact.

Cost - benefit considerations in tropical and intensive systems

In tropical production systems, the economic justification for lipid feeding often hinges on mitigating the financial losses associated with heat stress. Because lipids have a significantly lower "heat increment" of feeding compared to fibrous forages or starches, they generate less internal body heat during digestion, allowing animals to maintain essential energy intake, even when

high ambient temperatures suppress their natural appetite. This thermal advantage translates directly to farm profitability by preventing the severe drops in milk yield and fertility common in hotter climates. For instance, field research in tropical dairy conditions has demonstrated that supplementing rations with protected fats can increase daily milk output and improve conception rates, resulting in a positive net return on investment despite the higher cost of the lipid additives (de Souza et al., 2017).

Conversely, in intensive confinement systems, the cost-benefit analysis focuses primarily on maximizing "Income Over Feed Cost" (IOFC) through improved feed efficiency and throughput. In these high-input environments, lipids are utilized to dramatically increase the energy density of the diet, enabling high-genetic-merit animals to meet their massive caloric requirements without the physical limitation of gut fill. However, the economic success of this strategy depends heavily on the specific lipid source used; while some fats reduce methane emissions, they can occasionally depress dry matter intake if not carefully formulated. Studies on feedlot cattle indicate that while lipid sources like palm oil can lower greenhouse gas intensity, they must be balanced correctly to avoid reducing average daily gain, which would otherwise negate the economic benefits of the intervention (Ponnampalam et al., 2024).

Relevance to sustainable livestock production and climate-smart agriculture

The strategic incorporation of lipids into livestock rations aligns directly with the core pillars of Climate-Smart Agriculture (CSA) by simultaneously addressing the urgent need for greenhouse gas mitigation and the requirement for sustained food security, as the modulation of rumen fermentation pathways through fatty acid supplementation not only yields a direct reduction in enteric methane intensity a critical short-lived climate pollutant but also enhances the thermodynamic efficiency of feed conversion, thereby allowing producers to decouple the necessary expansion of animal protein supply from the historical trajectory of increased environmental degradation and resource depletion (FAO, 2023; Gerber et al., 2023).

In the context of adaptation to an increasingly volatile climate, lipid feeding provides a crucial physiological safeguard for livestock populations in warming regions by functioning as a "cool energy" source that minimizes the metabolic heat increment associated with digestion. Thus, enabling animals to maintain vital energy balances and reproductive viability during periods of severe heat stress that would otherwise compromise the economic sustainability of pastoral and mixed-farming systems, while simultaneously offering a pathway to reduce the sector's land-use footprint by valorizing industrial by-products and reducing the reliance on extensive grazing lands (Beauchemin et al., 2022; Makkar, 2018).

CONCLUSION

Dietary lipid supplementation offers a practical nutritional approach for mitigating enteric methane emissions in ruminants, while simultaneously improving feed efficiency. Methane production in the rumen is intrinsically linked to microbial fermentation patterns, hydrogen availability, and volatile fatty acid production, all of which can be modified through lipid inclusion in the diet. Lipids reduce methane emissions by decreasing fermentable substrate availability, acting as alternative hydrogen sinks through biohydrogenation, suppressing rumen protozoa and methanogenic archaea, and promoting fermentation pathways that favor propionate formation.

From a productivity standpoint, lipids enhance dietary energy density and can improve feed conversion efficiency, growth performance, and milk production when included at appropriate levels. However, excessive lipid supplementation may depress fiber digestibility, alter rumen microbial balance, and reduce feed intake, thereby limiting its overall effectiveness. Economic and environmental benefits of lipid supplementation vary across production systems, with particular relevance in intensive and tropical systems where

improved energy utilization and reduced heat increment of feeding are advantageous.

In conclusion, dietary lipid supplementation represents a promising strategy for climate-smart and sustainable ruminant production. Its successful application depends on careful selection of lipid sources, optimal inclusion rates, and consideration of system-specific constraints to achieve a balance between methane mitigation, animal performance, and economic viability.

Acknowledgement

The authors acknowledge the Department of Animal Production, Faculty of Agriculture, University of Jos, Nigeria, for providing the academic environment and resources that supported the completion of this review.

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Received: **January 27, 2026**; *Approved*: **March 04, 2026; *Published:*** **August, 2026**