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Review Article

Review on Potential of Feeding Strategies to Reduce Greenhouse Gas Emission from Ruminant Livestock in the Tropics

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Abstract

Ruminant livestock production plays an important role in food security, livelihoods, and economic development in tropical regions. However, it is also a major source of greenhouse gas (GHG) emissions, particularly methane (CH_4) from enteric fermentation and manure management. These emissions contribute to climate change and represent a loss of dietary energy that could otherwise support animal production. Therefore, improving feeding strategies is essential for reducing emission intensity while enhancing livestock productivity and environmental sustainability. This review aimed to examine the potential of different feeding strategies to mitigate GHG emissions from ruminant livestock in tropical production systems. Relevant scientific literature was reviewed to evaluate conventional feeding practices, dietary interventions, feed additives, and manure management approaches, with particular emphasis on their effects on rumen fermentation, methane production, feed utilization, and animal productivity. The reviewed strategies included improving forage quality and digestibility, enhancing feed efficiency, optimizing feed intake, adjusting forage-to-concentrate ratios, and supplementing diets with lipids, ionophores, nitrates, and plant-derived compounds such as tannins and saponins. The findings indicate that improved forage quality, balanced diets, and increased feed efficiency can reduce methane emissions per unit of animal product while supporting productivity. Dietary additives, particularly tannins, saponins, lipids, and nitrates, also demonstrate methane-mitigation potential, although their effectiveness varies depending on the source, inclusion level, animal species, and dietary composition. Furthermore, appropriate manure management, particularly anaerobic digestion, provides additional opportunities to reduce emissions and recover renewable energy. In conclusion, integrating improved forage production, balanced feeding practices, locally available feed additives, and appropriate manure management offers a promising approach to reducing GHG emission intensity and promoting sustainable and climate-resilient ruminant livestock production in tropical regions.

Keywords

Methane, Feeding Strategies, Improved Forage, Mitigation, Tropics, Ruminant Livestock

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1. Introduction

Driven by population growth and the ever-increasing global demand for nutrient rich animal source food such as milk and meat (in 2050 predicted to grow by 58% and 73% respectively), livestock production is rapidly expanding in the world [16]. Livestock farming supports the economies of developing countries, by contributing about 30–70% of rural household income, serving as a source of balanced nutrition, providing agricultural inputs, and creating job opportunities for over 1.3 billion people worldwide [46]. The livestock sector is making a significant contribution to the country's economy by serving as a source of food, fertilizer, irrigation tools, investment, income security, foreign exchange earnings, and social and cultural identity for tropical countries like Ethiopia [3].

In Ethiopia Livestock farming is considered a foundation of the national economy, contributing 16.5 percent to the national Gross Domestic Product, over 36 percent to the agricultural GDP, 30 percent to agricultural employment, and 16 to 19 per-cent of foreign currency earnings [35]. Agriculture the cornerstone of economic development of the developing countries is highly connected with environment. This is because agricultural activities contribute 80%, 40%, and 1% of N_2O, CH_4, and CO_2 emissions into the environment, respectively [2]. Despite their many advantages live-stock contribute to environmental pollution by producing GHGs such as methane (CH_4) and nitrous oxide (N_2O), which are primarily generated through enteric fermentation and manure management [60].

Cattle production is becoming increasingly important in sub-Saharan Africa due to the growing demand for food, but it is also a significant contributor to greenhouse gas emissions, particularly methane [52]. Methane is one of the most powerful greenhouse gases and has a significant impact on the environment. Methane released from livestock produc-tion contributes to climate change and causes environmental disruption [52]. This has led to criticism regard-ing the large-scale rearing of livestock [32, 41]. The livestock sub-sector of agriculture is facing three challenges. These are: matching the supply of livestock products with the increasing demand by improving production, adapting to environmental changes for a rapidly growing global economy, and increasing production while minimizing environmental pollution [42].

Through feed production, enteric fermentation, and animal wastes livestock production systems contributes to the emission of the major GHGs including Carbon dioxide (CO_2), methane (CH_4), and Nitrous oxide (N_2O). This also accounts for 37% of human-caused methane emissions [60]. In ruminant livestock, depending on the feed content, type of animal, and nutritional level between 8% to 12% of total energy intake is wasted [34, 47]. These indicates that enteric fermentation affects feed utilization of ruminants. This highlights the need for finding strategies that enhances feed utilization, reduce methane emission and ensures environmental sustainability in ruminant livestock production system [50]. Reducing CH_4 losses is an environmentally sound practice that can improve production efficiency [34], because it has both environmental protection and economic sustainability benefits [52].

The development of management strategies to mitigate CH_4 emissions from ruminant livestock is possible and desirable [50]. Most rumen manipulation strategies target ruminal methanogenesis and thus decrease absolute emissions, without affecting animal performance. Strategies that increase animal performance and efficiency of production tend to decrease CH_4 intensity because they dilute the feed energy associated with animal or herd maintenance [13]. Improved livestock genetics and management practices can reduce emission intensity per unit of product while maintaining livelihood benefits. The development of climate resilient breeds and feeding strategies represents important pathways for sustainable intensification of livestock systems [46].

Among the strategies that help reduce GHG emissions from livestock are improved management practices and technologies that increase feed quality, ensure animal health, implement genetic improvement programs, and increase carbon sequestration in soil and biomass, which could minimize global GHG emissions by 5.5–5.9 Gt CO2-equivalent per year [60].Additionally, he noted that to overcome CH_4 emission dietary strategies, such as feeding livestock with secondary plant metabolites and improved multi-purpose forages—specifically by cultivating selected forage legumes and grasses—are among the effective methods. Improved forage practices play a significant role in reducing methane emissions [59].

Though, the moder-ate solution for reducing methane emission from livestock production practices could be changing feeding practices and manure management [40].

However, a critical gap persists: Little research is available on studies on the effect of feeding strategies which have direct influence on rumen fermentation processes and animal productivity, as well as the extent of methane emissions released from the digestion of ruminant livestock. Sustainable Feeding strategies need to be investigated and developed, which should minimize ruminant energy loss and lead to increased productivity by reducing the number or activity of methanogens. Little research is available on the effect of feeding system (i.e. component feeding or selection of feed and concentrates versus TMR feeding) on CH_4 production. More research is needed to determine feeding regimes that improve feeding efficiency and lower CH_4 emissions. There is lack of research on the effect of feeding systems and feeding regimes, as well as the ex-tent of methane emissions release from the digestion of sheep, goats, buffalo and other ruminants [41]. Therefore, considering this, the objectives of this paper is to analyses feeding strategies that have potential in promoting sustainable greenhouse gas emission reduction from ruminant livestock and to outline future recommendations for tropical livestock production.

2. Literature Review

2.1. Major Greenhouse Gases Emitted from Ruminant Livestock

2.1.1. Methane

Methane is one of the three main greenhouse gases, together with CO_2 and nitrous oxide (N_2O). Its global warming potential is 25-fold than that of CO_2 [24]. Methane is a colorless, odorless, inflammable, and tasteless gas that is the primary component of natural gas [14, 26]. Methane is present naturally in the atmosphere; CH_4 is lighter than air and has a specific gravity of 0.554. Methane gas has a density of 0.717m-3/kg, melting point of -187 ℃, and a boiling point of -161 ℃. This gas is only not soluble in water but is soluble in organic solvents. Naturally occurring CH_4 is mainly pro-duced by the process of methanogenesis. The reaction is: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ [14].

Enteric methane (CH_4) is a natural end product of microbial fermentation of organic matter (OM) in the rumen and to a small extent in the large intestine. Methane is produced predominantly in the rumen (87%) and to a small extent in large intestines gas [26]. Rumen CH_4 is primarily emitted from the animal by eructation.

Methanogenesis is a strictly anaerobic process that involves a consortium of microorganisms in the rumen (bacteria, protozoa, archaea and fungi), with the last step being carried out by methanogenic archaea. The main products of rumen fermentation are volatile fatty acids (VFA), carbon dioxide (CO_2), hydrogen (H_2) and ammonia. Acting as a source of CO_2, formate is also a precursor of enteric CH_4 and accounts for about 15–20% of CH_4 in the rumen [41]. Even though H2 is one of the major end products of fermentation by protozoa, fungi and bacteria, it does not accumulate in the rumen. Other bacteria mainly the methanogens, which are present in the mixed microbial ecosystem, use it. [26], established that CH_4 production can be calculated from the stoichiometry of the main VFA formed during fermentation i.e., acetate (C-2), propionate (C-3) and butyrate (C-4) as follows: CH_4=0.45C2-0.275C3+0.40C4. Thus, the molar per-centage of VFA influences the production of CH_4. Acetate and butyrate microbial gas, fermentation of feed components. The conversion of feed material to CH_4 in the rumen involves the integrated activities of different microbial species, with the final step carried out by methanogenic bacteria [34]. Methane is also produced under anaerobic condition by archaea mainly in storage conditions, using the OM present in animal excreta. Hence, the production of CH_4 from manure mainly occurs in slurry and liquid manure [13].

2.1.2. Nitrous Oxide (N_2O)

Nitrous oxide is produced from manure by nitrification, denitrification, leaching, volatilization, and runoff. Nitrification and denitrification are direct emissions. N_2O is 16 times more potent than CH_4 and 310 times more potent than CO_2 over a 100-year period [22]. N_2O acts as a source of NO in the stratosphere, which indirectly causes depletion of ozone (O_3), increasing UV radiation reaching the Earth's surface [12]. An increase in animal stocking rates and intensive gazing results in the deposition of huge amounts of N via animal excreta (urine + dung); farm management practices that enhance soil organic N mineralization also led to N_2O production [50].

2.1.3. Carbon Dioxide (CO_2)

Carbon dioxide emissions associated with livestock production arise from both direct and indirect sources throughout the production chain. These sources include feed cultivation, feed processing and transportation, livestock management, manure handling, and animal slaughter [51]. During feed production, CO_2 is released through fossil fuel consumption, particularly diesel used in tractors and harvesting machinery, fuel used for drying feed, and natural gas consumed during the manufacture of synthetic fertilizers. Additional emissions occur during post-harvest feed processing, especially drying, and transportation [42].

Within ruminants, CO_2 is also produced during microbial fermentation in the rumen. Carbohydrates, including cellulose, are broken down by rumen microorganisms into volatile fatty acids (VFAs), gases, and other fermentation products. Similarly, protein degradation produces peptides and amino acids, which undergo microbial deamination to release ammonia and car-bon-containing compounds. Carbon dioxide is also generated during microbial transformations associated with nitrogen metabolism and urea degradation [30]. Furthermore, manure decomposition can release CO_2 alongside other greenhouse gases, depending on manure composition and management conditions.

The magnitude of carbon emissions associated with livestock production is influenced by several factors, including feed quality, feed intake, production practices, and the energy required for feed cultivation and processing [27, 39]. Locally produced feed may reduce emissions associated with transportation and processing, although the overall environmental benefit depends on production methods and land-use impacts [51]. It is important to distinguish CO_2 emissions from fossil fuel use and land-use change from CO_2 produced through biological respiration and ru-men fermentation, because biogenic CO_2 is generally treated differently in greenhouse gas inventories.

2.2. Ruminant Livestock and Greenhouse Gas Emission

2.2.1. Contribution of Ruminants to Global Greenhouse Gas Emissions

Agriculturally derived GHG emissions, and in particular methane (CH_4), primarily result from enteric fermentation of ruminant livestock and, to a lesser extent, storage of manure

[13]. It is known that from the agricultural sector, ruminant livestock (dairy, beef, goats, and sheep) substantially contributes to the increase in CH_4 production through continuous natural rumen fermentation process [14]. Methane produced in the rumen accounts for up to 90 per-cent of ruminant enteric CH_4 emissions, whereas microbial fermentation in the large intestine accounts for the remainder of emissions [13]. Livestock supply chains are estimated to account for 14.5 percent of total human-induced GHG emissions and it is estimated that about 80 percent of the GHG emissions from livestock and 90 percent of CH_4 emissions is derived from ruminant livestock [13, 60].

In developing country especially in Africa, there is an increase in CH_4 emission resulted from increased live-stock production. According to the report of [18] there was an estimation that African cattle, sheep and goat produce about 7.8mil tons of CH_4 in 2000 which are likely to in-crease to 11.1mil tons by 2030. As emphasized by [40], in case this linear relationship between methane emission and livestock population continues, it could be concluded that global methane emission form animals' production may increase 60% by the year 2030.

2.2.2. Major Sources of Greenhouse Gas Emissions from Ruminants

Greenhouse gas emissions from ruminant livestock production primarily originate from enteric fermentation and manure management. Methane emission is now the second contributor to global warming, which it has 23 times more influence than that of carbon dioxide (CO_2) [14].

Enteric fermentation is the major source of methane (CH_4), produced during microbial digestion of feed in the rumen, while manure management contributes methane and nitrous oxide (N_2O), depending on manure composition, storage conditions, and handling practices [50].

Methane emissions from manure are particularly associated with liquid manure storage systems, such as lagoons, ponds, and tanks, where anaerobic conditions favour methane production. In contrast, manure deposited on pastures or managed under suitable solid-storage conditions generally produces less methane, although nitrous oxide emissions may occur during nitro-gen transformations [13].

The relative contributions of these emission sources vary according to livestock species, feeding practices, production sys-tems, and environmental conditions [14]. Global estimates indicate that enteric fermentation contributes substantially more methane than manure management, with annual emissions estimated at approximately 85.6 million tonnes of CH_4 from enteric fermentation and 17.5 million tonnes from livestock manure [13]. These emissions highlight the importance of improving feed quality and utilization, enhancing animal productivity, and adopting appropriate manure management practices to reduce the environmental impact of ruminant production.

2.3. Rumen Carbohydrate Fermentation, Methane Production, and Energy Loss in Ruminants

Structural and non-structural carbohydrates are the main source of energy and carbon for ruminants. In the rumen, polymers such as cellulose, hemi cellulose and starch are digested by a complex consortium of bacteria, protozoa and fungi, and the resulting monomers are metabolized into volatile fatty acids (VFA; mainly acetate, propionate and butyrate), CO_2 and CH_4 as the main final products of fermentation [13].

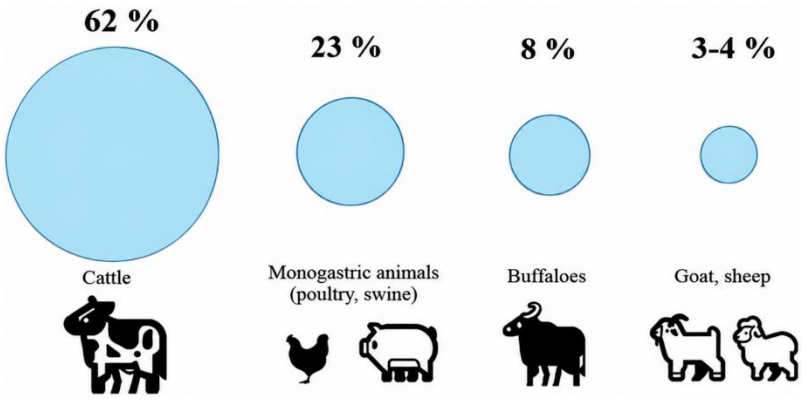
During feed fermentation and digestion in animals, methane gas is produced as by-product of digestion of structural carbohydrate majorly cellulose due to the action of microorganism (fungus, protozoa and bacteria) in the rumen [40]. Ruminal digestion of feed by the microorganisms, under anaerobic results in the production of acetate, propionate and butyr-ate, which are used by the animal as energy source, and the production of carbon dioxide (CO_2) and CH_4 which eliminated through eructation [14].

Methane production is a ubiquitous, apparently unavoidable side effect of fermentative fibre digestion by symbiotic micro-biota in mammalian herbivores [13]. Methane emission also contributes to substantial energy loss of animals [60]. Actually, this CH_4 production from the production from the rumen archaea result in 2-12% loss of metabolizable energy in the rumen [40]. Enteric methane emissions from ruminant livestock represent a major contributor to agricultural greenhouse gases and reflect an energetic inefficiency in ruminant metabolism [32].

Table 1. *Typical ranges in CH_4 emissions from ruminant and energy lost as CH_4.*

Animal Class	Average live weight (kg)	CH_4 (kg/head/year)	MJ CH_4 Lost/head/day	Average Daily Energy Requirement (MJ/head/day)	References
Mature Ewes	48	10-13	1.5-2	13	[8]
Beef	470	50-60	7.6-13.6	83	[26]
Lactating Cow	550	91-146	13.6-22.1	203	[23, 26]
Goat	35-45	8-12	1.2-1.8	11	[23, 45]

Animal Class	Average live weight (kg)	CH_4 (kg/head/year)	MJ CH_4 Lost/head/day	Average Daily Energy Requirement (MJ/head/day)	References
Buffalo	500-600	55-12	8.5-18.0	~90	[31]



Source: [32].

Figure 1. *Global enteric Emissions in livestock sector.*

2.4. Factors Affecting Manure Methane Emissions

Many factors affect the amount of ruminant CH_4 production, including level of feed intake, type and quality of feeds, energy consumption, animal size, growth rate, level of production, and environmental temperature. Methane also produced from manure of animals depending on the physical form of the faeces, the amount of digestible material, the climate, and the time they remained intact. The major part of methanogenesis in ruminants occurs in the large fermentative chamber, which is rumen [14].

There are several factors that affect the CH_4 production from manure, which includes temperature, organic matter present, microbe load, pH, moisture, and type of feed. However, CH_4 emitted from manure depends primarily on (i) the management system such as solid disposal system, liquid disposal systems, e.g., ponds, lagoons, and tanks, which can emit up to 80% of manure-based CH_4 emissions, while solid manure emits little or no CH_4. (ii) Environmental conditions are also important. The higher the temperature and moisture, the more CH_4 produced. (iii) CH_4 emissions also depend on the quantity of the manure produced, which depends on the number of animals housed, the amount of feed the consumed, and the digestibility of the feed. (iv) Manure characteristics depend on the animal type, feed quality, and rumen microbes present in the rumen and digestive tracks. Manure handled in liquid form tends to release more amount of CH_4 when compared to solid or manures thrown into the pasture, which do not decompose anaerobically. High temperatures with neutral pH and high moisture con-tent enhance CH_4 production [50].

2.5. Conventional Feeding Strategies to Reduce Ghg from Ruminants

2.5.1. Forage Quality Improvement

Reductions in methane production from ruminant animals can result from a reduction in rumen fermentation rate (suppression in microbial activity) or a shift in volatile fatty acid (VFA) production. An inverse relationship exists between the pro-duction of CH_4 in the rumen and the presence of propionate [14].

The highly variable nutritive profile of forages affects enteric CH_4 production. Improved forage quality typically results in greater CH_4 output per day because high-quality forages have a faster passage rate from the rumen, which leads to greater feed intake and more fermentable substrate in the rumen. The result is greater daily enteric CH_4 production per day. However, the amount of CH_4 produced per unit of energy consumed or kg-1 of milk typically decreases as the quality of forages in-creases. Therefore, investigating new and/or lesser-known species and varieties/cultivars capable of producing high-biomass of quality forage and decrease methane (CH_4) production in ruminants is particularly important to develop new sources of feed [48].

Feeding legumes compared to grasses tends to reduce CH_4 but this relationship is also influenced by the maturity of the for-age at the time of consumption. Legumes produce less CH_4because they have lower NDF content and pass more quickly through the rumen [34]. At the same physiological stage of maturity, legume forages contain less neutral deter-

gent fibre (NDF) than grasses, and although the fibre in legumes is more lignified, the decline in fibre digestibility with advancing maturity is much greater for grasses than for legumes. Fibre that is more digestible results in a ruminal fermentation that decreases the acetate to propionate ratio and methanogenesis. In addition, legumes contain secondary compounds that decrease CH_4 production [13].

Forage digestibility can be increased in several ways. Harvesting at younger maturity increases digestibility because of greater concentrations of nonstructural carbohydrates, such as sugars and fructans, along with lower lignification of plant cell walls. Some genetic variants have greater digestibility. For example, the stover from the bm-3 or brown midrib genetic variant of maize and sorghum is more highly digested than typical varieties. Cellulose, hemicellulose, and NDF were less digestible in diets containing 40% (DM) maize silage and 10% alfalfa silage than in diets containing 10% maize silage and 40% alfalfa silage. Finally, grass forage is typically more digestible than legumes, such as alfalfa, although the rate of fer-mentation is faster for legumes [11].

2.5.2. Improving Feed Efficiency

Improving feed efficiency, defined as the ratio of animal product to feed intake (i.e. kg of meat or milk per kg DMI), reduces CH_4 emission intensity. Feed efficiency may be improved by increasing the nutrient density or feed digestibility, altering the rumen microbial composition, enhancing feed management practices. Improving feed efficiency will reduce absolute CH_4 emissions, CH_4 intensity and upstream emissions associated with feed production because less feed is required to produce a given quantity of animal product. In addition, CH_4 and N_2O emissions from manure storage and land application are also reduced because less manure is produced [13].

Diet modifications reduce CH_4 emissions by decreasing the fermentation of feed in the rumen, shifting the site of digestion from the rumen to the intestines, diverting hydrogen away from CH_4 production during and supplemental feed additives as a means of reducing conversion rates [5, 6]. In addition, non-dietary approaches are being examined including vaccination, biological controls (bacteriophage, bacteriocins), chemical inhibitors that directly target methanogens, and promotion of acetogenic populations in the rumen to lower the supply of metabolic hydrogen to methanogens and ruminal fermentation, or by inhibiting the formation of CH_4 by rumen bacteria [34].

2.5.3. Increasing Feed Intake

Increasing feed intake increases total CH_4 emissions but reduces CH_4 emission rate (percent of GEI or Ym) and yield (CH_4/kg DMI). Increasing the feed intake of ruminants decreases the retention time of feed in the rumen due to higher pas-sage rates. Shorter retention time limits microbial access to OM, thus reducing the extent of ruminal fermentation and lead-ing to a decline in CH_4 losses per unit of DMI or as a percentage of gross energy intake (GEI) [21, 26]. In addition, a rapid passage rate increases the growth rate of methanogens and H2 concentration, inhibiting acetate, H2 and CH_4 production and favoring propionate production, which is a competitive pathway for the use of H2. Importantly, increased feed intake decreases the proportion of ingested and absorbed nutrients and of energy associated with animal maintenance. As a result, increased feed intake dilutes CH_4 production due to maintenance, and a greater proportion of CH_4 emitted is associated with animal production [13]. However, these effects depend on diet composition, digestibility, and feeding level; therefore, increased feed intake does not necessarily reduce methane emissions under all conditions [21].

2.5.4. Forage-to-Concentrate Ratio Adjustment

There is general agreement that feeding concentrates to ruminants reduces CH_4 emissions, expressed relative to GEI, DMI and product [21, 25]. Decreasing the forage to concentrate ratio of the diet in order to increase the energy density of the diet. Increasing concentrate in the ration reduces CH_4 emissions per unit feed intake and animal product if productivity remains the same or increases. fermentation of sugars and starch shifts rumen fermentation to propionate production when rumen pH decreases. A ration with concentrate of 72% vs. 52% resulted in a 59% increase in rumen propionate concentration and a 44% decrease in the Ac: Pr ratio in lactating dairy cows, accompanied by a depression of milk fat – 3.20 vs. 4.20%, respectively. Some experiments with lactating dairy cows and beef cattle have shown a linear decrease in CH_4 emissions with increasing concentrate in the ration [41].

The composition of the carbohydrates consumed affects the VFA profile and CH_4 production. Acetic acid production is pro-moted in high-forage diets, resulting in greater CH_4 production per unit of feed. A higher proportion of concentrates in the diet decreases the structural carbohydrate proportion and increases the rumen outflow rate. Higher growth rates of methanogens cause H2 to accumulate, which inhibits acetate and CH_4 production and favours propionic production as an alternative sink of metabolic hydrogen. Moreover, the rapid fermentation rate of grains lowers ruminal pH, which inhibits the growth of methanogens and protozoa thereby decreasing CH_4 production per unit of feed fermented [13]. Increasing the grain content of total mixed rations (TMR) also lowers the proportion of feed energy converted to CH_4 by decreasing the acetate: propionate ratio in the rumen fluid [34].

2.5.5. High-starch Forages

With high-starch forage there is an increase in starch and a decrease in the fibre concentration of the diet, resulting in a rumen fermentation that promotes propionate production [4, 21], which competes with methanogenesis for metabolic hydrogen. It may also decrease rumen pH [53], which inhibits methanogens. These forages can en-hance animal performance due to a high total digestible nutrient content and a

greater DMI Promoting starch fermentation in the rumen increases propionate production, which serves as an alternative sink of metabolic hydrogen to methanogenesis. Moreover, increasing starch fermentation decreases ruminal pH and inhibits the proliferation of methanogenic archaea.

Forages are composed of mainly structural carbohydrates while concentrates are high in sugars, starch and highly fermentable fibre. Feeding dairy cows a wheat-based diet reduces CH_4 emissions, yield and intensity by an average of 30, 48 and 41 percent, respectively, compared to corn-based and barley-based diets. oat-based diet decreased CH_4 emissions in dairy cows by 5 percent compared to a barley-based diet. It has also been shown in finishing feedlot cattle that feeding a corn-based diet reduced CH_4 yield by 30 percent in comparison with a barley-based diet possibly due to decreased ruminal starch digestibility [13].

2.6. Feed Additives as Nutritional Mitigation Tools

2.6.1. Lipid Supplementation

Dietary lipids produce their CH_4 mitigating effect through various mechanisms that modify the rumen ecosystem and fermentation. These mechanisms include toxicity against methanogens and protozoa; biohydrogenation of unsaturated fatty acids serving as a minor alternative H2 sink; shifting the ruminal fermentation process to promote the production of propio-nate resulting in lower CH_4 production; and decreasing feed fermentability in the rumen [13].

Lipid supplementation has been investigated as a dietary strategy for modulating ruminal methanogenesis and reducing me-thane emissions [20]. In rumen fermentation simulations, coconut oil supplementation reduced methane pro-duction, an effect attributed to lauric acid, its major fatty acid, which inhibits methanogenesis [58]. But it has negative effect on digestibility of feed so not feed lipid more than 10% to the animal [14].

2.6.2. Tannins

Tannins are naturally occurring plant polyphenols classified into two main groups: hydrolysable tannins and condensed tannins (CT). Their structural differences influence their interactions with rumen microorganisms and their effects on methane (CH_4) production. Tannins may reduce enteric methane emissions by directly inhibiting methanogenic archaea, interacting with proteins in their cell envelopes, disrupting associations between methanogens and protozoa, and reducing hydrogen transfer between microbial species [60]. Evidence from tropical livestock systems demonstrates the potential of tannin-rich plants to mitigate methane emissions. For example, condensed tannins in Leucaena leucocephala have been as-sociated with reduced methane emissions in dairy cattle [38], while Desmanthus species have shown potential to reduce methane emissions in grazing cattle [54].

The effectiveness of tannin supplementation, however, depends on the tannin source, dosage, and animal species. Supple-mentation with Acacia tannin extract at 2.5% of dry matter intake (DMI) reduced enteric methane emissions in sheep by ap-proximately 12%, with only a marginal reduction in fibre digestibility. In dairy cows, the same tannin source reduced me-thane emissions by 16% and 28% at the lower and higher supplementation levels, respectively, averaged over a five-week experiment. However, the higher dose initially caused a sharp decline in milk production of approximately 4 kg/day and signs of ill health, necessitating a reduction in the supplementation level [34]. These findings highlight the potential of tannins to mitigate methane emissions but also demonstrate the importance of determining appropriate inclusion levels to avoid adverse effects on animal health and productivity. In contrast, supplementation with quebracho tannin extract at up to 2% of dietary dry matter did not significantly reduce methane emissions in growing cattle [5].

2.6.3. Saponins

Saponins are high-molecular-weight glycosides composed of sugar molecules linked to non-sugar components, some of which possess steroid-like structures. They are widely distributed in plant parts, including leaves, roots, bark, tubers, seeds, and fruits, and produce stable, soap-like foam when dissolved in water [15]. Plant-derived saponins have been investigated as potential feed additives for reducing ruminal methane (CH_4) production, although their effectiveness varies considerably according to the plant source, extraction method, and dietary substrate. For instance, fenugreek and sesbania extracts prepared using water and different methanol concentrations reduced rumen protozoal populations by approximately 50% in vitro, but did not significantly decrease methane production under some experimental conditions. However, when these extracts were incorporated into hay, concentrate, or mixed substrates, methane production decreased by 5.1–11.9% [15]. Similarly, extracts of Sapindus mukorossi prepared using different solvents reduced methane production in vitro, with the ethanol extract achieving a reported reduction of up to 96% [1]. Saponins from Sapindus saponaria have also been reported to reduce methane production by up to 20% without decreasing methanogen populations [19].

The methane-mitigating effects of saponins are generally attributed to their antiprotozoal activity, because rumen protozoa often maintain symbiotic associations with methanogenic archaea and supply hydrogen that supports methane formation. By reducing protozoal populations, saponins may limit hydrogen availability for methanogenesis and consequently decrease methane production [17, 44]. In addition to their potential antimethanogenic effects, saponins may promote microbial protein synthesis, support fibre-degrading bacteria and fungi, and improve feed utilization, particularly when animals consume low-quality diets [60]. Other plant-derived feed additives, including tannins and essential oils, have

also been investigated for their potential to modify rumen fermentation and reduce methane emissions [28]. Essential oils may influence rumen microbial activity by inhibiting certain bacterial groups, including Gram-positive bacteria, although their effects depend on their chemical composition and supplementation level [14].

2.6.4. Ionophores

Ionophores have been used in livestock production for more than four decades to improve animal health and feed efficiency. More recently, their effects on rumen microbial communities and methane (CH_4) emissions have attracted considerable attention. The ionophores most commonly used in livestock production include monensin, salinomycin, lasalocid, and laidlomycin. Their mode of action involves disrupting ion gradients across the cell membranes of susceptible Gram-positive bacteria and protozoa, impairing cellular function and potentially leading to cell death. This selective antimicrobial activity favors Gram-negative bacteria in the rumen, thereby promoting propionate production and reducing hydrogen availability for methanogenesis [10].

Ionophores are commonly incorporated into high-concentrate diets to help control ruminal acidosis and can reduce total CH_4 production by approximately 5%. In high-fiber diets, monensin may inhibit cellulolytic bacteria, thereby altering rumen fermentation and contributing to reduced CH_4 emissions [36]. Similarly, ionophores can decrease the abundance of certain Gram-positive bacteria, including cocci, and suppress acetate production, which may indirectly reduce methanogenesis [4]. However, the effectiveness of ionophores in mitigating CH_4 emissions tends to decline over time, potentially because of microbial adaptation [7, 57]. Despite their benefits, the use of ionophores is restricted in some countries because of concerns about antimicrobial resistance, potential residues, and long-term microbial adaptation. These limitations highlight the need to investigate safe and effective alternatives that can maintain animal health and productivity while reducing enteric CH_4 emissions [53].

2.6.5. Nitrate

Nitrate has a higher affinity for hydrogen than CO_2, allowing it to reduce methane (CH_4) emissions through two primary mechanisms: directly competing with methanogens for hydrogen and indirectly inhibiting methanogenesis through its intermediate metabolite, nitrite [53]. [6] reported that dietary nitrate supplementation reduced CH_4 production by 10%–22% without significantly affecting neutral detergent fiber (NDF) digestion. Furthermore, long-term nitrate supplementation over several months consistently reduced CH_4 emissions by approximately 12% in beef cattle and 16% in dairy cows [29].

Despite its potential to mitigate CH_4 emissions, nitrate supplementation may reduce feed intake and raise safety concerns. Studies have shown that dietary nitrate supplementation at 15 $g \cdot kg^{-1}$ dry matter (DM) decreased dry matter intake (DMI) by approximately 8%, potentially because of its bitter taste and reduced palatability [37, 49]. Consequently, the observed reduction in CH_4 production may partly result from lower feed intake rather than solely from the inhibitory effects of nitrate on methanogenesis. However, [43] demonstrated that nitrate-induced CH_4 mitigation was independent of changes in DMI. They also reported that nitrate supplementation reduced the relative abundance of methanogens and promoted propionate production through ruminal fermentation, suggesting that nitrate can sup-press methanogenesis through microbial and metabolic pathways.

Nevertheless, nitrate supplementation presents potential health risks because its metabolite, nitrite, can impair the oxygen-carrying capacity of hemoglobin and may contribute to carcinogenic effects under certain conditions. These concerns have led to restrictions on nitrate supplementation in some countries [53]. To improve the effectiveness and safety of nitrate-based CH_4 mitigation, combining nitrate with dietary lipids or other mitigation strategies may help reduce nitrite accumulation while enhancing methane reduction.

2.7. Manure Management Strategies for Greenhouse Gas Mitigation

Effective manure management is an important strategy for reducing greenhouse gas (GHG) emissions from livestock pro-duction. Methane (CH_4) emissions can be minimized through appropriate manure storage and handling, anaerobic digestion, composting, and dietary manipulation to improve manure characteristics [55]. Among these approaches, anaerobic digestion is particularly promising because it captures methane generated during the decomposition of organic matter and converts it into biogas for energy production. When properly managed, anaerobic digesters can reduce methane emissions from manure by approximately 60–80%, while providing renewable energy that can substitute for fossil fuels [56]. This approach offers environmental and economic benefits by limiting methane release, improving waste management, and potentially reducing farm energy costs. However, the overall climate benefit depends on methane capture efficiency, energy substitution, and emissions associated with digestate storage and application [9].

The potential benefits of anaerobic digestion are illustrated by a study of dairy farms in northern Spain, where methane emissions associated with slurry management, including storage and fertilizer application, ranged from 34 to 66 kg CH_4 per dairy cow annually and from 13 to 25 kg CH_4 per suckler calf annually [33]. Across the farms examined, total emissions ranged from 22,223 to 107,949 kg CO_2-equivalent per year. The assessment reported potential annual savings of 978–1,776 kg CO_2-equivalent per farm through anaerobic digestion, primarily by preventing methane emissions during slurry management [55]. These findings highlight the importance of selecting manure management practices suited to farm size, available resources, and local conditions to reduce the environmental impact of livestock production.

3. Conclusion and Recommendation

3.1. Conclusion

Greenhouse gas emissions from ruminant livestock production are primarily associated with enteric fermentation and manure management, with methane representing a major environmental concern and a source of dietary energy loss. This review indicates that feeding strategies can contribute to reducing methane emissions while improving feed utilization and animal productivity. Improving forage quality and digestibility, optimizing feed intake, adjusting forage-to-concentrate ratios, and supplementing diets with lipids, Ionophores, Nitrates, tannins, and saponins are promising mitigation approaches. However, their effectiveness varies with feed composition, animal species, supplementation levels, and production conditions. Excessive use of concentrates or plant-derived additives may adversely affect rumen function, fibre digestion, animal health, or productivity if not properly managed. Furthermore, integrating improved feeding practices with effective manure management, including anaerobic digestion, can strengthen overall emission reduction efforts. Therefore, combining locally appropriate feeding strategies with improved livestock management offers a practical pathway toward more productive, environmentally sustainable, and climate-resilient ruminant production systems in the tropics.

3.2. Recommendation

1) Farmers should prioritize the production and use of high-quality, digestible forages, including suitable tropical grasses and legumes, to improve feed utilization and reduce methane emissions per unit of animal product.
2) Feeding programs should be optimized by balancing forage-to-concentrate ratios and maintaining adequate nutrient intake without compromising rumen health, animal welfare, or productivity.
3) Further research should evaluate locally available lipid sources and tannin- and saponin-rich plants to establish effective supplementation levels, methane reduction potential, and possible effects on animal performance.
4) Researchers should conduct more long-term studies under tropical production conditions to compare feeding systems and quantify methane emissions from cattle, sheep, goats, and buffaloes.
5) Livestock producers should adopt appropriate manure storage and handling practices and consider anaerobic digestion where technically and economically feasible to capture methane and generate renewable energy.
6) Agricultural extension services and policymakers should promote farmer training, access to improved feed resources, and affordable emission-monitoring technologies to support the adoption of effective and locally adapted GHG mitigation strategies.

Abbreviations

CH_4	Methane
CO_2	Carbon Dioxide
CT	Condensed Tannins
DM	Dry Matter
DMI	Dry Matter Intake
FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse Gas
GEI	Gross Energy Intake
GDP	Gross Domestic Product
H_2	Hydrogen
N	Nitrogen
N_2O	Nitrous Oxide
NDF	Neutral Detergent Fiber
NO	Nitric Oxide
OM	Organic Matter
TMR	Total Mixed Ration
UV	Ultraviolet
VFA	Volatile Fatty Acids

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Conflicts of Interest

The author declares no conflict of interest.

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