IMPLEMENTING NUTRITIONAL STRATEGIES TO REDUCE METHANOGENESIS IN LIVESTOCK

Abstract

This chapter delves into the realm of nutritional strategies aimed at mitigating methanogenesis, the production of methane gas, in livestock production systems. Methane, a potent greenhouse gas, emerges primarily from ruminant digestion processes and significantly contributes to global warming. The chapter explores a range of innovative approaches to address this concern, focusing on enhanced feed quality, strategic supplementation, methane inhibitors, fermentation modulation, and dietary adjustments. The chapter commences by highlighting the pivotal role of livestock in anthropogenic greenhouse gas emissions, particularly methane. It underscores the intricate interplay of factors such as land use change, feed production, animal husbandry practices, manure management, and processing in shaping livestock-related emissions. The chapter then delves into the specifics of nutritional strategies, offering a comprehensive overview of each approach's mechanisms and potential benefits. Challenges, considerations, and the importance of maintaining animal welfare and performance throughout these strategies are critically addressed. The significance of individual animal variability, the broader sustainability implications of these strategies, and their potential to reduce methane emissions in livestock production are explored. By examining the interplay of science, environmental concerns, and livestock productivity, the chapter provides a holistic perspective on the journey toward sustainable livestock practices. Ultimately, the chapter underscores the critical importance of mitigating methanogenesis in livestock systems, both for ecological conservation and improved livestock efficiency.

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I. INTRODUCTION

Methane is a potent greenhouse gas, and livestock, particularly ruminant animals like cattle, sheep, and goats, are substantial contributors to its emission. These animals possess unique digestive systems that foster the growth of methanogenic archaea, resulting in methane production during the breakdown of ingested feed. Addressing this issue is not only vital for curbing climate change but also for optimizing energy utilization within livestock systems. Methanogenesis, the production of methane through microbial activity in the digestive systems of livestock, poses significant challenges in terms of environmental sustainability, feed efficiency, and greenhouse gas emissions. This chapter delves into the various nutritional strategies that can be employed to effectively reduce methanogenesis in livestock, thereby contributing to both ecological conservation and enhanced livestock productivity.

The staggering reality of our planet's environmental challenges comes to the forefront when considering that livestock operations contribute a significant 14.5% to the total annual anthropogenic greenhouse gas (GHG) emissions on a global scale, as highlighted by Gerber et al.'s 2013 study. Livestock, through their multifaceted activities, wield a substantial influence on our climate. This impact extends across several domains, including alterations in land usage, the production of animal feed, the processes of animal husbandry, the management of manure, and the stages of processing and transportation. These activities, in turn, have ramifications for the emission of greenhouse gases, namely carbon dioxide (CO2), nitrous oxide (N2O), and methane (CH4), ultimately contributing to climate change. Particularly noteworthy is the role of animal production in elevating CH4 emissions, emphasizing the intricate linkages between livestock and the global climate system.

II. LIVESTOCK'S ROLE IN GREENHOUSE GAS EMISSIONS

The intricate interplay between livestock and greenhouse gas (GHG) emissions is a crucial facet of the global climate challenge. The principal contributors to livestock-related GHG emissions encompass carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O). These emissions hold substantial implications for anthropogenic climate change. Notably, CH4 takes the lead, accounting for the largest portion at 44%, trailed by N2O at 29%, and CO2 at 27%, as underscored by Gerber et al.'s research in 2013.

1. **Distribution of Livestock-Related GHG Emissions:** On a global scale, the cumulative GHG emissions originating from livestock are distributed as follows: livestock contribute to 44% of anthropogenic CH4 emissions, 53% of anthropogenic N2O emissions, and 5% of anthropogenic CO2 emissions. Of particular note is the preeminent role of cattle, responsible for the sector's emissions, contributing a substantial 5.0 gigatonnes of CO2-equivalent emissions. This figure represents a staggering 62% of the sector's total emissions. Intriguingly, both beef and dairy cattle wield comparable emissions profiles. In contrast, other livestock categories like pigs, poultry, buffaloes, and small ruminants register significantly lower emissions, collectively constituting 7% to 11% of the sector's emissions.

2. **Insight into Indian Livestock Emissions:** India's livestock landscape also plays a significant role in global GHG emissions. According to the Department of Animal Husbandry, Dairying, and Fisheries, Ministry of Agriculture, Government of India (2012), enteric CH4 emissions from Indian livestock tally up to 13.27 teragrams (Tg) annually. This statistic implicates cattle and buffalo as the prime contributors, accounting for 6.73 Tg and 6.56 Tg per year, respectively. This combined contribution translates to a substantial 91% of the nation's total emissions from this source. Emission figures further underscore the potency of cattle emissions, with a single cow emitting approximately 220 pounds of methane annually. Although CH4's atmospheric lifespan is shorter compared to CO2, its warming impact is an astonishing 28 times greater.

2. **Deciphering GHG Emission Components:** GHG emissions stemming from livestock rearing can be compartmentalized into two key constituents: enteric fermentation and excreta. Enteric fermentation, a predominant contributor, constitutes nearly 90% of the total CH4 emissions from ruminants. The remainder emerges from hindgut fermentation.

3. **Emerging Insights from Research:** Recent strides in research have yielded noteworthy insights. ICAR-NIANP (Bhatta et al., 2017) has meticulously developed a state-wise enteric methane emission inventory, revealing an emission estimate of 9.252 Tg of methane per year from Indian livestock. Remarkably, this figure stands lower than estimations provided by various other agencies.

4. **Visualizing GHG Emissions from Livestock:** This complex interplay of emissions is visually represented in Figure 1, as demonstrated by Bhatta et al.'s research in 2017. This graphical depiction serves as a potent tool in comprehending the magnitude and distribution of GHG emissions arising from livestock activities.

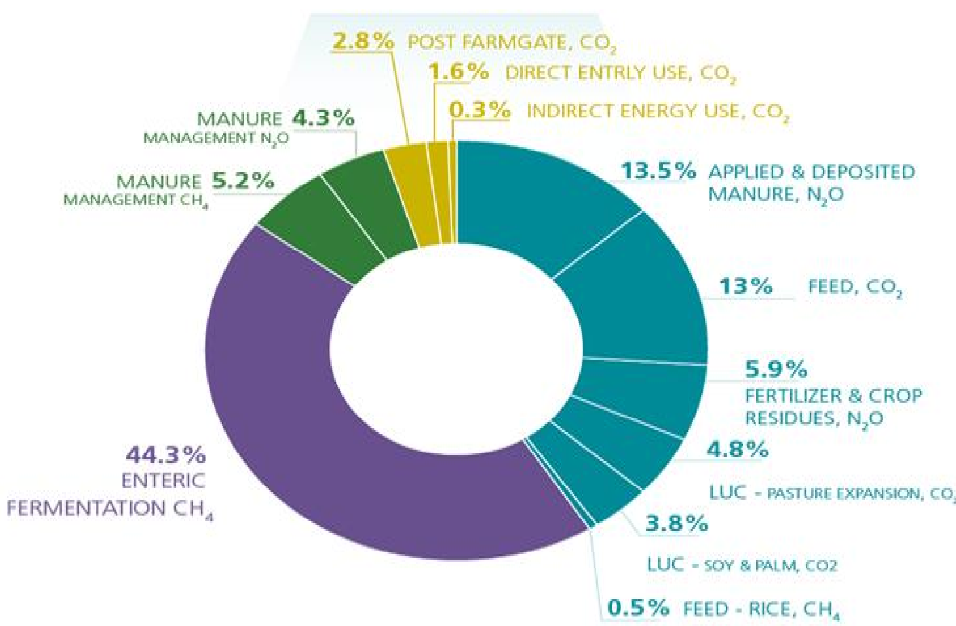

Figure 1: GHG Emission from Livestock

In conclusion, the relationship between livestock activities and GHG emissions emerges as a pivotal arena in the fight against climate change. The nuanced understanding of emissions' sources, distribution, and impacts forms a bedrock for devising targeted mitigation strategies that reconcile the necessity of livestock with the urgency of environmental conservation.

III. NUTRITIONAL STRATEGIES TO REDUCE METHANOGENESIS

1. **Feeding Management:** Effective methane reduction in ruminants hinges on holistic feeding management. This approach considers the complex interplay between rumen microbiota, animal physiology, and diet composition. Fresh grass, for instance, has been found to yield lower methane emissions than dry forage. Often, primarily forage diets are complemented with sugar-based concentrates. These concentrates offer readily available energy sources for rumen microbes and enhance diet digestibility.

   Furthermore, the maturity of forage influences methane production, with legume forages generally emitting less methane than grass forages. Utilizing grass-legume mixtures not only benefits animal nutrition but also has agronomic advantages such as increased biomass yield and reduced fertilizer use. Forage quality, particularly water-soluble carbohydrate content, plays a substantial role in reducing methane emissions. Clovers and grasses with high water-soluble carbohydrates have shown promise in methane reduction.

   When animals are fed concentrate-based diets, there's a notable decrease in methane production, especially when sugars and starches are part of the diet. High-grain diets can be particularly effective, with maize showing greater reductions compared to barley. For example, feeding maize distillers' dried grains to growing beef cattle resulted in nearly 24% less methane compared to a diet containing barley grain.

   Balancing rations with locally available feed resources is an effective way to reduce methane emissions without compromising animal production or health. Initiatives like the National Dairy Development Board's ration balancing program cater to small dairy farmers, ensuring optimized nutrition for livestock.

   Substituting structural carbohydrates (cellulose, hemicellulose) with non-structural carbohydrates (starch and sugars) found in energy-rich concentrates can reduce methane production. This shift alters rumen conditions and microbial populations, lowering the proportion of hydrogen sources while increasing hydrogen sinks.

2. **Mineral Supplementation:** Cattle's primary osmotic regulator, potassium (K^+), becomes crucial during heat stress. Dietary levels of sodium (Na^+) and magnesium (Mg^+) should also be increased to compete with K^+ for intestinal absorption. Zinc and chromium supplementation can improve heat tolerance and metabolic processes, particularly in glucose utilization during heat stress.

3. **Antioxidant Supplementation:** Feeding antioxidants like vitamins A and E, selenium, and zinc can alleviate the negative impacts of heat stress. These supplements reduce oxidative stress, enhancing reproductive efficiency and overall well-being during heat

stress episodes. Vitamin C, along with electrolyte supplementation, has also demonstrated heat stress mitigation benefits in livestock.

4. **Defaunation:** Complete removal of protozoa from the rumen, known as defaunation, can reduce methane emissions by 20-30%. This process alters rumen ecology by increasing total bacterial numbers while reducing methanogen populations. This effect is due to the loss of colonization sites within protozoa that methanogens depend on. Research by Nguyen et al. (2016) exemplifies the impact of defaunation on rumen microbial populations and methane reduction in cattle.

Table 1. The pH, ammonia concentration and concentration and molar proportions of major volatile fatty acids (VFA) in rumen fluid, and changes in gas and methane production *in-vitro* after refaunation

Item[1]	Treatment								SEM	p-values		
	Defaunated				Refaunated					Trt	Time	Trt×time
	Day 0	Day 7	Day 14	Day 21	Day 0	Day 7	Day 14	Day 21				
pH	6.41	6.46	6.87	6.83	6.62	6.69	6.86	6.91	0.10	0.02	<0.001	0.34
Ammonia (mg/L)	32.68	30.76	59.04	62.92	36.88	69.52	86.24	117.00	9.56	<0.01	<0.001	0.08
Total VFA(mM/L)	64.43	59.67	50.92	57.95	59.46	63.43	63.03	58.16	8.05	0.63	0.18	0.39
VFA molar proportion (%)												
Acetate (%)	71.06	74.55	75.32	79.01	73.67	73.49	73.39	76.74	1.76	0.59	0.04	0.51
Propionate (%)	19.15	16.61	15.05	14.46	17.75	15.66	14.52	12.30	1.40	0.12	0.02	0.95
Butyrate (%)	8.38	7.05	6.54	6.39	6.77	8.03	8.44	7.39	0.65	0.37	0.60	0.03
Acetate/propionate	4.07	4.65	5.08	5.57	4.58	4.77	5.07	6.29	0.51	0.26	0.44	0.90
Total gas[2] (mL/g DM)	102.33	128.67	144.07	157.00	103.67	135.67	152.00	149.33	4.71	0.55	<0.001	0.34
CH_4 (mL/g DM)	6.44	13.60	16.86	20.66	6.99	16.76	21.68	21.47	1.29	0.07	<0.001	0.19

SEM, standard error of the mean; Trt, treatment (defaunated and refaunated); DM, dry matter.
[1] pH, ammonia and VFA analyses on samples collected from animals on d 0, 7, 14, and 21.
[2] Gas and methane production data collected from *in-vitro* incubations.

IV. MITIGATION THROUGH CHEMICAL INHIBITORS

1. **Mitigation Using Nitrates and Sulphates:** Nitrates can serve as terminal electron acceptors, functioning as alternative hydrogen sinks in the rumen. They can be converted to ammonia, serving as a nitrogen source in the rumen. Similarly, sulphates are reduced to sulphides. In the large intestine of humans and pigs, sulphate-reducing bacteria (SRB) outcompete methanogenic bacteria (MB), leading to reduced methane production. Stoichiometric calculations indicate that reducing methane emissions in sheep by 50% would necessitate daily ingestion of 0.75 moles of sulphate or nitrate. When both nitrate and sulphate are added to the diet, their effects on methane production are additive.

   In an experiment by Van Zijderveldet et al. (2010) involving crossbred texel lambs, nitrate and sulphate supplementation resulted in decreased methane production. Nitrate supplementation reduced methane by 32%, sulphate by 16%, and a combination of nitrate and sulphate by 47% relative to the control group.

2. **Mitigation Using Organic Acids:** Fumaric and malic acids, precursors of propionate, serve as alternative hydrogen sinks in the rumen. Their inclusion in diets shifts rumen fermentation toward propionate production, reducing methane emissions. Sodium fumarate supplementation consistently decreased methane production in vitro by 2.3-41%.

3. **Mitigation Using Ionophores:** Monensin, an ionophore antibiotic, is extensively studied in ruminants for its methane-reduction potential. It targets hydrogen and formate-producing bacteria, reducing the availability of hydrogen for methanogenic bacteria. Monensin attaches to the cell membranes of ruminal bacteria and protozoa, altering rumen fermentation towards less acetate and more propionate production. In vitro, monensin can decrease methane production by up to 76%, while in vivo studies report an average reduction of 18%. A meta-analysis of controlled studies revealed that monensin reduced methane emissions by 19 ± 4 g/animal/day in beef steers and 6 ± 3 g/animal/day in dairy cows.

4. **Mitigation Using Dietary Lipids:** Dietary oils, both of plant and animal origin, are considered effective in reducing rumen methanogenesis. Adding dietary oils can result in methane reduction between 10% to 25%. The mechanisms behind this reduction include a decrease in fibre digestion, lower dry matter intake (if dietary fat exceeds 6-7%), direct inhibition of microbes including methanogens, and the suppression of rumen protozoa.

   Various oils, such as soya, coconut, canola, linseed, and rapeseed, have been shown to reduce methane production by 18% to 62% in sheep, beef cattle, and dairy cows. Additionally, essential oils derived from garlic, thyme, oregano, cinnamon, rhubarb, and others have demonstrated dose-dependent reductions in methane production in vitro. However, at high doses, these reductions were accompanied by adverse effects on fermentation, including reduced volatile fatty acid production and feed digestibility.

Table 3. Dry matter intake, gaseous exchange, and heat production of growing male lambs fed nitrate and sulfate sources[1]

Item	$-NO_3$		$+NO_3$		Pooled SEM	*P*-value of effects		
	$-SO_4$	$+SO_4$	$-SO_4$	$+SO_4$		NO_3	SO_4	$NO_3 \times SO_4$
DMI (g/d)	999	982	985	990	12.3	0.791	0.647	0.372
CH_4 (L/d)	25.5	21.6	17.3	13.6	1.54	<0.001	0.033	0.941
CH_4 (L/kg of $BW^{0.75}$ per day)	1.48	1.30	1.01	0.80	0.10	<0.001	0.082	0.899
CH_4 (L/kg of DMI)	25.5	22.0	17.6	13.9	1.54	<0.001	0.041	0.910
CO_2 (L/kg of $BW^{0.75}$ per day)	25.9	26.4	24.3	25.5	0.40	0.011	0.050	0.391
O_2 (L/kg of $BW^{0.75}$ per day)	26.2	27.0	24.3	25.7	0.50	0.008	0.057	0.568
Heat (kJ/kg of $BW^{0.75}$ per day)	550	566	513	542	9.95	0.010	0.048	0.522

[1] NO_3 = nitrate added to the diet (26 g of nitrate/kg); SO_4 = sulfate added to the diet (26 g of sulfate/kg); + or − indicate whether the component was added or not to the respective treatment.

Propionate Enhancers: In the rumen, hydrogen, a product of the fermentation process, can lead to the production of either methane or propionate. Increasing the availability of propionate precursors, such as pyruvate, oxaloacetate, malate, fumarate, citrate, succinate, and others, can divert more hydrogen toward propionate production, thereby reducing methane production (O'Mara, 2004).

These propionate precursors can be introduced into the diet of livestock as feed additives, particularly for animals receiving concentrate-based diets. Additionally, some propionate precursors, like malate, occur naturally in grasses. Research is ongoing to identify cost-effective natural sources of these precursors, such as alfalfa and engineered feedstocks with high concentrations of propionate precursors. Since these precursors are naturally present in the rumen, they are likely to be more readily accepted by livestock than antibiotic or chemical additives. This approach holds promise as a sustainable and biologically aligned method to reduce methane emissions from livestock while promoting efficient energy utilization in the rumen.

V. MANIPULATION OF RUMEN MICROBIAL ECOSYSTEM

1. **Yeast Culture:** Yeast cultures play a multifaceted role in reducing methane production. They achieve this by

    - **Reducing Protozoa Numbers:** Yeast cultures have been found to decrease the population of protozoa in the rumen.
    - **Increasing Butyrate or Propionate Production:** They can stimulate the production of butyrate or propionate, which are alternate hydrogen sinks, leading to reduced methane formation.
    - **Stimulating Acetogens:** Yeast cultures can stimulate acetogens, which compete with methanogens for hydrogen or co-metabolize hydrogen, further decreasing methane production (Chaucheyras et al., 2008).

2. **Methane Oxidisers:** Methane-oxidising bacteria, known as methanotrophs, can be introduced as direct-fed microbial preparations. These bacteria oxidize methane, competing with its production. Since methane production is a strictly anaerobic process, methanotrophs, being aerobic, disrupt this process. They are a unique group of bacteria that utilize methane as their sole carbon and energy source (Sejian et al., 2015).

3. **Use of Bacteriocins:** Bacteriocins are antimicrobial proteins produced by various bacteria. They play a role in microbial competition within the rumen. Some bacteriocins can directly inhibit methanogens and redirect hydrogen to other reductive bacteria like propionate producers or acetogens. The most well-known bacteriocin, nisin, has been shown to reduce methane production in vitro. Combining nisin with nitrate, an alternative electron receptor, has also been reported to reduce methane emissions in sheep (Sar et al., 2005). Bovicin HC5, a bacteriocin from Streptococcus bovis HC5, reduced methane production by 50% in vitro (Lee et al., 2002). Other bacteriocins like PRA-1 from Lactobacillus plantarum TUA1490L have shown highly specific antibacterial activity against methanogens.

4. **Fungal Metabolites:** Secondary fungal metabolites from Monascus spp. have demonstrated the ability to reduce enteric methane emissions in sheep by 30%. This reduction is accompanied by shifts in volatile fatty acid pathways, a decrease in methanogen numbers, and a specific toxic effect on methanogens (Morgavi et al., 2013).

5. **Secondary Plant Metabolites – Tannin and Saponins:** Tannins, particularly hydrolysable tannins, can directly inhibit rumen methanogens. In contrast, condensed tannins affect methane production by inhibiting fibre digestion. Saponins indirectly reduce methane emissions by reducing protozoa, which are associated with methanogens. Research has explored the supplementation of saponins, either directly or through plant sources, to reduce enteric methane emissions (Sirohi et al., 2014).

   For instance, soapnut (Sapindus mukorossi), known for its high saponin content, has been shown to significantly reduce methane production in vitro (Malik et al., 2009). Recent studies have investigated the combined supplementation of tamarind seed husk (tannins) and soapnut fruit pulp (saponins), revealing a synergistic reduction in enteric methane emissions by 20% when formulated at a 60:40 ratio and supplemented at 5.1% of the diet (Poornachandra et al., 2019). This combination approach holds promise for more effective methane mitigation in livestock.

VI. CHALLENGES AND CONSIDERATIONS IN IMPLEMENTING METHANE-REDUCTION STRATEGIES

Efforts to curtail methanogenesis in livestock systems present a complex interplay of challenges and considerations that demand meticulous attention. The successful implementation of methane-reduction strategies hinges upon a delicate balance between environmental objectives and livestock welfare. This section delves into the multifaceted challenges that need to be navigated and the vital considerations that guide these strategies.

1. **Animal Health and Performance:** The welfare and productivity of livestock remain at the forefront of any intervention. The introduction of nutritional strategies should be carried out with a keen eye on their potential impact on animal health and performance. This encompasses monitoring digestive processes, nutrient utilization, and overall well-being. Any compromise on these aspects could negate the benefits of methane reduction, highlighting the necessity of a comprehensive approach that safeguards the animals' physiological equilibrium.

2. **Sustainability Assessment:** While the primary objective of methane-reduction strategies is mitigating its impact on climate change, the broader environmental consequences demand scrutiny. The intricate relationship between methane, other greenhouse gases, and resource utilization warrants a holistic sustainability assessment. This entails evaluating potential trade-offs and unintended outcomes that might arise from these strategies. The path toward sustainability necessitates not only reduced methane emissions but also a net-positive impact on the environment.

3. **Embracing Individual Variation:** The intricacies of livestock physiology introduce another layer of complexity: individual variation. Animals within the same species respond differently to various nutritional interventions. Genetics, age, and dietary preferences underscore this variability, impacting the efficacy of methane-reduction strategies. Tailoring these approaches to suit the unique needs of each animal and accounting for their diverse responses is a dynamic challenge that demands a nuanced, personalized approach.

VII. CONCLUSION

The intricate nexus between livestock activities and greenhouse gas (GHG) emissions underscores the pressing need for comprehensive strategies that balance the demands of food production with environmental sustainability. The statistics and insights presented in this discourse emphasize the pivotal role of livestock in the global emissions landscape and underscore the urgency of implementing mitigation measures. Livestock's contribution of 14.5% to annual anthropogenic GHG emissions serves as a stark reminder of the industry's profound impact on climate change. The emissions trio - carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) - emerges as the key players in this ecological drama. Methane, with its substantial 44% share, leads the pack, followed by N2O at 29% and CO2 at 27%. This distribution highlights the unique and varied mechanisms through which livestock influence climate dynamics.

Globally, livestock's share in the emissions pie is even more telling. Anthropogenic CH4 emissions are significantly influenced, with livestock contributing to 44% of the total. Similarly, 53% of anthropogenic N2O emissions and 5% of anthropogenic CO2 emissions can be attributed to livestock activities. Cattle, the focal point of the sector, bear the brunt of responsibility, accounting for a remarkable 62% of emissions. Beef and dairy cattle share comparable emission levels, while other livestock categories contribute 7% to 11% of emissions. In India, the situation is equally significant, with cattle and buffalo assuming the leading roles in enteric methane emissions. The alarmingly potent warming impact of methane, despite its shorter atmospheric lifespan, reinforces the criticality of addressing livestock emissions.

However, these challenges do not stand without potential solutions. Research breakthroughs have yielded insights into mitigation strategies. Strategies range from improving feed quality and production to innovative additives, inhibitors, and fermentation modulation techniques. In the grand tapestry of climate change, livestock's role as both a contributor and a potential solution presents an opportunity for transformative change. As we seek to nourish a growing global population while safeguarding our planet, the dialogue between science, policy, and practice becomes paramount. The integration of sustainable practices, technological innovation, and informed policies will pave the way toward a future where livestock can coexist harmoniously with a climate-resilient world.

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