



Nutrition Management for Methane Mitigation: A Circular Bioeconomy Approach to Sustainable Ruminant Production

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Methane emissions from ruminant livestock represent a critical environmental challenge, accounting for approximately 14.5% of global anthropogenic greenhouse gas emissions. Despite this burden, ruminants provide essential nutrient-dense foods and support hundreds of millions of rural livelihoods. This integrated review examines evidence-based nutritional strategies for methane mitigation within a circular bioeconomy framework. By combining precision nutrition, anti-methanogenic feed additives, agricultural byproduct valorization, and systems modeling, ruminant production systems can simultaneously reduce emissions by 20-40%, improve productivity, and enhance resource efficiency. Success requires context-specific implementation, supportive policy frameworks, and equitable financing mechanisms, particularly in low- and middle-income countries, where over 80% of livestock emissions originate.

Keywords: circular bioeconomy, enteric fermentation, feed additives, methane mitigation, nutrition management, ruminant livestock

Introduction

Ruminant livestock occupy a paradoxical position in global food systems: they are vital for food security and rural livelihoods, yet major contributors to climate change. Enteric fermentation is the anaerobic digestive process in ruminant stomachs that generates methane as a metabolic byproduct, with 2-12% of gross energy consumed lost through this inefficiency (Kebreab *et al.*, 2026). Globally, grasslands occupy nearly 70% of agricultural land, much of which is unsuitable for crop production due to soil, climate, or topographic constraints. This reality positions ruminants uniquely within a circular bioeconomy, where they convert fibrous, non-arable biomass into nutrient-dense foods while avoiding direct competition with human food crops. However, current production trajectories are unsustainable. Without intervention, livestock-related methane emissions will increase by approximately 12% by 2050 due to growing global demand for animal products (Kebreab *et al.*, 2026). With methane's global warming potential 25-28 times greater than carbon dioxide over 100 years, even modest reductions carry significant climate mitigation value. The solution lies not in eliminating ruminant agriculture but in strategically redesigning it through nutrition management, feed additives, circular resource utilization, and systems-level optimization.

Precision Nutrition as a Sustainability Lever

Precision nutrition represents the operational interface between diet formulation and environmental performance. Rather than generic feeding strategies, precision ration design advances sustainability through three mechanisms:

1. Prioritizing low-opportunity-cost feeds, byproducts, and crop residues that do not compete with human diets.

2. Reducing reliance on human-edible feed resources and improving the net food contribution of livestock;
3. maximizing system-level feed efficiency, since over 70-80% of enteric methane emissions scale directly with dry matter intake (Beauchemin *et al.*, 2022; Kebreab *et al.*, 2026).

Dietary Energy and Composition

Increasing dietary energy density through concentrate supplementation reduces methane by 15-30% relative to forage-based diets. High-quality concentrates are digested more rapidly, providing less substrate for methane-producing microorganisms. However, producers must balance benefits against potential rumen health risks and economic considerations (Beauchemin *et al.*, 2008).

Protein Optimization

Feeding dietary protein levels precisely aligned with animal requirements rather than in excess reduces methane by 10-20% by decreasing rumen ammonia concentrations and shifting fermentation patterns away from methanogenesis. Enhancing protein quality by increasing bypass protein while reducing rumen-degradable protein offers additional emissions reductions without productivity losses (Kebreab *et al.*, 2026).

Lipid Supplementation

Dietary fats suppress methane through multiple mechanisms, either directly inhibiting methanogenic archaea or reducing fiber digestibility in ways favoring propionate over acetate production, and decreasing overall rumen methane-producing organisms. Practical sources, including canola, palm, and coconut oils, along with oilseeds, reduce methane by 15-25% when incorporated at 4-8% of dry matter (Benchaar & Greathead, 2011).

Anti-Methanogenic Feed Additives and Emerging Technologies

Recent advances offer powerful tools for targeted methane suppression across diverse production systems.

Direct Methanogenesis Inhibitors

3-Nitrooxypropanol (3-NOP), dosed at 60-180 mg/kg dry matter, inhibits methyl-coenzyme M reductase, the critical enzyme in methanogenesis. Meta-analyses confirm consistent reductions across cattle types, with 3-NOP now commercially deployed in over 70 countries, reducing methane by 25-35% depending on diet and dose (Kebreab *et al.*, 2023). Asparagopsis seaweed (0.25-1% of dry matter) provides bromoform compounds suppressing methane by 40-80%, with meta-analyses reporting average reductions of 39-47% depending on bromoform dose (Kebreab *et al.*, 2025). However, high inclusion levels may depress intake and yield, and concerns persist regarding cultivation scalability, necessitating further long-term research before widespread adoption (Kebreab *et al.*, 2026).

Rumen Modifiers

Tannins and plant secondary compounds suppress methane by 10-25% through direct anti-methanogenic activity and protozoal reduction, though effectiveness depends on botanical source and concentration. Saponins found in certain legumes reduce methane by 10-20% through similar mechanisms with favorable cost-effectiveness profiles.

Circular Bioeconomy Integration

Beyond feed additives, transforming ruminant systems into circular platforms maximizes environmental and economic gains. Ruminants uniquely upcycle low-opportunity-cost feeds inedible to humans. Incorporating almond hulls, grape pomace, citrus pulp, and oilseed meals diverts waste streams from landfills while reducing reliance on primary crops. California life cycle assessments demonstrate that replacing conventional ingredients with almond hulls substantially reduces dairy carbon footprints while maintaining productivity (Naranjo *et al.*, 2020). Livestock manure contains nitrogen, phosphorus, and potassium recyclable into crop

systems, reducing synthetic fertilizer dependence. Anaerobic digestion simultaneously captures biogas energy while processing solid fractions into bio-based fertilizers or soil amendments (Kebreab *et al.*, 2026).

Life Cycle Assessment and Systems Modeling

Life cycle assessment (LCA), standardized internationally, captures cradle-to-farm complexity, including on-farm activities and upstream feed production. Mechanistic models explicitly represent biological processes governing feed digestion and methane production, accounting for dietary composition, microbial activity, and animal variability. Integration of mechanistic models with LCA translates animal-level predictions into farm- and sector-level climate impacts, providing precise emissions factors superior to generic methodologies (Dijkstra *et al.*, 2025). Despite advances, methodological challenges persist, particularly regarding the allocation of co-product impacts and treatment of soil carbon sequestration, which require urgent attention to support circular bioeconomy goals (Kebreab *et al.*, 2026).

Co-Benefits and Trade-Offs

Improved feed formulations and circular resource use generally enhance productivity, lowering greenhouse gas intensity. Critically, interventions preventing human-edible protein diversion to livestock substantially improve food system efficiency, redirecting 1.5 kg human-edible protein from dairy to human consumption would save 12.6 kg CO₂, 1.15 kg CH₄, and 0.02 kg N₂O emissions (Wang *et al.*, 2025). This emphasizes prioritizing low-opportunity-cost feeds and byproducts to achieve genuine circular sustainability. Circular strategies generate new revenue streams through biogas sales, carbon credits, and bio-based fertilizers, while reducing feed costs through byproduct substitution. However, adoption barriers in low- and middle-income countries include inconsistent supply chains, limited transport infrastructure, and restricted credit access (Balehegn *et al.*, 2020). Efficiency gains, lowering emissions per unit, may paradoxically increase total emissions if cheaper outputs stimulate herd expansion. Systems-level management addressing herd dynamics, reproductive efficiency, health status, and replacement rates is therefore critical (Beauchemin *et al.*, 2022).

Policy and Implementation Pathways

Achieving large-scale circular livestock transitions requires enabling frameworks beyond farm-level innovation. International initiatives, including the UN Sustainable Development Goals and the Global Methane Pledge, provide entry points for integrating livestock circularity. National policies such as the EU's Circular Economy Action Plan and the US Inflation Reduction Act demonstrate how targeted incentives unlock investment in manure-to-energy systems. Carbon markets, renewable energy credits, and ecosystem service payments create viable revenue streams. Yet current schemes often favor large, capital-intensive operations, raising equity concerns. Cooperative models for byproduct aggregation, shared infrastructure, and tailored credit mechanisms for smallholders are essential to prevent benefit concentration and ensure inclusivity. Investment in nutritionist training, farmer education, and digital measurement systems is particularly critical in low- and middle-income countries where livestock infrastructure and data access remain limited (Kebreab *et al.*, 2026).

Conclusion

Nutrition management for methane mitigation transcends simple feed additive deployment. Within a circular bioeconomy framework integrating precision nutrition, anti-methanogenic interventions, agricultural byproduct valorization, nutrient recycling, and systems modeling, ruminant production can reduce emissions intensity by 20-40% while improving productivity and resource efficiency. Success requires context-sensitive, systems-aware approaches, avoiding unintended consequences. Multi-strategy integration tailored to specific production contexts, coupled with life cycle assessment and mechanistic modeling, enables quantified environmental benefits. Achieving widespread adoption demands enabling policies, equitable

financing, supportive institutions, and capacity-building investments extending to both large and small producers. By repositioning ruminants not merely as emitters but as biological upcyclers embedded in nutrient, carbon, and energy cycles, livestock systems can evolve into drivers of climate mitigation, resource efficiency, and resilient food systems.

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