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Bibliometric Analysis of Inhibitory Compounds in the Reduction of Enteric Methane in Ruminants: Trends, Advances and Sustainable Perspectives

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Abstract: Enteric fermentation is a major agricultural source of methane (CH_4), accounting for about 32% of anthropogenic emissions and contributing significantly to global warming. Research increasingly investigates natural and synthetic inhibitory compounds in ruminant diets to reduce emissions without compromising digestion or productivity. This work presents a bibliometric analysis of studies published between 2005 and 2025, using the *Web of Science* (WoS) database and 20 keywords in four thematic categories combined with Boolean operators. Of 1,058 publications retrieved, 115 met the co-occurrence criteria. Analysis with *VOSViewer®* identified five key research areas, including rumen physiology, nutritional strategies, and bioactive compounds, with strong alignment to Sustainable Development Goals (SDGs), particularly Climate Action. Publication trends show marked growth since 2020, underscoring the topic's rising scientific and societal relevance. The results position methane mitigation in livestock as a research priority, supporting the development of sustainable production pathways.

Keywords: **Ruminant; Inhibitory Compounds; Enteric Methane; In vitro; Agroindustrial By-products.**

1. Introduction

In 2022, the IPCC estimated that enteric fermentation emitted 118 Tg CH_4, representing 32% of anthropogenic methane. FAO and UNFCCC inventories show a ~20% variation due to different reporting methodologies, highlighting underestimation and the need for harmonization. The livestock sector remains a major global methane source [1] [2].

In the rumen, cellulolytic bacteria degrade fibrous carbohydrates into volatile fatty acids, releasing H_2, which methanogenic archaea (mainly *Methanobrevibacter* spp.) use to reduce CO_2 to CH_4, expelled mainly by eructation [3]. Diet composition influences the acetate:propionate ratio, affecting hydrogen availability and methane output. Inhibitory compounds, natural or synthetic, reduce methanogenesis by inhibiting archaea, redirecting hydrogen, or altering substrate degradation [4], [5], [6].

Natural options like tannins, saponins, pectin, and essential oils have shown potential to lower methane without harming digestion, while synthetic additives such as nitrate, 3-NOP, and brominated algae expand mitigation strategies [6], [7], [8].

This study conducts a bibliometric analysis of inhibitory compounds in ruminant feed to assess trends and opportunities for reducing methane while maintaining productivity.

2. Methodology

The research was based on a bibliometric analysis, aiming to identify collaborative trends and emerging patterns in the respective scientific field, considering the last 20 years, from 2005 to 2025, specifically until July 2025. The database used was Web of Science (WoS), due to its scope and relevance as a scientific database, where descriptors were assigned in four categories, (I) *Animal: "Ruminant", "Rumen ferment", "Rumen microbio", "Methanogen archaea", "microorganism"*, (II) *Biology: "Inhibit", "Redox potential", "Methane", "Carbon sequest", "Methane mitigation"*, (III) *Analytical Methodologies: "ampts", "Batch ferment", "Methane quantif", "Anaerobic digestion", "In vitro ferment"*, (IV) *Raw Material: "Orange peel", "Cacao pod husk", "pectin", "Phenolic compound", "Hesperidin"*, with an emphasis on compounds that inhibit methane production in ruminants. Using Boolean operators *"AND"* and *"OR"* to formulate the search phrase, multiple combinations between categories were created, according to the Table 1.

Table *1*. Keyword combination

Search Line	Combination	Description
7	#1 AND #2 AND #3 AND #4	("Ruminant*" OR "Rumen ferment*" OR "Rumen microbio*" OR "Methanogen archaea*" OR "microorganism*") AND ("ampts*" OR "Batch ferment*" OR "Methane quantif*" OR "Anaerobic digestion*" OR "In vitro ferment*") AND ("Inhibit*" OR "Redox potential*" OR "Methane* " OR "Carbon sequest*" OR "Methane mitigation*") AND ("Orange peel*" OR "Cacao pod husk*" OR "pectin*" OR "Phenolic compound*" OR "Hesperidin*")
9	#1 AND #2 AND #4	("Ruminant*" OR "Rumen ferment*" OR "Rumen microbio*" OR "Methanogen archaea*" OR "microorganism*") AND ("Inhibit*" OR "Redox potential*" OR "Methane* " OR "Carbon sequest*" OR "Methane mitigation*") AND ("Orange peel*" OR "Cacao pod husk*" OR "pectin*" OR "Phenolic compound*" OR "Hesperidin*")
10	#1 AND #3 AND #4	("Ruminant*" OR "Rumen ferment*" OR "Rumen microbio*" OR "Methanogen archaea*" OR "microorganism*") AND ("ampts*" OR "Batch ferment*" OR "Methane quantif*" OR "Anaerobic digestion*" OR "In vitro ferment*") AND ("Orange peel*" OR "Cacao pod husk*" OR "pectin*" OR "Phenolic compound*" OR "Hesperidin*")

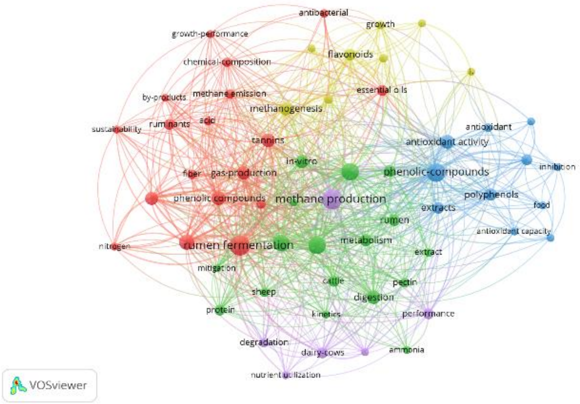
Source: Author's own elaboration.

The research focused on articles, including studies, conferences, and review articles from *Web of Science* (WoS). The search was refined to titles, keywords, and abstracts, resulting in more accurate data. *VOSviewer®* software was used to analyze and visualize the thematic groups and clusters.

3. Results and Discussions

The analysis of 1,058 publications retrieved from the WoS database identified 115 articles meeting all three thematic co-occurrence criteria. Thematic focus and predominant approaches were examined through a keyword co-occurrence network (**Figure** 1), organized into five clusters representing the core research axes on enteric fermentation and sustainability.

Figure *1*. Representation of the keyword network and correlation of the most relevant themes

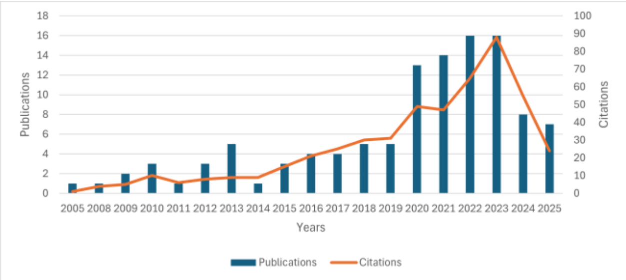


Source: *VOSViewer*, 2025.

The Red Cluster forms the structural core, integrating terms such as “rumen,” “fermentation,” “methane emission,” and “gas production,” which describe the physiological basis of methanogenesis, alongside “tannins” and “phenolic compounds,” indicating the role of natural compounds in environmental mitigation. The Green Cluster combines “digestion,” “metabolism,” “cattle,” and “sheep,” reflecting interspecies comparisons, while “protein,” “pectin,” and “kinetics” highlight nutritional optimization, and “performance” with “mitigation” indicate the challenge of balancing productivity and emission reduction. The Blue Cluster links “antioxidant activity,” “polyphenols,” and “inhibition,” signaling the potential of bioactive compounds for microbial control and animal health via “extracts” and “food.” The Yellow Cluster connects “flavonoids,” “essential oils,” and “antibacterial” with “methanogenesis” and “in vitro,” supporting their role as methane inhibitors, with “growth” suggesting systemic effects. The smaller Purple Cluster associates “methane production” and “dairy cows” with “degradation,” “ammonia,” and “nutrient utilization,” pointing to precision nutrition strategies. Overall, research is concentrated on physiological mechanisms and environmental mitigation (Red and Green), with complementary approaches exploring bioactive solutions (Blue/Yellow) and targeted nutritional management (Purple).

Scientific output trends (**Figure 2**) show modest, irregular publication rates between 2005 and 2014 (1–5 papers/year, <10 citations/year), with occasional peaks (e.g., 2013). From 2015, publication numbers rose steadily, with citations surpassing 30 in 2019. A major increase occurred in 2020 (13 papers, 49 citations), followed by sustained high output through 2023 (16 papers, 88 citations). Together, 2020–2023 account for over half of the analyzed output. The apparent decline in 2024–2025 likely reflects incomplete indexing. These trends indicate growing relevance of methane mitigation research for ruminants, sustainability, and climate change.

Figure 2. Several publications and citations vs. years.



Source: Web of Science (WoS), 2025.

Analysis of Sustainable Development Goal (SDG) alignment (**Figure 3**) reveals a predominance of environmental goals, especially SDG 13 – Climate Action (72 publications, 62.6%), linked to Target 13.2 through emission mitigation and adaptation in agriculture. Other relevant goals include SDG 12 – Responsible Consumption and Production (15; Target 12.3), via agro-industrial waste valorization; SDG 7 – Affordable and Clean Energy (13; Target 7.2), via methane-to-biogas conversion; and SDG 6 – Clean Water (implicit; Target 6.3) through effluent management. Social goals are led by SDG 3 – Good Health and Well-being (19; Target 3.9), focusing on animal health and reduced antibiotic use, and SDG 2 – Zero Hunger (2; Target 2.4), promoting sustainable food systems. SDG 11 – Sustainable Cities (1; Target 11.6) addresses waste management. Eight publications were technical/methodological without direct SDG linkage.

Figure ***3***. The Most Common Sustainable Development Goals

Sustainable Development Goal	Record Count	Percentage
13 Climate Action	72	62.61%
03 Good Health And Well Being	19	16.52%
12 Responsible Consumption And Production	15	13.04%
07 Affordable And Clean Energy	13	11.30%
06 Clean Water And Sanitation	12	10.44%
02 Zero Hunger	2	1.74%
14 Life Below Water	2	1.74%
11 Sustainable Cities And Communities	1	0.87%
Do not contain data in the field being analyzed	8	6.96%

Source: Author's own elaboration.

The 20 most relevant and cited studies are summarized in **Table 2**, with objectives and associated clusters from Figure 1. While most address enteric fermentation, others focus on anaerobic digestion of lignocellulosic biomass or agro-industrial residues. Notable works [9, 11, 12, 14] expand biochemical and microbiological understanding of methanogenesis and its mitigation. The breadth of approaches highlights the interdisciplinarity of the field and points to promising, sustainable innovations for animal production.

Table *2*. Comparative table of the 20 most relevant and cited articles

Authors	Study Objective	Associated Cluster and Keyword
[9]	To assess the enzymatic potential for the valorization of agro-industrial by-products.	**Blue:** Bioactive compounds ("polyphenols", "enzymes").
[10]	To evaluate the effect of including tannins, pectin, and polyethylene glycol in rumen fermentation, aiming to reduce the negative impacts of tannins on microbiota and gas production.	**Red and Green:** Methanogenesis physiology ("tannins") and nutritional optimization ("pectin").
[11]	To optimize orange peel waste ensiling for sustainable anaerobic digestion, evaluating d-limonene removal.	**Yellow and Blue:** Essential oils ("essential oils") and antimicrobial activity ("antioxidant activity").
[12]	To evaluate the integration of pyrolysis and anaerobic digestion in the conversion of lignocellulosic biomass into methane.	**Purple and Red:** Application in dairy cow nutrition ("methane production") and methanogenesis ("methane production").
[13]	To review lignocellulosic biomass liquefaction for methane production via anaerobic digestion.	**Red and Purple:** Methanogenesis ("methane production") and dairy cow nutritional management ("nutrient utilization").
[14]	To evaluate carbohydrate sources and protein degradability on lactation, rumen fermentation, and blood profile in dairy cows.	**Green and Purple:** Nutritional optimization ("protein", "pectin") and precision feeding in dairy cows ("dairy-cows").
[15]	To evaluate the antimicrobial and antioxidant activity of pomegranate, orange, and banana peel extracts.	**Blue:** Antioxidant bioactive compounds ("antioxidant activity").
[16]	To evaluate the expression of bacterial genes in the rumen related to methane emission, linked to methyl compound production.	**Red and Purple:** Methanogenesis ("methane emission") and specific nutritional management ("nutrient utilization").
[17]	To evaluate the effect of biochar in the anaerobic digestion of citrus residues, focusing on microbial communities and methane production.	**Purple and Green:** Precision nutrition ("dairy-cows") and digestive optimization ("metabolism").
[18]	To investigate the effect of phloroglucinol on rumen fermentation and methane emissions.	**Blue and Red:** Microbial inhibition ("inhibition") and methanogenesis ("methanogenesis").
[19]	To review the use of plant secondary metabolites as feed additives in calves, evaluating antimicrobial mechanisms.	**Blue and Yellow:** Bioactive compounds ("polyphenols") and essential oils ("essential oils").
[20]	To review the antibacterial mechanisms of plant phenolic compounds using systems biology.	**Blue and Yellow:** Phenolic compounds ("phenolic compounds") and flavonoids ("flavonoids").
[21]	To assess the antimicrobial activity of fruit peels against pathogenic bacteria and fungi.	**Blue and Yellow:** Bioactive compounds ("phenolic compounds") and essential oils ("essential oils").
[22]	To evaluate the effect of flavonoids (Bioflavex®) on rumen fermentation and in vitro methane production.	**Red, Yellow, and Blue:** Methanogenesis ("methanogenesis"), flavonoids ("flavonoids"), and bioactive compounds ("polyphenols").
[23]	To evaluate the effects of essential oils on in vitro rumen fermentation, analyzing end products such as volatile fatty acids and ammonia.	**Yellow:** Essential oils in methanogenesis inhibition ("essential oils").
[24]	To investigate the diversity of the intestinal archaeome in animals, analyzing its relationship with diet and intestinal physiology.	**Red and Green:** Methanogenesis physiology ("methane emission") and nutritional optimization ("digestion").
[25]	To evaluate the antifungal activity of orange peel essential oil against *Aspergillus flavus*, by direct contact and vapor exposure.	**Blue and Yellow:** Essential oils ("essential oils") and antimicrobial activity ("antibacterial").
[26]	To evaluate cashew nut shell liquid as a methane inhibition and propionate promoter in rumen fermentation.	**Red, Blue, and Green:** Methane inhibition ("methane-inhibiting"), phenolic compounds ("phenolic compounds"), and nutritional optimization ("propionate").
[27]	To assess the effects of fermentation on the composition and bioactivity of polyphenols in fermented foods.	**Blue and Red:** Bioactive compounds ("polyphenols") and fermentation processes ("fermentation").
[28]	To produce single-cell protein through solid-state fermentation	**Blue and Green:** Bioactive compounds

	of orange waste, investigating synergistic microbial interactions.	("protein") and nutritional optimization ("food").

Source: Author's own elaboration

4. Conclusions

Over the past two decades, research on enteric methane mitigation in ruminants has grown steadily, integrating physiology, nutrition, and biotechnology. Remaining gaps include standardization in bioactive compound use and economic viability assessments. Continued applied research is essential to develop efficient, sustainable nutritional strategies aligned with global environmental goals.

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