



AI-Enhanced Comprehensive Analysis Of The Research Perspective On The Microbiome And Methane Production In Cow Rumen

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ABSTRACT

Methane emissions from ruminant livestock, particularly cows, have been a topic of interest because of their negative environmental impact, including contributing to greenhouse gas accumulation and accelerating climate change. Understanding the cow's rumen microbiome can provide valuable insights for devising effective emission reduction strategies. Despite the recognized environmental impact of methane emissions from cows, however, a systematic review on the cow rumen microbiome has not yet been done. This study aims to fill this gap by performing an unbiased bibliometric analysis to review the effect of the rumen microbiome on methane emissions through cross-check of multiple data sources. While the bibliometric analysis offers a quantitative approach to assess research trends and identify areas of potential exploration within the field of the cow rumen microbiome, this study also evaluated the concurrently growing interest in the potential of artificial intelligence (AI) tools, specifically ChatGPT by OpenAI in terms of its efficacy and accuracy in enhancing scientific research project. Through the fusion of conventional research methodologies and AI-driven insights, this study aspires to provide a holistic perspective on the cow rumen microbiome's profound influence on methane emissions, while also exploring the untapped potential of AI in advancing scientific inquiry.

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Keywords: *Rumen microbiome, methane, bibliometric, artificial intelligence - AI, ChatGPT*

1. Introduction

The interactions within the microbiome of a cow's rumen have gained substantial interest in recent years, particularly due to their implications on environmental health. Ruminant livestock, such as cows, are significant contributors to methane emissions - a potent greenhouse gas that exacerbates climate change (Johnson & Johnson, 1995). Undoubtedly, understanding the cow rumen microbiome can provide valuable insights into potential strategies for mitigating these emissions.

Bibliometric analysis is an established methodology enabling quantitative assessment of research trends and knowledge structures within a specific field. The traditional bibliometric methodology consists of the follow components: (1) Defining the aims and scope of the bibliometric study, (2) Choosing the techniques for

bibliometric analysis, (3) Collecting the data for bibliometric analysis, and (4) Running the bibliometric analysis to report the findings (Donthu et al., 2021). While this technique has the power to illuminate the key research focuses within the field of the cow rumen microbiome and identify potential gaps in current understanding, a systematic bibliometric study remains notably absent.

To fulfill this research gap, conventional bibliometric analyses are proposed here with large databases including PubMed and Scopus. At the same time, the study will also incorporate OpenAI's chatbot ChatGPT-4 as a resource for comparative evaluation. This is in consideration that artificial intelligence has emerged as a rapidly growing topic of interest over recent years. Originating from the pursuit of creating machines that can simulate human intelligence, AI encompasses a range of techniques, including machine learning and deep learning. These algorithms can process large amounts of data at fast speeds, identify patterns, and make predictions based on the input they receive. Especially relevant to the current study is the application of AI in research, where it has the potential to analyze and synthesize literature, potentially uncovering insights that might be overlooked by traditional methods.

In particular, the study aims to analyze and compare the research focus areas identified by PubMed, Scopus, and ChatGPT, discerning overlaps, discrepancies, or unique insights. This approach cross-validates findings to ensure accuracy. More importantly, however, the use of ChatGPT allows the study to evaluate the ability of AI to conduct or aid in research. This is an intriguing test of novel technology that may influence the way research is conducted in the future. It would be intriguing to find out whether the responses of ChatGPT will agree with the results of the bibliometric analysis, as there are inherent differences between how ChatGPT processes information and structured bibliometric analyses. Traditional bibliometric analyses rely on more systematic approaches, while ChatGPT, as a neural network, derives patterns from a broader and more diverse dataset, which may lead to different interpretations or focus areas. Through this study, it also provides a perspective on how OpenAI can support research.

2. Methodology

2.1. Data Collection

A search using the terms TITLE-ABS-KEY ("microbiome" OR "rumen" AND "cow" OR "cattle" AND "methane" OR "CH4") was performed in July 2023 on both the PubMed and Scopus databases. The search results were downloaded as excel files and a survey of 100 records from the top and bottom was performed to validate the queries.

2.2. Data Analysis

Three different pieces of information were extracted from the data: Historical Development, Global Collaboration, and Research Focus (**Figure 1**).

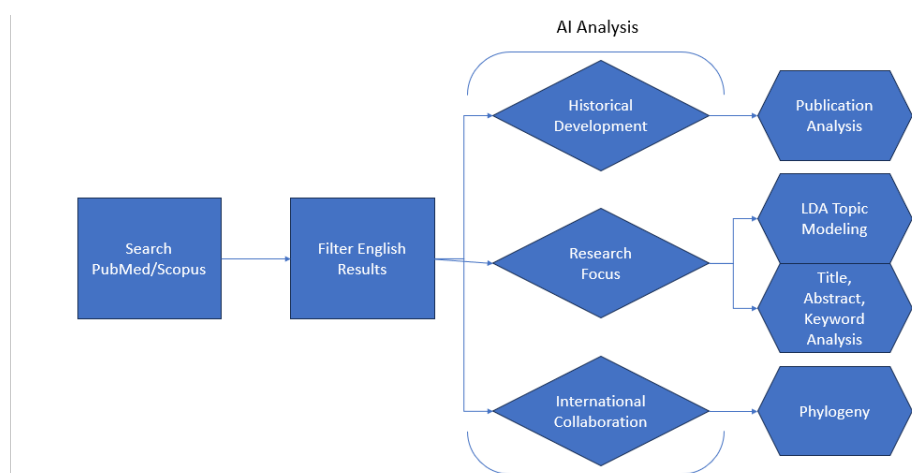


Figure 1: Visual representation of the systematic methodology employed in this study. The process consists of: (1) a comprehensive literature search was conducted on prominent databases, PubMed and Scopus, to gather initial results; (2) the search data were screened to filter out only the eligible results; (3) various analytical processes were performed to assess the historical development, international collaboration, and

research focus; (4) prompt generation for the ChatGPT model was done separately from bibliometric analysis for comparative evaluation.

The methodology for research trend identification incorporated an analysis of titles, abstracts, and keywords, followed by Latent Dirichlet Allocation (LDA) topic modeling. The data was analyzed using Microsoft Excel and Python, with the detailed process for LDA topic modeling elaborated by Kherwa et al (2018). For tracing the historical development of the research field, the study conducted a thorough review of the yearly distribution of publications from 1930 to 2023. Regarding international collaboration, the study produced a phylogenetic tree and scrutinized the proportion of environmentally-focused research output from different nations. The type of collaboration was ascertained based on the address provided by each author in the publications.

2.3. ChatGPT

Simultaneously, a set of prompts was crafted and supplied to the ChatGPT model, GPT-4, to enable it to conduct a similar analysis. The query to the GPT-4 was made on 11/15/2023. The AI-generated responses to these prompts were subsequently compared with the outcomes of the bibliometric analysis. The prompts for each section could be found in the AI analysis in the below results section.

2.4. Comparison

The results from the bibliometric analysis conducted using PubMed and Scopus would be compared to evaluate the level of agreement and the bias from the databases. Furthermore, the outcomes of traditional bibliometric analysis from these two databases would be compared with the insights gleaned from the AI analysis via ChatGPT. This would be expected to highlight unique capabilities and limitations of AI tools in research analysis. This comparative analysis aims to showcase the complementary nature of AI in augmenting traditional research methods, offering identifying potential areas for methodological enhancements in future studies.

3. Results

3.1. Publication Output and History

The initial search yielded 1597 records from PubMed and 1582 from Scopus. Of these, 1572 from PubMed and 1536 from Scopus were written in English. The results from PubMed ranged from 1951 to 2023, while those from Scopus ranged from 1930 to 2023. A survey by reading 100 records from the top and bottom confirmed that they are the relevant records queried for this study. According to publication output from the Scopus database, research in the field of cow microbiome and methane production exhibited a gradual development before 2005, and after which it displayed a rapid surge (**Figure 2**). The publication count rose from 44 articles in the period 1994-2000 to 83 articles between 2001 and 2005. Publication output exponentially increased to 150 articles in 2022. The same can be said based on publication output from the PubMed database. There were only 46 articles published between 1994 and 2000, which then increased to 62 articles in the period from 2001 to 2005. Then, there was a significant upswing in research output, eventually reaching 181 publications in 2022. Publications decreased in 2023 because not all the publications have been indexed in the databases this year upon the completion of the analysis in this study. Overall, the trend in publications has been a strong upward trajectory, indicating growing scientific interest and increasing research efforts in understanding the role of the cow microbiome in methane production.

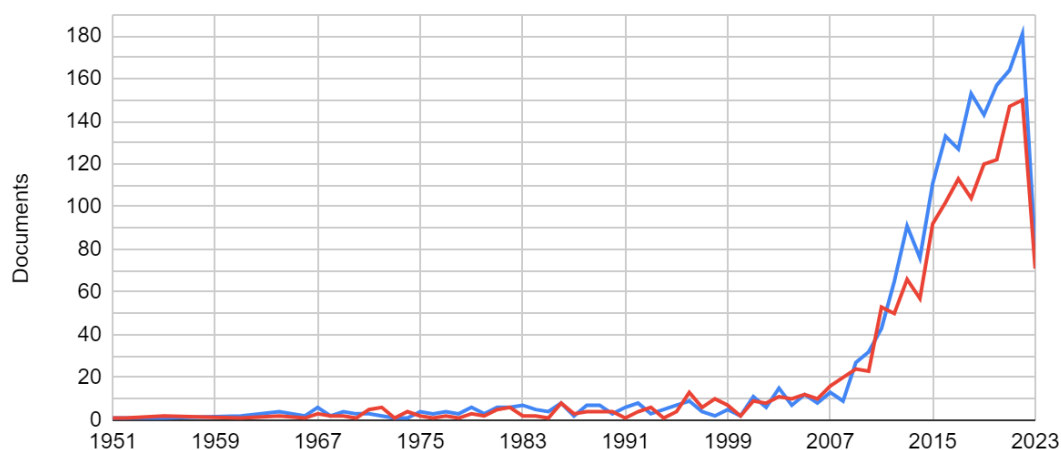


Figure 2: The number of publications referring to methane production and the cow microbiome in Scopus (red) and PubMed (blue) databases

3.2. International Collaboration

A phylogenetic tree was created in MEGA software based on publication data to map collaboration between top publishing countries (**Figure 3**). The findings are organized into regional and thematic groupings.

Collaborations between Major Countries: Canada, Australia, and China emerge as a closely connected group, with Canada and Australia showing a particularly close collaboration. China is also related to this group but with a slightly more distant connection. The USA and Brazil form another significant collaboration, and they are interconnected with the Canada-Australia-China group. These countries make up the Top 6 in terms of total number of publications, with only the UK being excluded, meaning that the greatest contributors to cow microbiome research tend to collaborate closely.

European Collaborations: The European region showcases several key collaborations and relationships. The UK and Ireland exhibit a close collaboration, as do Germany and Switzerland. France appears to be related to the Germany-Switzerland collaboration. The Netherlands and Denmark form their own collaboration. Spain and Italy are also closely connected, forming a distinct subgroup within the European context. Countries tend to collaborate more closely with their neighboring nations, indicating that geographical proximity influences collaboration. Belgium is the only exception, and it appears to be the outgroup in this phylogenetic tree.

Latin American Collaborations: Mexico and Colombia are close collaborators, forming a Latin American subgroup. They do not collaborate particularly closely with any other countries particularly closely.

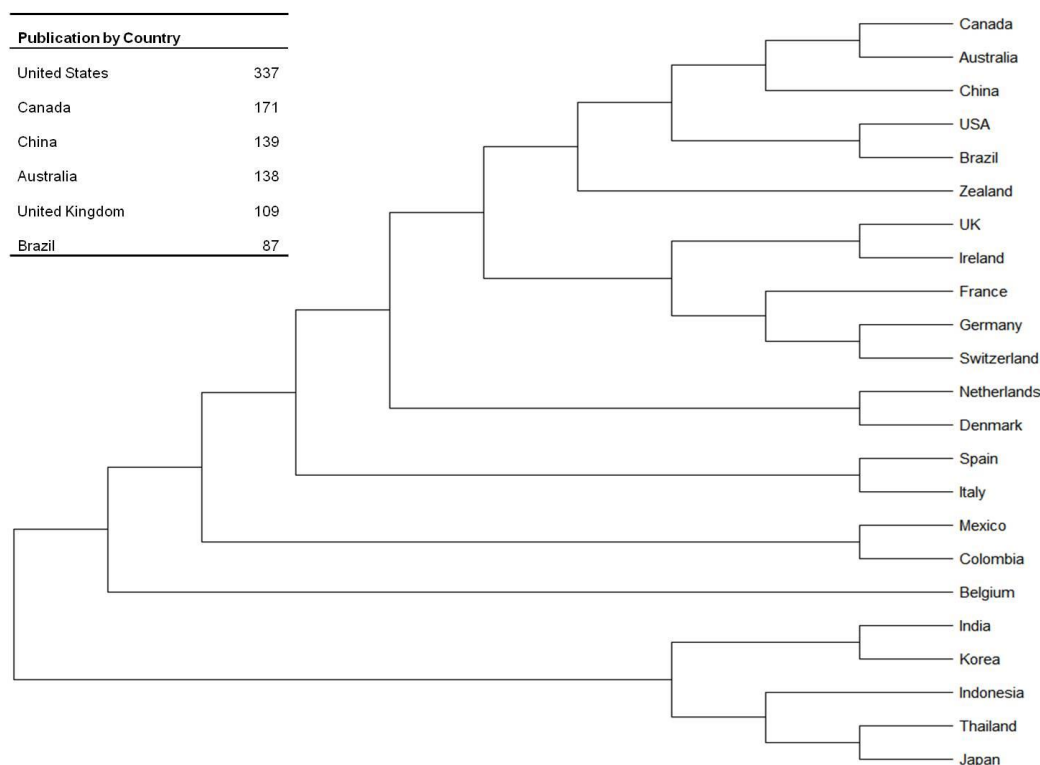


Figure 3: Collaboration between the top contributing countries towards cow microbiome research. The table shows the top 6 productive countries in terms of the number of publications.

Asian Collaborations: The Asian region is characterized by collaborations between India and Korea, Thailand and Japan, and a connection with Indonesia. These collaborations form a distinct Asian subgroup, reflecting specific research interests or methodologies within this region. Surprisingly, China is extremely disconnected from this group, likely because it is a larger country and tends to collaborate more with other major contributors.

3.3. Research Focus

In the presented data analysis, a specific notation is employed to track the prominence and frequency of certain keywords and bi-grams across various time frames. The format "X --> Y --> Z" illustrates the ranking progression of a particular term over three distinct periods. A shift from a higher to a lower number indicates an increase in the term's prominence and frequency in the literature over time. Conversely, a shift from a lower to a higher number or the term becoming 'unranked' indicates a decrease in its prominence. Each term was sorted into one of four categories: Animal Productivity, Management and breeding, Nutrition, and Rumen microbiome / Fermentation manipulation, as defined by Beauchemin et al. (2020).

3.3.1. Analysis for Title

Top Single Words in Title

In the title analysis of both Scopus and PubMed results, meaningless words such as prepositions have been excluded, as well as the part of the search terms "microbiome", "cow", "cattle", "cattle", "methane", and "rumen". Additionally, the words "microbiome", "cow", "cattle", "methane", and "rumen" were excluded, as they were part of our search terms.

Trends in Single Words in Title

Three 10-year periods ranging from 1993-2023 (1993-2002, 2003-2012, and 2013-2022) were analyzed to identify the trend of frequent words over the years (**Table 1**; Supplementary Information Table S1). The results from 1930-1992 were excluded because there were too few publications during that period to draw any reasonable conclusions from the titles. In general, the frequency of substantives increased at the same rate as the number of publications increased.

Table 1: Notable terms in title and their overtime rankings

Term	Category	Scopus	PubMed
Digestibility	Nutrition		
Feed	Nutrition		
Dietary	Nutrition		
Tannin	Nutrition		
Performance	Animal Productivity		
Milk	Animal Productivity		
Vitro	Rumen Microbiome / Fermentation Manipulation		
Methanogen	Rumen Microbiome / Fermentation Manipulation		

For the single word title analysis of both databases, terms regarding animal breeding, such as “phenotype”, “genetics”, and “heritability” were not identified within the top 50 most common terms for any time period. A bigram analysis was not conducted for the title because given the shorter length of titles, there was not enough meaningful data to analyze.

3.3.2: Abstract Analysis

In the abstract analysis, significant bigrams were extracted from the abstracts of both PubMed and Scopus articles (**Table 2**; Supplementary Information Table S2). Single words were not analyzed for abstracts. Just like the title analysis, meaningless words and search terms were excluded from the analysis.

Table 2: Notable bigrams in abstract and their overtime rankings

Term	Category	Scopus	PubMed
Dry, Matter	Nutrition		
Neutral, Detergent	Nutrition		
Latin, Square	Nutrition		
Organic, Matter	Nutrition		
Milk, Yield	Animal Productivity		
Ruminal, Fermentation	Rumen Microbiome / Fermentation Manipulation		
Fatty, Acid	Rumen Microbiome / Fermentation Manipulation		
Rumen, Fluid	Rumen Microbiome / Fermentation Manipulation		
Acetate, Propionate	Rumen Microbiome / Fermentation Manipulation		
Molar, Proportion	Rumen Microbiome / Fermentation Manipulation		

3.3.3: Author Keyword Analysis

In the author keyword analysis, both single terms and bigrams were included for analysis of their frequency and trend over time (**Table 3**; Supplementary Information Table S3). Unfortunately, a large number of PubMed articles did not contain author keywords, and there was not enough data to draw significant results.

Table 3: Notable author keywords, categories and their overtime rankings

Term	Category	Overitme Rank in Scopus
Digestibility	Nutrition	
Nitrate	Nutrition	
Forage	Nutrition	
Tannin	Nutrition	
3-Nitrooxyprop anol	Nutrition	
Digestion	Animal Productivity	
Metagenomics	Rumen Microbiome / Fermentation Manipulation	
In Vitro	Rumen Microbiome / Fermentation Manipulation	
Protozoa	Rumen Microbiome / Fermentation Manipulation	
Anaerobic Digestion	Rumen Microbiome / Fermentation Manipulation	
Rusitec	Rumen Microbiome / Fermentation Manipulation	
Monensin	Rumen Microbiome / Fermentation Manipulation	
Volatile Fatty Acids	Rumen Microbiome / Fermentation Manipulation	
Methanogen	Rumen Microbiome / Fermentation Manipulation	

3.3.4: LDA Topic Modelling

Latent Dirichlet Allocation (LDA) topic modeling was employed to extract underlying themes from the abstracts of publications listed in the Scopus database. The analysis aimed to distinguish separate research topics, as well as determine which topic was the most common. Search terms and generic terms, including "methane", "cows", "effect", "rumen", "production", "different", "using", "system", "performance", "fermentation", and "cattle", were removed from the data to better observe underlying trends in the research. The optimal number of topics based on coherence value was determined to be sixteen (**Figure 4**). Terms that were particularly prominent in a topic were marked with an exclamation (!) mark. As the topic numbers increase, the size of the topics decreases, with topic 1 being the largest and topic 16 the smallest (**Table 4**).

Table 4: Topics identified in the LDA Modelling analysis

Topic #	Potential Topic	Frequent Terms
1	Milk Production and Nitrate Supplements	milk, intake, diet, digestibility, dry matter, production, nitrate!, 3-nitrooxypropanol!, increased, decreased
2	Animal Productivity and Quality of Feed	Diet, milk, production, increased, decreased, intake, dry matter, digestibility, concentration, energy, concentrate, corn silage!, protein, compared, linearly
3	Microbiome Diversity and Function	Microbiome!, bacterial, archaeal!, abundance!, microbiota!, taxonomic!, model, community, methanogenic, genetic, sequencing, data, metagenome!, dna!
4	Diet to alter VFA production patterns	Volatile fatty acids, model, fat, protein, milk, chitosan!, rapeseed!, odd and branched chain fatty acids!
5	Supplemental rumen modifiers	Cassava!, substrate, gas, vitro, incubation, essential oils!, meal, leaf!, emissions, quercetin!, docosahexaenoic acid!
6	Optimizing Maize and Grass Silage Quality of Feed	Silage, maize!, grass, pulp!, fermentation, concentration, gas, microbial
7	Herbal Additives in Diet for Rumen Modification	Vitro, incubated, oil, blue panic grass, cultures, oregano!, clover!
8	Direct fed rumen modifiers	e. coli!, husks!, stalks!, leaves, cultures, vitro, monensin, feed, energy
9	Biogas Production and Waste Anaerobic Digestion	Biogas!, waste!, anaerobic!, extracts!, substrate, degradation, plant, inoculum, rate, batch!, bioaugmentation!, volume, reactor!, digester!, cellulose!, mesophilic!, co-digestion!
10	Feed management / Rate of Passage	Monensin, age, particle!, anaerobic, measurements, time, species, function, sheep, escsg!, n2o
11	Molly models	Strain!, model, rate, fatty acid, microorganism!, within, vitamin!, phase, variation, molly!, experiments
12	Metagenomics analysis of rumen microbes	Methanogens, methanobrevibacter, gene, community, libraries!, 16s, diversity, rna, sequences, population, artificial
13	Pasture and Grazing Management	Grazing, fat, forage, high-starch!, pasture, management, fat, gut!, improved
14	Uses of cow manure and feces	Manure, digesta, pretreatment, archaeol!, dh2!, wall!, tannin, fecal, anaerobic, stomach
15	Breeding and Selection	Nitrate, coconut!, dry matter index, lactation, correlations!, data, trait!, selection, indicator, powder
16	Specific Forage Management	Nitrate, ryegrass, urea, infected!, endophyte!

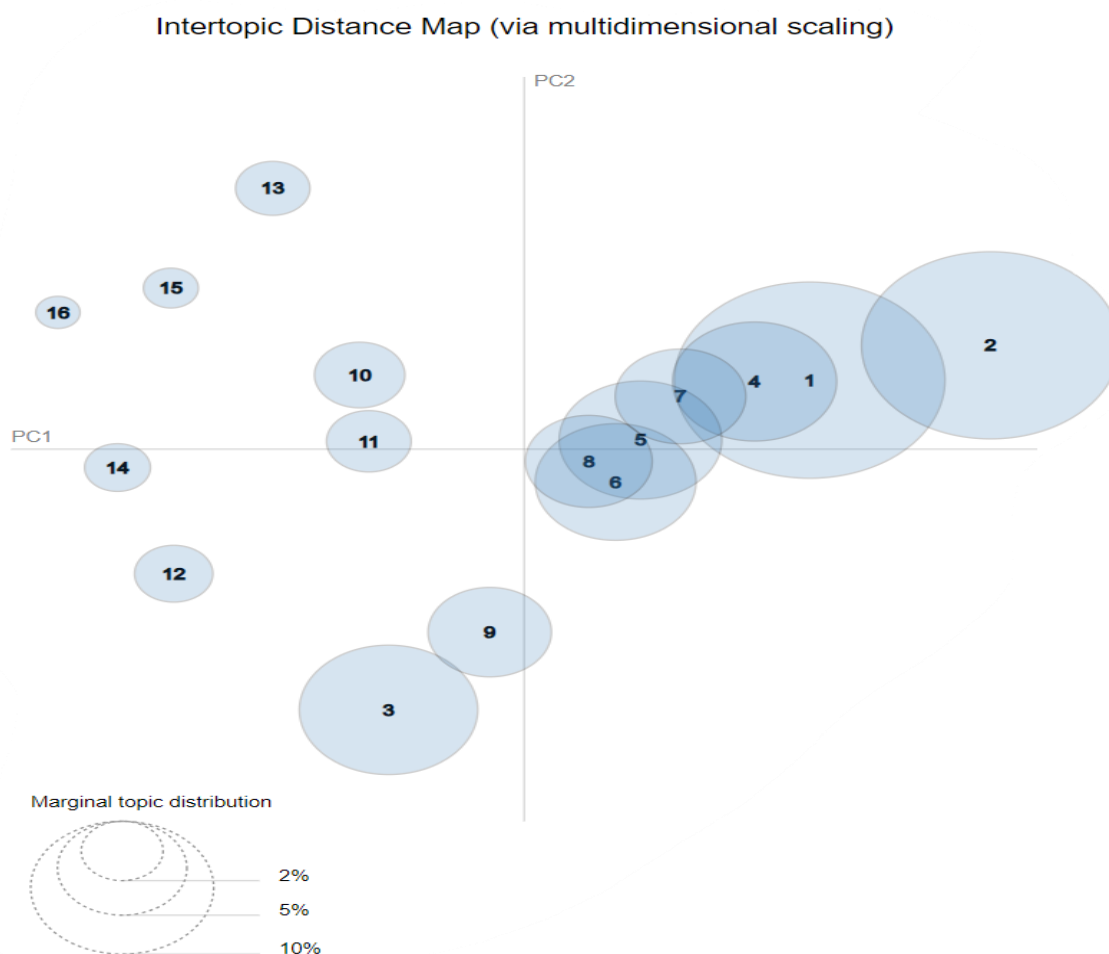


Figure 4: A pyLDAvis visualization of the LDA topic modelling. The closer two topics are, the more closely related they are.

3.4. ChatGPT Analysis

3.4.1. Publication Output

TL

What is the history of research on methane production from the cow microbiome? Has research increased or decreased? How quickly, when, and why?

CHATGPT

Overall, research in this area has increased, particularly in the last two decades. The reasons for this include:

- **Environmental Concerns:** The urgency to address climate change has spotlighted methane emissions from livestock.
- **Technological Advancements:** Tools like next-generation sequencing have revolutionized our ability to study complex microbial communities.
- **Economic Factors:** There's a drive to improve the efficiency of livestock farming, and understanding the microbiome can contribute to this.

TL

When?

CHATGPT

To specify a year, the early 2000s is a reasonable estimate. This period marked:

- **Global Climate Awareness:** The early 2000s saw significant international efforts to address climate change. The Kyoto Protocol, an international treaty aimed at greenhouse gas reduction, came into force in 2005, driving research in emissions across various sectors, including agriculture.
- **Technological Advancements:** The turn of the century also brought about significant advancements in genetic sequencing technologies. The Human Genome Project was completed around 2003, and the

techniques and technologies developed during and after this project drastically reduced the cost and time required for DNA sequencing. This revolution in sequencing tech made it easier for researchers to delve deep into the intricacies of the rumen microbiome.

- **Increased Funding:** With heightened global awareness about climate change and the potential of livestock as a significant source of methane, research funding in this specific domain probably saw an increase.

TL

How quickly?

CHATGPT

It's hard to give an exact rate without a bibliometric analysis of published papers over time. But it's safe to say that the rate of research has accelerated, especially in the 21st century.

3.4.2. Research Focus

TL

Based on the titles, abstracts, and author keywords of research papers written on methane production from the cow microbiome, what are the common research trends? What are the research hotspots? What still remains to be researched?

CHATGPT

Common Research Trends (areas that have been widely researched or have a significant number of studies associated with them):

1. **Microbiome Composition:** Understand the microbial community in the rumen - which microbes (bacteria, archaea, fungi, and protozoa) are present, their proportions, and their specific roles.
2. **Methanogenesis Mechanism:** Delve into the biochemical pathways, mainly of the archaea, that lead to methane formation. Understanding how hydrogen and carbon dioxide are converted to methane is fundamental.
3. **Feed and Diet Impact:** Investigate how changes in the cow's diet can impact methane production. This includes exploring alternative feeds or additives, such as tannins, that might reduce methane emissions.
4. **Genetic Aspects:** Study the genetics of the cow to understand if some breeds produce less methane than others and why.
5. **Interventions:** Development of methane-reducing interventions, from vaccines to inhibitors that target methanogenic microbes.
6. **Environmental Impact:** Assess how methane production from cows impacts the environment and contributes to global warming.

TL

What are the research hotspots?

CHATGPT

Research Hotspots (emerging areas of interest that have seen a recent surge in research activity):

1. **Methane Inhibitors:** Finding chemicals or biological compounds that can reduce methanogenesis without harming the cow or reducing its productivity.
2. **Alternative Feeds:** Research into seaweeds (e.g., *Asparagopsis taxiformis*) or other non-traditional feeds that have shown promise in reducing methane emissions.
3. **Microbiome Manipulation:** Using probiotics or other methods to change the microbial community in the rumen to one that produces less methane.
4. **Technology & Measurement:** Development of new technologies to accurately and conveniently measure methane emissions from livestock in various settings.

TL

What still remains to be researched?

CHATGPT

Potential Research Gaps:

1. **Long-term Effects:** While many interventions might show short-term reductions in methane, their long-term effects on the cow's health, productivity, and the environment might not be well-studied.
2. **Microbial Interactions:** While individual microbes might be studied, the complex interactions between various members of the microbiome might still need more research.

3. **Economic Viability:** Many solutions, while effective, might not be economically viable for farmers, especially in developing countries.
4. **Global Differences:** Research might predominantly come from specific regions. There's a need to understand if findings apply globally, considering the varied diets and breeds in different parts of the world.
5. **Integration with Technology:** Using IoT, AI, and other modern technologies to better monitor, analyze, and predict methane emissions and devise reduction strategies in real-time.

3.4.3. International Collaboration

TL

Which countries have collaborated the most closely while researching methane production from the cow microbiome?

CHATGPT

1. **Developed Countries with Strong Agricultural Research:** Countries with well-established agricultural research institutions often lead and collaborate on such studies. This includes countries like the United States (e.g., USDA research), Canada, Australia, and many countries in the European Union (e.g., the UK, France, the Netherlands, and Germany).
2. **Countries with Large Ruminant Populations:** Countries with significant livestock industries, especially those focusing on cattle like Brazil, India, and New Zealand, have shown interest in this research. Their large cattle populations naturally make methane emissions a significant concern.
3. **Collaborative Initiatives:** Some international research initiatives and programs bring together experts from different countries. For instance, the Global Research Alliance on Agricultural Greenhouse Gases is an initiative that sees collaboration between many countries to address greenhouse gas emissions from agriculture, including methane emissions from livestock.
4. **Collaborative Patterns:** Often, collaboration patterns emerge based on geographic proximity, historical or linguistic ties, or shared environmental and economic concerns. For example:
 - European countries often collaborate with each other due to proximity and shared EU research initiatives.
 - Australia and New Zealand collaborate due to their proximity and shared agricultural challenges.
 - The US and Canada might collaborate given their shared border and similar agricultural practices in many regions.
5. **Emerging Collaborations:** With the increasing recognition of the global nature of climate change challenges, collaborations have been emerging between developed countries with advanced research infrastructure and developing countries with large ruminant populations. Such collaborations often aim to transfer knowledge, techniques, and solutions to places where they might have the most significant impact.

3.5. Bibliometric analysis versus ChatGPT queries

The results from the bibliometric analysis were compared to the ChatGPT responses to determine the viability of the AI in research.

Publication Output and History: For publication output, the AI determined that “research in this area has increased” and that “the rate of research has accelerated” starting from “the early 2000s”. In this regard, the AI completely agrees with the results of the bibliometric analysis. The AI also identified the reasons for the exponential increase in publications to be rising environmental concerns, technological advancements, and economic factors. One specific helpful technology that the AI identified was next-generation sequencing, which can be used to evaluate microbiome changes in response to various stimuli (Tian et al., 2018). However, in general, the AI analysis revealed the same trends in publication output as our bibliometric analysis.

Research Focus: The AI identified various areas of research focus, highlighting common research trends, emerging hotspots, and potential research gaps. According to the AI's findings, common research trends that align with bibliometric analysis include “microbiome composition”, “feed and diet impact”, “interventions”, and “environmental impact”. However, the AI also pinpointed areas not reflected in the bibliometric analysis, specifically “methanogenesis mechanism” or biochemical pathways, and “genetic aspects”. When delving deeper into both areas, it has been realized that the methanogenesis biochemical pathway and other

microbiome pathways are potentially significant to microbiome research although it is currently not a research focus yet. The methanogenesis pathway, having been extensively studied, offers insights into segments that can be targeted by specific agents for suppression (Lyu et al., 2018). Moreover, the symbiotic relationships between methanogens and other microbes in the rumen suggest that investigating other biochemical pathways could serve as competition to the methanogenesis pathway, providing alternative methods to counter methanogenesis (López-García et al., 2022). A potential reason for the diminished focus on the methanogenesis pathway itself is that the steps have already been thoroughly researched, prompting a shift towards strategies that inhibit this pathway. However, competing biochemical pathways are also not without challenges, producing inconsistent results and possessing uncharted side effects. Regarding genetics, the inherent genes of ruminants play a role in methane production, indicating that selective breeding for reduced methane emissions is a promising mitigation strategy. However, genetic research is time-intensive and comes with its own set of unexplored side effects, making it difficult to research (Bagi et al., 2017). Nonetheless, both the study of ruminal biochemical pathways and ruminant genetics are viable options that should be considered for future research. In general, the research focuses identified by the AI matched with those identified by the bibliometric analysis with a couple exceptions. However, both exceptions, while not necessarily hotspots, were viable options for the mitigation of methane emissions that had been researched at least to some extent.

International Collaboration: Recall that the primary collaboration trends identified by the phylogenetic analysis were related to the size of the country as well as the distance between countries. Some of the collaboration trends identified by the AI and the phylogenetic analysis were similar. Firstly, the AI determined that “Developed Countries with Strong Agricultural Research” tended to collaborate often, which is similar to the idea from the phylogenetic analysis that major contributors towards microbiome research collaborate more. Secondly, the AI identified “geographical proximity” and “historical or linguistic ties” as factors leading to more collaboration, a trend also identified by the phylogenetic analysis. However, the idea of collaboration between countries with high ruminant populations, including “Brazil, India, and New Zealand”, was not reflected in the analysis. While Brazil and New Zealand were relatively close on the tree, India was on the complete opposite side, meaning that there were very few collaborations between India and the other ruminant-dense countries. There was also the idea of “between developed countries with advanced research infrastructure and developing countries with large ruminant populations”. The AI considered developed countries to include the United States, Canada, Australia, and many countries in the European Union, and developing countries with large ruminant populations to include Brazil, India, and New Zealand. However, it is hard to argue that New Zealand, with its advanced agricultural research systems, fits the profile of a developing country, and this misclassification may skew the analysis of collaboration patterns. Otherwise, the AI's identification of collaboration trends broadly aligns with the phylogenetic analysis.

4. Discussion

The primary objective of this study was to fill systemic gap regarding the cow rumen microbiome through comprehensively presenting the research scene behind the published literature. The study utilized data from the Scopus and PubMed databases to conduct analyses of publication output, international collaboration, LDA topic modeling, and frequency and trend of topic terms. By complementing the bibliometric analysis with the ChatGPT query, this study also evaluated the efficacy of AI in scientific research.

According to the bibliometric analysis, outputs have seen a substantial upward trend, mirroring the global awareness of climate change and the mounting need to address methane emissions. This growth in publications may be attributed to growing global consciousness of climate change, such as with the Kyoto Protocol in 2005, and advancements in scientific techniques such as Next Generation Sequencing (Van Dijk et al., 2014). This trend also implies that more funding and resources are being directed towards cow microbiome research, meaning that expensive mitigation strategies may be more strongly considered in the future. During the increase in publications, there were several international collaboration patterns. As charted by a phylogenetic tree, several groups of collaboration were identified. Major contributors to the field, such as Canada, Australia, China, the USA, and Brazil, tend to collaborate more often. The remaining collaboration was regional, with European, Asian, and South American countries showing distinct collaborative subgroups due to their geographical proximity. However, collaboration beyond regions is scarce except for the major contributors above. Increased international collaboration in methane mitigation is crucial for policy harmonization, enhancing research funding, and applying insights to smaller countries with

large ruminant populations. This approach ensures the development of globally united methane reduction strategies.

Building on the observed trends of increasing publication volume and international collaborations, LDA topic modeling organized the corpus of abstracts into more specific categories. Research regarding animal productivity, encompassing Topics 1 and 2, had the greatest volume of research, focusing on how diets and supplements enhance productivity. Furthermore, studies on supplementation and rumen modifiers (Topics 4, 5, 7, 8), as well as general feed management (Topics 6, 10, 13, 16), seemed more spread out across multiple topics, implying greater diversity in mitigation strategies. Contrarily, breeding research (Topic 15) was significantly less explored, aligning with the aforementioned difficulties of breeding research. The final area, waste management and biogas production (Topics 9, 14), had a relatively small volume of research compared to the others. Following the determination of the topics, trends in which topics were growing or losing prominence were analyzed through the frequency of terms and bigrams. The analysis of words and bigrams in titles revealed trends in research direction and intensity. Nutrition and animal productivity consistently gained prominence across all time periods at the same rate in both Scopus and PubMed, with exceptions like "forage" and "tannin" in Scopus, and "tannin" in PubMed. All nutrition and animal productivity terms were unranked or ranked lower than 35 in 1993-2002, indicating scarcer research in that area before the dramatic increase in publications during the 2000s. Indeed, research on rumen microbiome conditions and fermentation was most prominent in that period, with terms such as "monensin", "vitro", and "methanogen" being particularly prominent either in 1993-2002 or 2003-2012. The abstract analysis revealed similar trends. In Scopus, all bigrams related to nutrition and animal productivity increased in prominence over time. Microbiome conditions were significantly more notable in 1993-2002 and 2003-2012, with bigrams like "fatty acid" and "rumen fluid" being most distinguished from 2003-2012, thus indicating that microbiome research was most prominent in that period. However, the PubMed abstract analysis trends diverged from the Scopus analysis. Animal productivity and nutrition terms were still generally more concentrated in 2013-2023, but microbiome condition terms fluctuated in prominence across all three time periods, with no period being more significant for this area than the others. The keyword analysis also went against the trend determined in the title and Scopus abstract analyses, showing no distinguishable trend, probably due to the small sample size, as the majority of the terms in 1993-2002 had merely one or two instances. This suggests that certain types of terms might not be commonly included in keywords, and ultimately, that keywords may not be the best candidates for topic trend analyses. From all of this information, the overall research trend from 1993-2023 is a shift from microbiome conditions to animal productivity and nutrition. It can be generalized that the topics of animal productivity and nutrition have been growing in prominence, and that the topic of microbiome conditions has remained consistently important throughout all of 1993-2023. Currently, focusing on animal productivity and nutrition seems to be the most practical strategy for mitigating methane emissions. Increasing animal productivity is an effective way of mitigating methane emissions, as the overall CH₄ intensity decreases due to fewer animals and less feed needed to produce the same amount of product (Capper et al., 2009). As it happens, animal productivity and nutrition are closely related, hence why research trends between these areas have been observably tied. This is because many nutritional supplements, such as various lipids, are fed to cows with the purpose of increasing productivity (Beauchemin et al., 2020). Significant disparities in the research include the lack of focus on animal breeding, due to challenges in correlating methane production with animal phenotype, and the underrepresentation of biogas production as a mitigation strategy. Furthermore, the emerging but infrequent use of metagenomics is another gap. Metagenomics, crucial for analyzing microbial genetic material in cattle rumen, is useful for identifying methane-producing microbes and their interactions. Sequencing rumen microbial genomes is also a promising approach, helping the development of targeted interventions and enhancing understanding of microbial dynamics for effective methane inhibition.

In comparing ChatGPT's responses with traditional bibliometric analyses, AI excels at mapping out the growth in research publications, confirming its ability to process extensive data. AI also agreed with the majority of the research hotspots identified by the bibliometric analysis. This by itself does not mean that AI can generate new ideas by itself, although it does mean that AI is proficient at summarizing information. However, AI's challenges in accurately assessing international research collaborations, such as wrongly categorizing New Zealand's research scene, show that it still needs the nuanced understanding that humans bring to the table. The oversight in recognizing collaboration trends, particularly the limited interactions between India and other countries with many ruminants, reveals that AI does not have a deep understanding of specific interactions. Instead, most likely, AI simply guesses on these collaborations based on more

general information it knows about relationships between countries. In summary, AI can be used for enhancing bibliometric studies because it can handle large amounts of data and spot emerging research topics. However, it is not to be trusted to create its own connections or generate its own ideas, as AI will often guess or produce inaccurate information in the absence of hard data.

Researchers can utilize the lessons learned from this study when incorporating AI tools in their analyses by feeding it data that they have gathered and using its output as a starting point. Oftentimes, the output generated by AI is more or less accurate, although it is necessary to validate the information through other sources. Furthermore, the discrepancies in the PubMed and Scopus results, as well as between title and abstract analyses, demonstrates that it may be challenging to get a complete idea of the research scene while sticking with one database or analysis method. To account for potential biases of certain sources of information, researchers should at least briefly consider other sources to verify or corroborate ideas. Finally, limitations of this study could be the relatively small number of articles extracted on the subject from the databases. Because there was not enough content, many of the frequency analyses, such as the PubMed keyword analysis, could not be performed, and the existing analyses contained a significant number of unranked terms. This, on the other hand, might be also attributing to the scope that ChatGPT can reach since there are not enough data for AI to get trained yet.

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