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# Global Research Trends and Knowledge Structures on the Role of Fermented Feed in Modulating Rumen Microbiota: A Scopus-Based Bibliometric Analysis

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***ABSTRACT.*** This bibliometric study maps the global development of research on fermented feeds for rumen microbiota modulation, addressing the lack of quantitative synthesis on publication dynamics, thematic evolution, and collaboration structures in this rapidly expanding field. Bibliographic data retrieved from the Scopus database covering the period 1961–2024 yielded 620 peer-reviewed journal articles, analyzed using VOSviewer and the Bibliometrix R package. The results show sustained long-term growth in research output, with a pronounced acceleration since 2010. Citation analysis reveals a high degree of citation concentration, whereby a limited number of seminal studies published in the mid-1970s account for a disproportionate share of total citations. Canada (2,518 citations), the United States (2,502), and Spain (1,927) emerged as the most influential countries, while contributions from developing regions remain comparatively limited. At the journal level, the Journal of Dairy Science (87 articles) and Journal of Animal Science (83 articles) dominate publication output, indicating strong disciplinary concentration. Thematic evolution analysis demonstrates a clear transition from early research focused on rumen fermentation and digestion toward more integrative frameworks encompassing microbial ecology, nutritional interventions, and environmental sustainability. Rumen fermentation, microbial community dynamics, and methane mitigation currently dominate the research landscape, with methane mitigation identified as a high-impact yet structurally fragmented research frontier. Unlike previous bibliometric studies that examined fermented feeds or rumen fermentation in isolation, this study integrates thematic evolution and collaboration network analyses to capture the interdisciplinary progression of the field. These findings highlight the need for future experimental studies combining fermented feed strategies with rumen physiological mechanisms, molecular-based microbial analyses, and environmental performance indicators, while also providing evidence-based insights to support future research development, targeted research investment, and capacity building aligned with global sustainability and climate agendas.

*Keywords: science mapping, scopus database, enteric methane mitigation, bibliometric analysis, ruminant nutritionn*

## INTRODUCTION

The ruminant digestive system relies heavily on the metabolic activity of rumen microbiota to degrade fibrous feed components and convert them into energy-yielding metabolites. Rumen microorganisms play a central role in fermentation processes, microbial protein synthesis, and the production of volatile fatty acids, which constitute the primary energy

source for ruminant animals (Atasoy et al., 2019; Gomaa & Gado, 2021). Consequently, the composition and functional balance of the rumen microbial community critically influence nutrient utilization efficiency, animal productivity, and environmental outcomes, particularly enteric methane emissions (Ingle et al., 2017; Lee et al., 2019).

Fermented feeds have emerged as a strategic nutritional intervention to modulate rumen microbiota and enhance fermentation efficiency. Through microbial pre-digestion and the enrichment of bioactive compounds, fermented feeds can improve fiber degradability, stabilize rumen pH, and promote beneficial microbial populations (Krehbiel et al., 2003; Chaucheyras-Durand & Ossa, 2014). In parallel with increasing demands for sustainable and environmentally friendly livestock production systems, global research on fermented feeds has expanded rapidly, encompassing diverse feed resources, fermentation technologies, microbial inoculants, and functional outcomes related to productivity and methane mitigation (Makkar, 2018). However, the rapid growth and fragmentation of scientific publications in this field have made it increasingly difficult to obtain a coherent and objective overview using conventional narrative reviews. A bibliometric approach is therefore necessary to systematically map the structure and evolution of the literature, identify leading countries, institutions, and authors, reveal collaboration patterns, and detect dominant as well as emerging research themes in fermented feed and rumen microbiota research.

Although numerous narrative and systematic reviews have summarized experimental findings on fermented feeds and rumen fermentation, most existing reviews focus on specific feed types, fermentation methods, or physiological outcomes. As a result, they provide limited insight into global publication patterns, long-term thematic evolution, and international collaboration structures. Importantly, a holistic global mapping of research trends and knowledge structures in fermented feed–rumen microbiota research is still lacking.Bibliometric analysis offers a quantitative framework to systematically map the development of scientific fields by analyzing publication outputs, citation patterns, collaboration networks, and thematic evolution (Aria & Cuccurullo, 2017; Donthu et al., 2021). Unlike traditional reviews, bibliometric approaches enable the identification of influential research hubs, emerging research frontiers, and structural gaps at a global scale. To date, no bibliometric study has comprehensively examined the global evolution of research on fermented feeds in relation to rumen microbiota by integrating publication trends, collaboration networks, and thematic evolution analyses.

Bibliometric analysis is a quantitative approach widely used to evaluate and map the development of scientific fields based on publication and citation data (Aria & Cuccurullo, 2017; Donthu et al., 2021). By enabling the identification of global research trends, influential journals and authors, collaborative institutions, and the temporal evolution of research topics, this method provides a comprehensive perspective on the structural and intellectual dynamics of a research field. In the context of ruminant nutrition, bibliometric analysis offers strategic insights into the evolution of research on fermented feeds and their role in modulating rumen microbiota, particularly with respect to feed efficiency, methane mitigation, and the sustainability of livestock production systems (Mulianda et al., 2015).

Therefore, the present study aims to analyze global research trends concerning the role of fermented feeds in modulating rumen microbiota using a bibliometric approach. Specifically, this study examines publication and citation trends, leading journals, countries, institutions, and authors, as well as collaboration networks and keyword co-occurrence patterns. The results are intended to support the

identification of well-established and underexplored research directions, thereby providing a structured reference for future studies and innovation in ruminant feed strategies, rather than evaluating biological efficacy directly.

Accordingly, this study aims to systematically analyze global research trends concerning the role of fermented feeds in modulating rumen microbiota using a bibliometric approach. The findings are expected to clarify the structural and thematic development of this research domain, identify existing knowledge gaps, and provide a scientific foundation for future research directions and innovation in fermented feed-based strategies for sustainable ruminant production.

## MATERIALS AND METHODS

### Ethical Approval

As this study relied exclusively on previously published literature indexed in the Scopus database and did not involve human or animal participants, ethical approval was not required.

### Study Period and Location

This bibliometric study analyzed peer-reviewed journal articles retrieved from the Scopus database, covering the period from 1961 to 2024.

### Search Strategy and Data Sources

Scopus was selected as the data source due to its broad interdisciplinary coverage, comprehensive citation indexing, and suitability for bibliometric and network analyses. Compared with Web of Science and PubMed, Scopus provides wider coverage of journals in applied animal science and greater representation of publications from emerging research regions. The search strategy was developed through an iterative refinement process, in which Boolean operators and keyword combinations were tested to ensure comprehensive yet specific retrieval of relevant literature. Keywords were chosen based on domain logic in ruminant nutrition and microbiology, encompassing terms related to fermented feeds (e.g., 'fermented feed', 'silage', 'ensiled feed') and rumen microbial processes (e.g., 'rumen microbiota', 'rumen fermentation', 'microbial community'). The final search was conducted on 15 June 2024, and all eligible peer-reviewed journal articles published up to this date were included for analysis. Which was designed to capture studies related to ruminant feed preservation and digestive processes.

The analysis followed a systematic multi-stage protocol consisting of: (i) development of search terms, (ii) application of inclusion and exclusion criteria, (iii) document screening, (iv) data cleaning, and (v) data analysis. The overall research workflow is illustrated in Figure 1 (Prihambodo et al., 2025).

### Inclusion and Exclusion Criteria

Only peer-reviewed original research articles published in English and explicitly addressing the role of fermented feeds in modulating rumen microbiota were included in the analysis. Review articles were excluded to avoid redundancy and potential distortion of citation-based indicators, as reviews synthesize existing literature rather than presenting primary research findings. Conference proceedings and other non–peer-reviewed publications were also excluded to ensure data consistency and analytical robustness. Studies not directly focused on fermented feeds and rumen microbiota were removed during the screening process. The initial search yielded 735 records, of which 620 articles met the inclusion criteria and were retained for subsequent bibliometric analysis.

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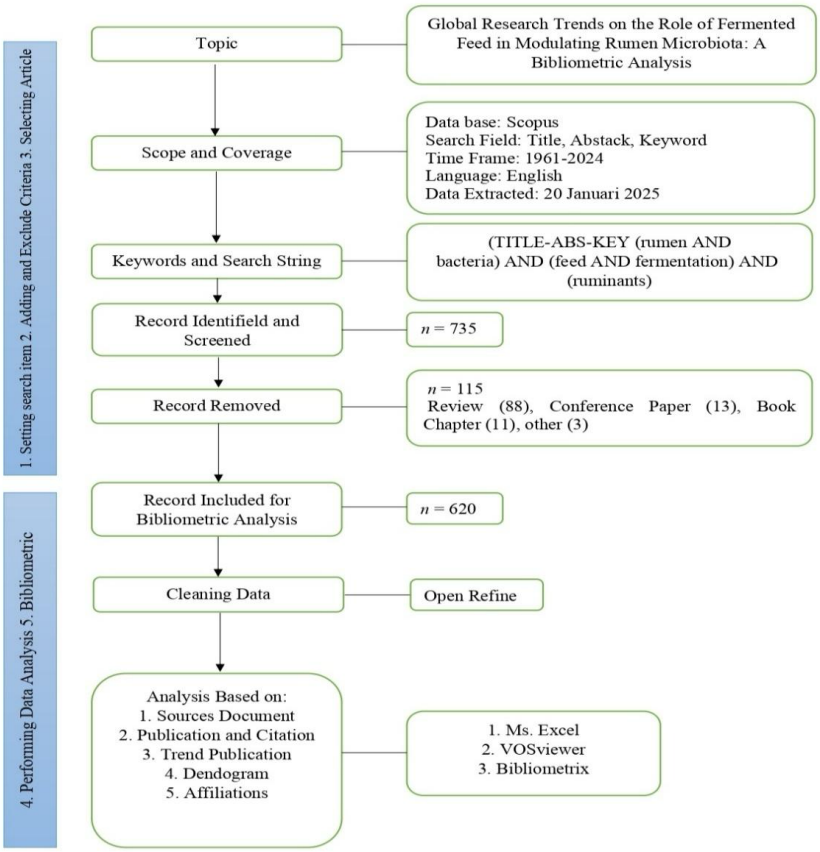


Figure 1. Research flow diagram

**Data Extraction and Pre-processing**

Scopus metadata including authors, titles, publication years, affiliations, keywords, funding sources, countries of origin, and citation counts were extracted on 22 February 2025 and exported in CSV format. Data pre-processing was conducted using OpenRefine software and involved three main steps: (i) removal of duplicate records, (ii) standardization of author and institutional names, and (iii) normalization of keywords to ensure dataset consistency (Mulianda et al., 2025; Donthu et al., 2021).

**Bibliometric and Network Analysis**

A comprehensive bibliometric analysis was conducted using VOSviewer (version 1.6.20), the Bibliometrix R package (version 4.2.2), and Microsoft Excel. Publication productivity, citation performance, keyword co-occurrence networks, co-authorship patterns, institutional collaborations, and inter-country research linkages were systematically examined. In this study, themes were defined as coherent groups of frequently co-occurring keywords representing dominant research topics, while clusters referred to sets of related keywords identified through network-based clustering algorithms. Centrality was used as an indicator of the relative importance of keywords or clusters within the network, reflecting their degree of connectivity to other research topics. To enhance analytical robustness and reduce noise, only keywords with a minimum occurrence frequency of five were included in the co-occurrence analysis, and network

normalization was performed using the association strength method.

VOSviewer was employed for network visualization and clustering analyses due to its strength in graphical representation, whereas the Bibliometrix R package was used for quantitative performance indicators and thematic evolution analysis. Microsoft Excel was utilized for data cleaning, descriptive statistics, and result summarization. The resulting analyses provide a structured overview of thematic development, key contributors, citation patterns, and the temporal evolution of research on fermented feeds and rumen microbiota.

## RESULT AND DISCUSSION

### Temporal Trends of Publications and Citations

The following sections provide an integrated interpretation of bibliometric findings across temporal trends, citation structures, collaboration patterns, and thematic evolution to elucidate the development of research on fermented feeds and rumen microbiota.

Data The temporal trends in publications and citations (Figure 2) indicate that research on fermented feeds and rumen microbiota has evolved through several distinct phases. During the early period, spanning the 1960s to the late 1970s, the volume of publications remained relatively limited, while the average citation impact was notably high. This pattern reflects the predominance of foundational studies that established the theoretical and experimental basis for understanding rumen fermentation, microbe–substrate interactions, and the role of feed in regulating rumen microbial activity. Research output during this phase primarily addressed core concepts in rumen microbial ecology and fermentation biochemistry, which continue to serve as seminal references underpinning the development of modern fermented feed technologies (Atasoy et al., 2019).

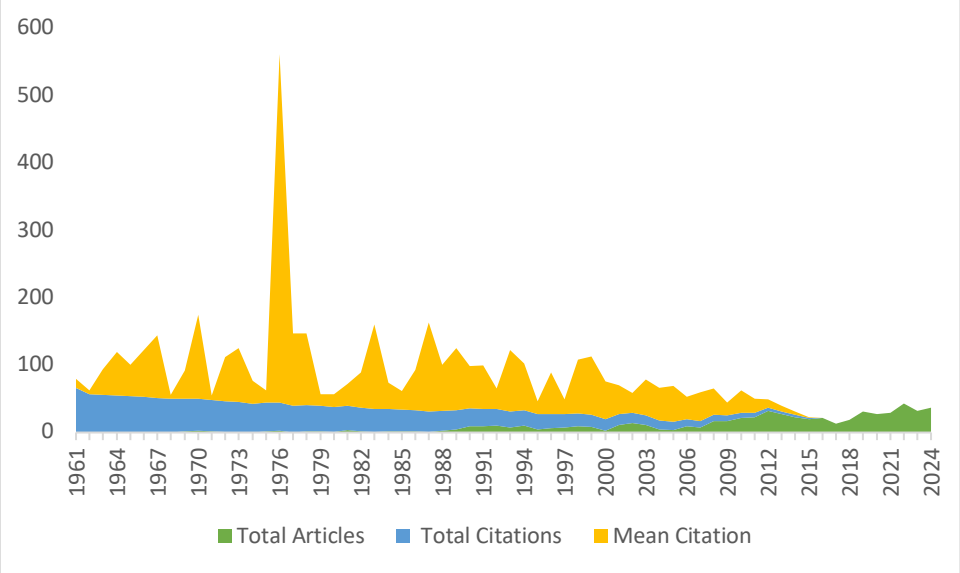


Figure 2. Temporal trends in annual publications and citations related to fermented feeds and rumen microbiota (1961–2024).

From the 1980s to the early 2000s, a more stable increase in publication output was observed, accompanied by a gradual decline in average citation rates. This phase reflects a shift in research emphasis from predominantly conceptual studies toward more application-oriented approaches, particularly the development of ensiling technologies, the use of microbial inoculants, and the exploitation of fibrous feed resources and agro-industrial by-

products as fermentation substrates. The decline in average citation counts does not indicate a reduction in research quality; rather, it reflects thematic diversification and the growing number of publications addressing increasingly specialized topics. Within the context of rumen microbiota, this period was also marked by enhanced understanding of the roles of cellulolytic and amylolytic bacteria in improving the efficiency of fermented feed utilization (Koh et al., 2016; Kung et al., 2018).

In the period from 2010 to 2024, publication output exhibited a consistent upward trend, although average citation values remained relatively lower. This pattern suggests that research on fermented feeds and rumen microbiota has entered a mature phase, characterized by an expanded focus on sustainability, production efficiency, and methane emission mitigation. The lower average citation rates observed in more recent publications are largely attributable to citation lag, as newly published articles require time to accumulate scholarly recognition through citations. In addition, advances in molecular analytical techniques, such as 16S rRNA gene sequencing and metagenomic approaches, have facilitated the emergence of numerous exploratory and context-specific studies, further contributing to the observed publication growth (Gomaa & Gado, 2021; Yang et al., 2021).

Citation distribution by country (Table 1) shows that Canada and the United States lead in publication output, while several European countries, including the United Kingdom, France, Germany, and the Netherlands, exhibit strong citation impact and international visibility. These countries have made substantial contributions to the conceptual and technological development of fermented feeds, particularly in studies addressing rumen microbiota modulation, microbe–substrate interactions, and their implications for animal performance and greenhouse gas emissions. Notably, the high average citation rates per article observed in countries such as the Netherlands and the United Kingdom indicate that research originating from these regions tends to be strategically oriented and high-impact, frequently serving as key references for subsequent studies (Wang et al., 2024; Waltman, 2016).

Table 1. Top 10 most citation countries

| Country | TC | Average Article Citations (%) |
|---|---|---|
| Canada | 2518 | 89.9 |
| USA | 2502 | 45.5 |
| Spain | 1927 | 55.1 |
| China | 1717 | 19.1 |
| France | 1058 | 81.4 |
| United Kingdom | 780 | 97.5 |
| Germany | 504 | 25.2 |
| Ireland | 478 | 68.3 |
| Thailand | 461 | 20 |
| Netherlands | 354 | 118 |

Tables In contrast, the contribution of developing countries, including Indonesia, remains relatively limited within the global citation landscape. This pattern highlights a substantial research gap between the availability of local resources and their scientific visibility at the international level. Indonesia possesses a strong comparative advantage in the abundance of fibrous feed resources and agro-industrial by-products such as rice straw, oil palm residues,

and other crop residues which hold considerable potential for development as fermented feeds. However, much of the existing domestic research has predominantly focused on digestibility assessments and animal performance metrics, with relatively limited in-depth investigation into changes in rumen microbiota structure and function using molecular-based approaches.

This gap presents a strategic opportunity for advancing research in Indonesia, particularly through the integration of fermentation technologies utilizing local feed resources with rumen microbiota analysis based on omics methodologies (Abbasi et al., 2018). Such an approach has the potential not only to enhance the quality and efficiency of ruminant feeds but also to generate scientific contributions that are more impactful and globally relevant. Furthermore, strengthening international collaborations with institutions from countries exhibiting high citation impact may represent a critical strategy for improving methodological rigor, increasing publication visibility, and enhancing the global competitiveness of Indonesian research on fermented feeds internasional.

Although different bibliometric techniques were applied across analyses, all methods were based on the same dataset and selection criteria, ensuring methodological consistency while allowing complementary perspectives on the research landscape.

**Concentration and Implications for Fermented Feed Rumen Microbiota Research**

An integrated analysis of the most relevant sources (Figure 3), local impact metrics (Table 2), and Bradford's Law (Figure 4) indicates that the global knowledge structure in fermented feed and rumen microbiota research is highly centralized and hierarchical. A small number of journals, most notably the Journal of Dairy Science and the Journal of Animal Science not only dominate publication output but also concentrate a substantial proportion of scientific influence, as reflected by their superior h-index, g-index, and m-index values. This dual dominance underscores that the conceptual frameworks, experimental standards, and interpretative narratives surrounding fermented feed–rumen microbiota interactions are largely shaped within a narrow epistemic core.

Furthermore, the application of Bradford's Law confirms that these journals constitute the core zone of knowledge production, whereas the majority of other journals occupy peripheral zones characterized by fragmented contributions and relatively limited cumulative impact. This concentration suggests that advances in fermented feed research are not evenly distributed across publication outlets but are instead filtered through journals that have historically maintained a strong focus on ruminant nutrition, rumen fermentation kinetics, and host microbe interactions (Wang et al., 2024). As a consequence, research published outside this core including studies emphasizing region-specific feed resources or applied fermentation technologies faces structural barriers to achieving comparable scientific visibility, regardless of its local relevance or practical significance.

From a thematic perspective, the dominance of journals rooted in animal nutrition and production sciences indicates that fermented feed research is predominantly framed around performance optimization, improvements in nutrient digestibility, and enhanced rumen fermentation efficiency. Although rumen microbiota analyses are increasingly incorporated into these studies, they often function primarily as mechanistic validation tools rather than as central research foci (Henderson et al., 2015; Gomaa & Gado, 2021). While this trend reflects notable methodological progress, it also reveals an implicit bias toward intensive production systems in temperate regions. Such a bias may marginalize research contexts in tropical regions, where fermented feeds are more commonly

employed to enhance the nutritional value of low-quality fibrous biomass.

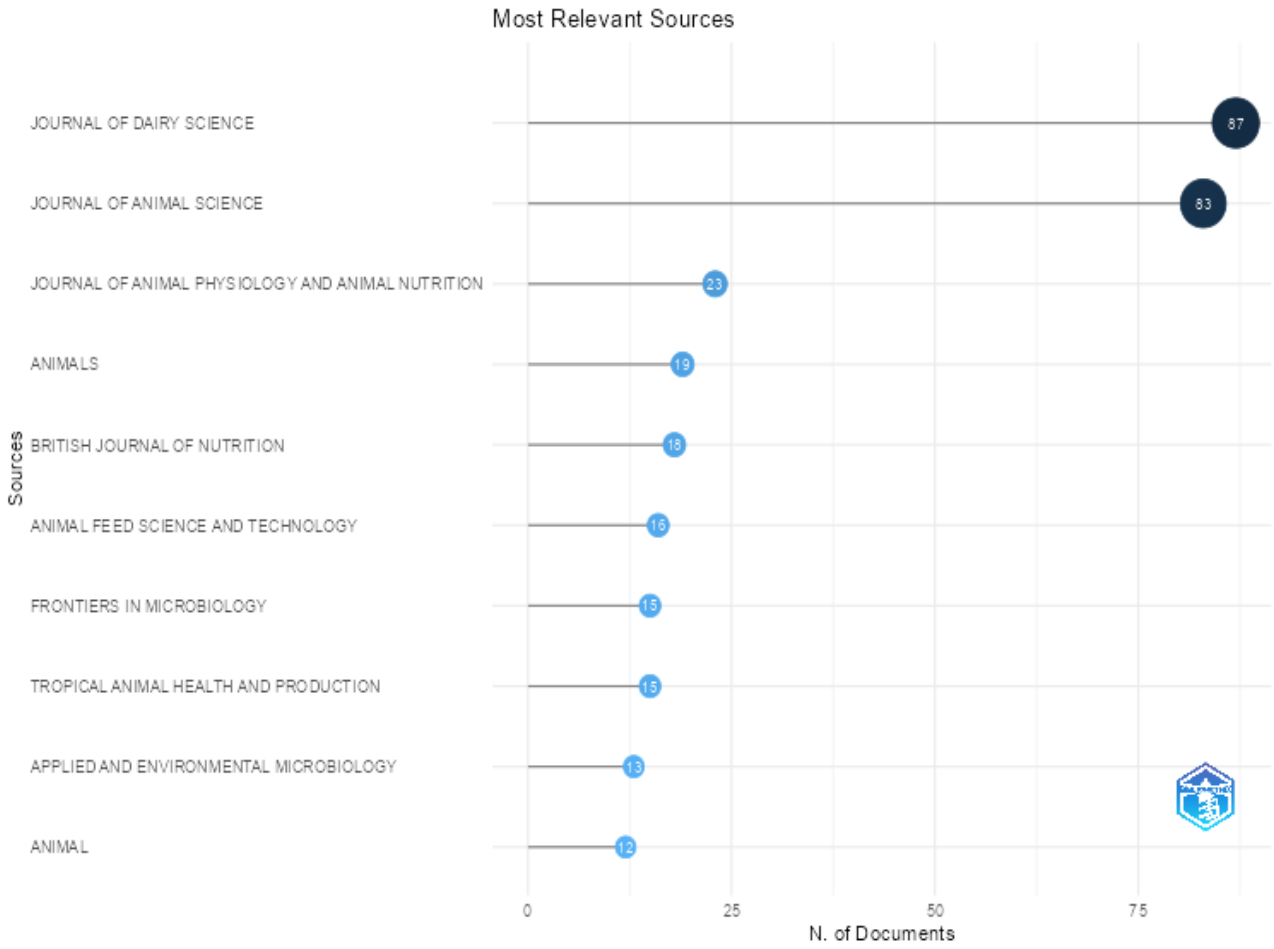


Figure 3. Most relevant sources

Table 2. Top 10 sources local impact

| Source | h_index | g_index | m_index | TC |
|---|---|---|---|---|
| Journal of dairy science | 44 | 79 | 0.862 | 6278 |
| Journal of animal science | 39 | 62 | 0.735 | 4163 |
| British journal of nutrition | 15 | 18 | 0.2678 | 1463 |
| Animal feed science and technology | 13 | 16 | 0.4482 | 1677 |
| Applied and environmental microbiology | 13 | 13 | 0.2765 | 1463 |
| Journal of animal physiology and animal nutrition | 11 | 17 | 0.5 | 321 |
| Frontiers in microbiology | 10 | 15 | 0.909 | 504 |
| Tropical animal health and production | 10 | 15 | 0.666 | 251 |
| Animal | 9 | 12 | 0.6 | 364 |
| Journal of the science of food and agriculture | 9 | 9 | 0.5625 | 281 |

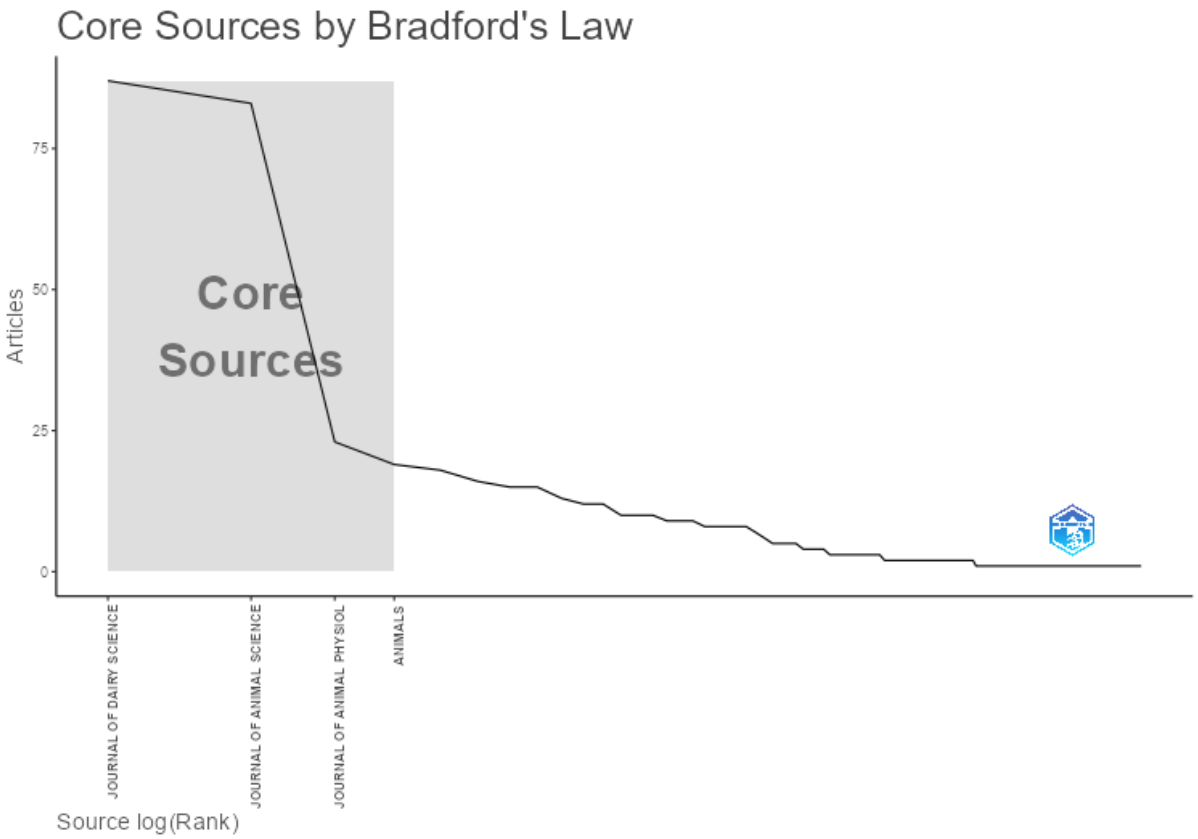


Figure 4. Bradford law's

These structural patterns have direct implications for Indonesia and other developing countries. Despite Indonesia's abundant availability of lignocellulosic biomass and its long-standing tradition of fermented feed practices, its scientific contributions remain marginal within the identified core journals. Much of the existing research continues to focus on proximate analysis, in vitro digestibility, or basic fermentation parameters, with limited integration of molecular-based rumen microbiota analyses or systemic interpretations aligned with contemporary global research directions (Makkar, 2018; Jiang et al., 2024). As a result, feed innovations derived from local resources risk receiving insufficient recognition in the international literature, thereby reinforcing existing knowledge asymmetries between developed and developing countries.

From a practical perspective, the Bradford's Law distribution offers clear publication strategy implications, particularly for authors from developing countries seeking to publish in international journals. Targeting core journals identified in the Bradford zone can substantially increase research visibility, citation potential, and integration into global research fronts. Moreover, international collaboration frequently observed among publications in core journals can help authors overcome structural barriers such as limited institutional visibility and resource constraints. Therefore, rather than prioritizing publication quantity in peripheral journals, researchers from developing countries may benefit from focusing on collaborative, high quality submissions to core and middle zone journals.

**Author Collaboration Patterns and Distribution of Affiliated Countries**

Based on the collaboration patterns illustrated by the Sankey diagram (Figure 5) and the distribution of Single Country Publications (SCP) and Multiple Country Publications (MCP) (Figure 6), the findings suggest evidence-based

implications for research internationalization strategies at institutional and governmental levels. The higher prevalence of Multiple Country Publications among countries such as China, the United States, and Spain is associated with greater research productivity and scientific visibility. However, given the bibliometric nature of this study, these relationships should be interpreted as correlational rather than causal. From an analytical perspective, the results indicate that international collaboration may represent a relevant mechanism for enhancing integration within the global knowledge network, as also noted in previous studies (Wagner et al., 2015; Nascimento et al., 2025).

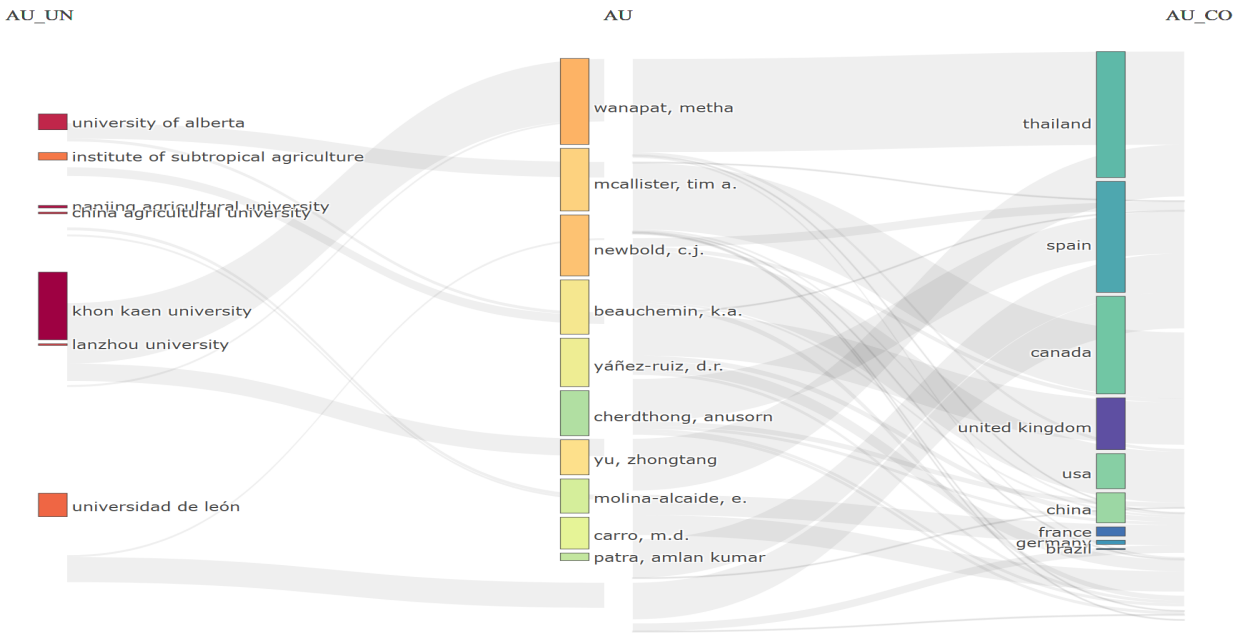


Figure 5. Diagram sankey

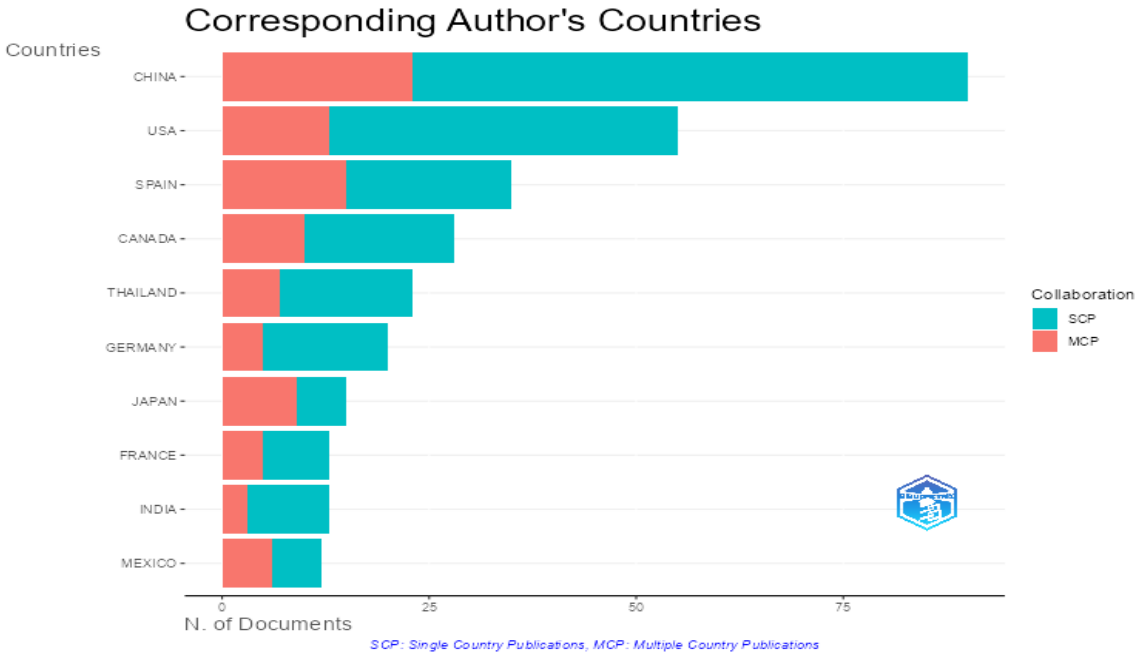


Figure 6. Corresponding author's countries

Moreover, the active involvement of institutions from developing countries, such as Thailand and India, within international collaboration networks underscores the strategic role of affirmative policies targeting non-elite institutions in promoting a more equitable distribution of research capacity. Support for capacity-building initiatives, enhancement of early-career researcher competencies, and the provision of incentives for collaboration with internationally reputable partners can accelerate the integration of these institutions into the global research ecosystem. This perspective aligns with the view that international collaboration functions as a critical mechanism for knowledge transfer and research quality enhancement in developing countries (Dai et al., 2021).

Furthermore, the role of certain countries as hubs for corresponding author affiliations highlights the importance of scientific leadership within research collaborations. Institutional policies that encourage researchers to assume corresponding author roles through career incentives, performance recognition, and administrative support can enhance an institution's bargaining position within global collaborative networks. Accordingly, research policies should not focus solely on publication volume but also emphasize the strategic positioning of researchers within international collaboration structures, which ultimately influences national scientific reputation and competitiveness (Aria & Cuccurullo, 2017).

**Productivity Institutional Productivity and Author Publication Dynamics**

The visualization of the most relevant affiliations (Figure 7) illustrates the distribution of institutions based on publication output, thereby highlighting the principal centers of research productivity within the analyzed corpus. Khon Kaen University emerges as the most prolific institution, followed by Nanjing Agricultural University and the University of Alberta. The prominence of these institutions suggests a concentration of research capacity within specific universities, particularly in Asia and North America. The presence of multiple agricultural universities from China and Thailand further indicates that this research domain is closely linked to applied agricultural science and livestock production.

Such institutional concentration is commonly associated with the continuity of established research groups, where sustained leadership and mentorship by senior researchers facilitate long-term scientific output through the training of graduate students and early-career scientists. In addition, higher institutional productivity appears to be associated with the availability of research funding and infrastructure, including specialized laboratories, experimental facilities, and access to international collaboration networks. Although funding levels were not directly assessed in this bibliometric analysis, the observed patterns suggest that institutional support and resource availability may play an important role in shaping research productivity, as also noted in previous studies (Dai et al., 2021; Chang-qing et al., 2019).

Meanwhile, the Authors' Production over Time visualization (Figure 8) illustrates the temporal dynamics of author productivity, capturing both publication output and annual citation impact (total citations per year). Several authors, including Wanapat, Metha, and Yu, Zhongtang, exhibit relatively consistent and, at times, increasing productivity, as reflected by larger and more intense bubble sizes. This pattern indicates sustained research agendas and positions these authors as key contributors within the field. In contrast, other authors display more sporadic publication trajectories, which may be associated with temporary collaborations or involvement in specific research projects. Temporal analyses of this nature are instrumental in identifying influential authors, delineating growth phases within a

research field, and tracking shifts in research focus over time (Aria & Cuccurullo, 2017).

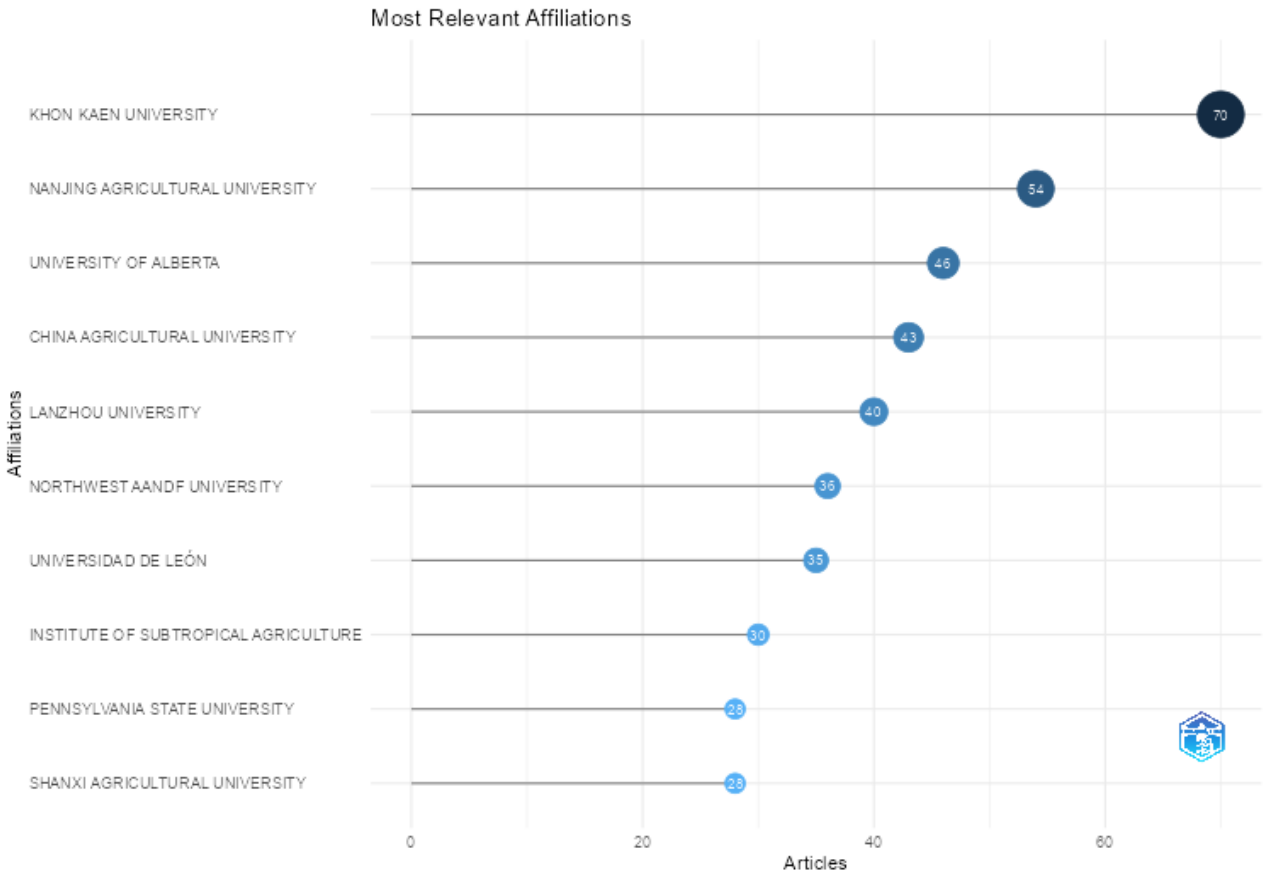


Figure 7. Most relevant affiliations

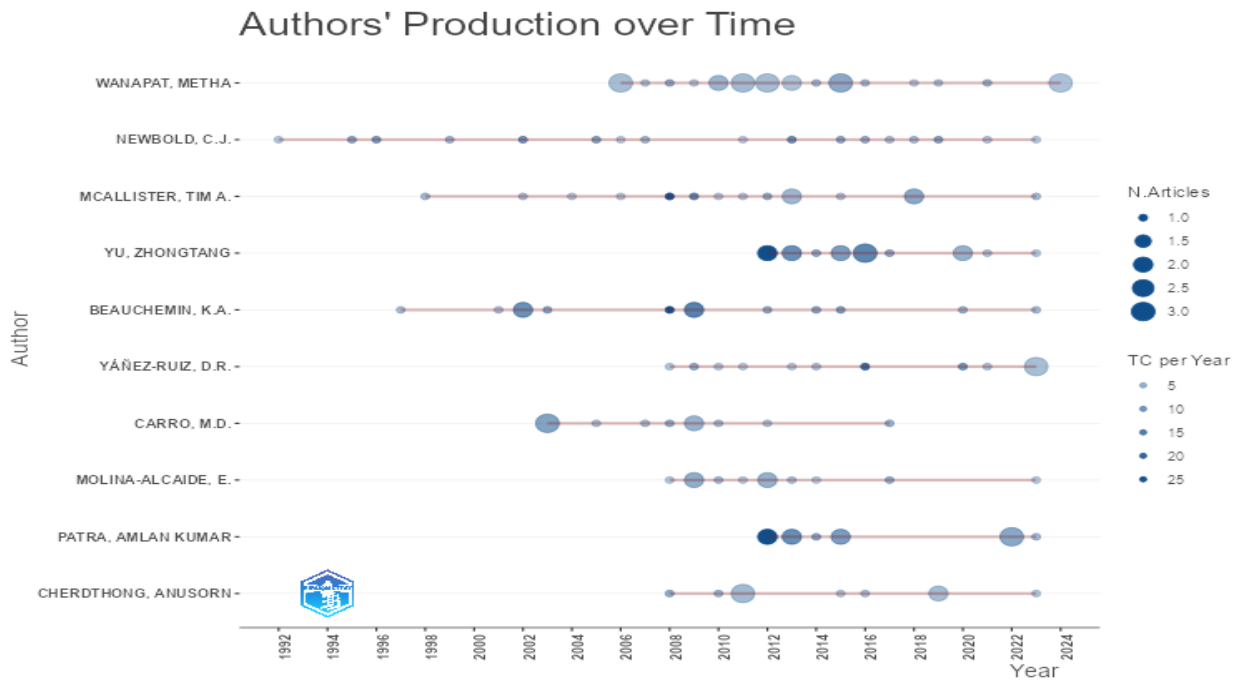


Figure 8. Authors' production over time

When these two visualizations are considered jointly, a strong association emerges between author productivity and institutional strength (Salami et al., 2019; Zheng et al., 2024). Authors with long-standing and high-impact publication records are typically affiliated with institutions that also exhibit high research productivity. This finding carries important implications for research future research, suggesting that institutional investments in the development of research groups, researcher career support, and sustained funding continuity play a critical role in ensuring the stability and impact of scientific publications. Moreover, policies that promote researcher regeneration and cross-generational collaboration are essential for maintaining long-term research productivity and continuity (Wagner et al., 2015; Chen et al., 2024).

**Keyword Mapping and Trend Topics**

The keyword co-occurrence map generated using VOSviewer (Figure 9) indicates that rumen fermentation research is strongly centered on the interconnections between fermentation processes, microbial dynamics, and methane production. Keywords such as rumen fermentation and methane occupy central positions within the network, highlighting fermentation efficiency and methane mitigation as closely linked research themes. Microbiological clusters, including rumen microbiota, methanogens, methanogenesis, and microbial diversity, further emphasize the role of microbial ecology in shaping fermentation outcomes. Consequently, the identified research cluster highlights a strong emphasis on biologically driven approaches, particularly the use of probiotics and methanogen inhibitors, as key areas of scientific attention in efforts to mitigate enteric methane emissions (Lee et al., 2019; Zhu et al., 2021).

Despite this strong internal connectivity, methane-related research appears to be only partially integrated with other major thematic domains of buffalo research, such as reproduction, genetics, and milk production. This partial conceptual separation may reflect the interdisciplinary nature of methane studies, which are often framed within environmental science, climate change mitigation, and feed efficiency research rather than traditional buffalo production biology. Consequently, methane-focused studies are frequently conducted by distinct research communities and published in different journal outlets, resulting in weaker conceptual linkages with the core production-oriented clusters observed in the broader keyword network.

In addition, the nutrition and feed additive cluster encompassing grass silage, starch, urea, fatty acids, as well as additives such as monensin, saponins, and fumarate highlights feed-based interventions as the most practical and future research-relevant strategies for methane mitigation. The dense interconnections among clusters indicate that effective methane mitigation requires the integration of fundamental research, innovations in animal nutrition, and coherent environmental regulatory frameworks. Accordingly, methane mitigation policies should be designed in a cross-sectoral manner to promote the adoption of low-emission feed technologies and sustainable livestock management practices aligned with global climate change agendas (Aguzey et al., 2020; Wang et al., 2024).

Trend topic analysis (Figure 10) further reveals a marked shift in research focus within ruminant nutrition and microbiology over the past two decades. During the early phase (late 1990s to early 2000s), research was dominated by descriptive approaches centered on fundamental rumen fermentation processes, digestion, and general microbial characterization, with recurring keywords such as rumen, fermentation, digestion, and bacteria. As the field advanced, the subsequent phase (approximately 2005–2013) was characterized by increasing attention to metabolic processes, volatile fatty acids (VFAs), animal physiological

responses, and the effects of diet on performance and nutrient efficiency, reflecting a more integrated experimental and nutritional–physiological research paradigm (Owens & Basalan, 2016).

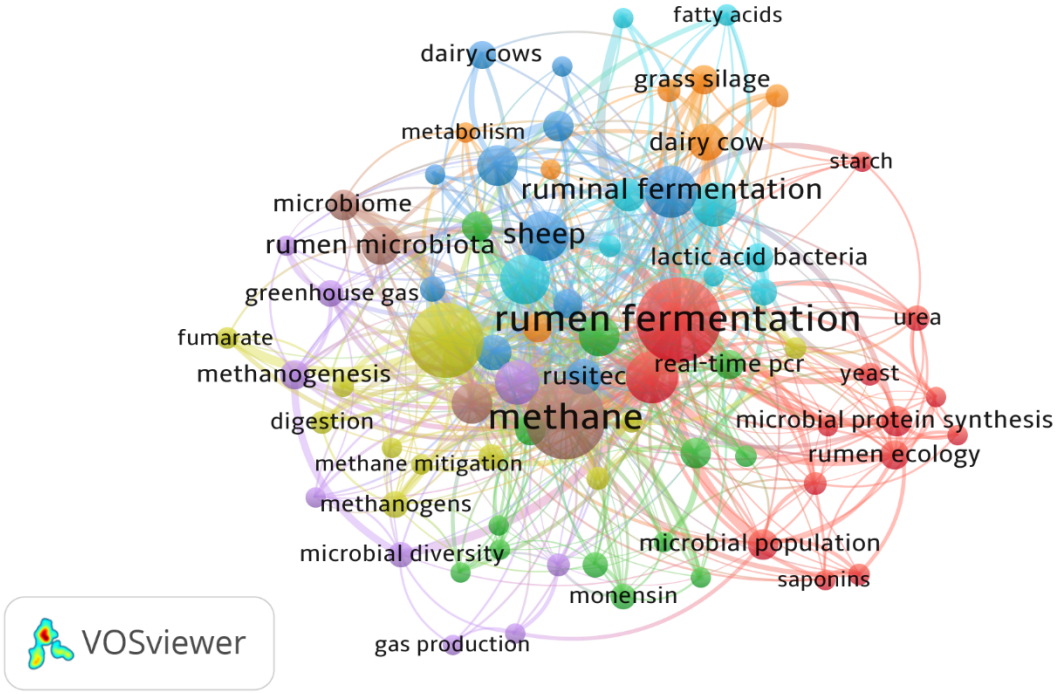


Figure 9. Co occurrence author keywords

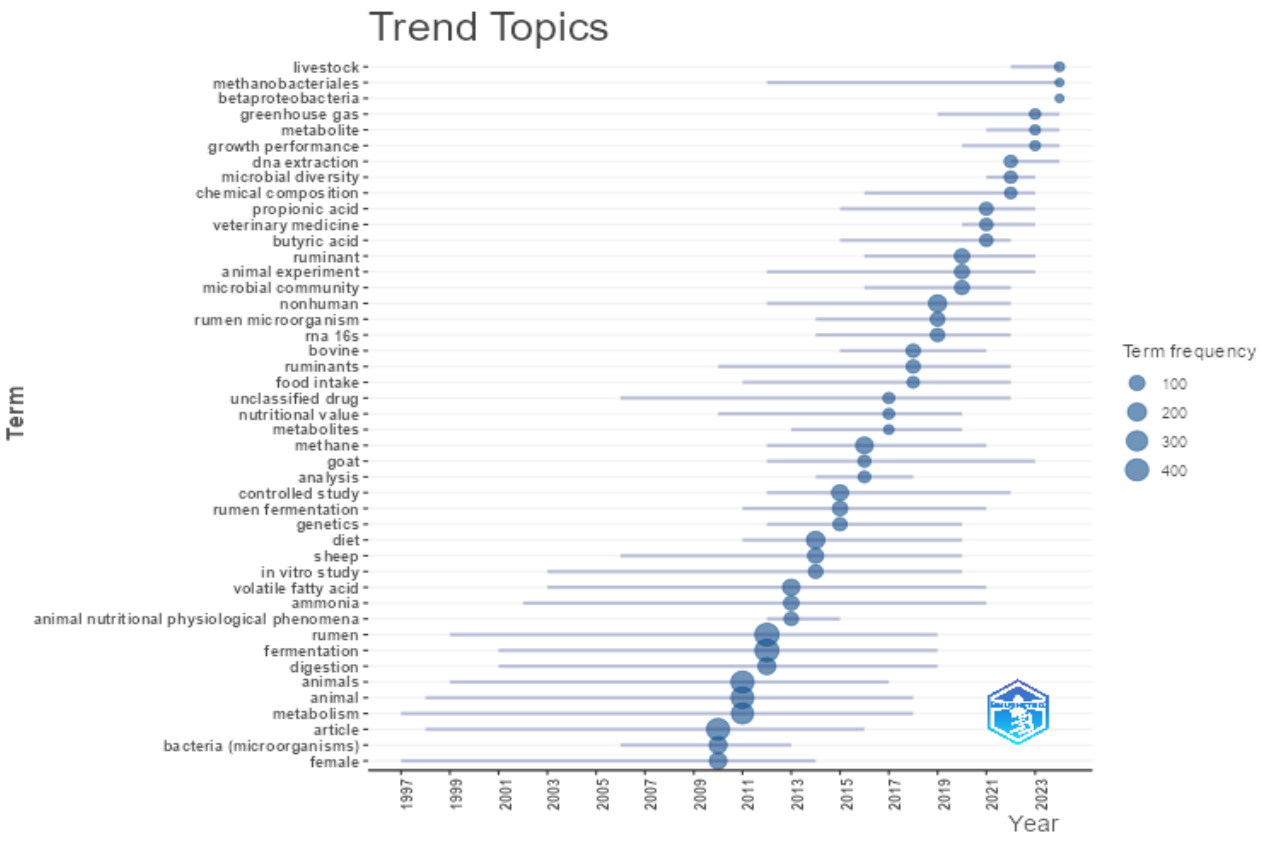


Figure 10. Trend topic analysis

Over the past decade, research trends have undergone a paradigmatic shift toward molecular and microbial ecology–based approaches, as evidenced by the increasing prominence of terms such as microbial community, microbial diversity, 16S rRNA, and DNA extraction. This transition reflects the widespread adoption of next-generation sequencing technologies, which have enabled a more comprehensive understanding of rumen microbial community dynamics and their interactions with host metabolism (Jiang et al., 2024; Ong et al., 2024). In the most recent period (approximately 2018–2023), research focus has increasingly converged on global sustainability issues (Röös et al., 2017; Mulianda et al., 2018), particularly enteric methane and greenhouse gas emissions, as indicated by the rising frequency of keywords such as methane, greenhouse gas, and specific methanogenic groups. This trend underscores growing interest in methane mitigation strategies based on rumen microbiota manipulation and nutritional interventions aimed at enhancing livestock production efficiency while reducing environmental impacts (Beauchemin et al., 2020; Lee et al., 2019).

**Thematic Clustering Based on Document Coupling**

An integrated bibliometric analysis combining document coupling, conceptual structure mapping, and MCA-based dimensional analysis shows a clear and consistent development of research on fermented feeds for rumen microbiota modulation. Across all mapping approaches, rumen fermentation, methane mitigation, and rumen microbial processes emerge as the dominant and most influential research themes. The strong connections among methane-related studies indicate that recent research increasingly links fermented feed strategies with global environmental challenges, particularly enteric methane reduction. At the same time, this trend reflects a growing integration of nutritional interventions with microbial ecology perspectives in rumen research (Lee et al., 2019; Beauchemin et al., 2020).

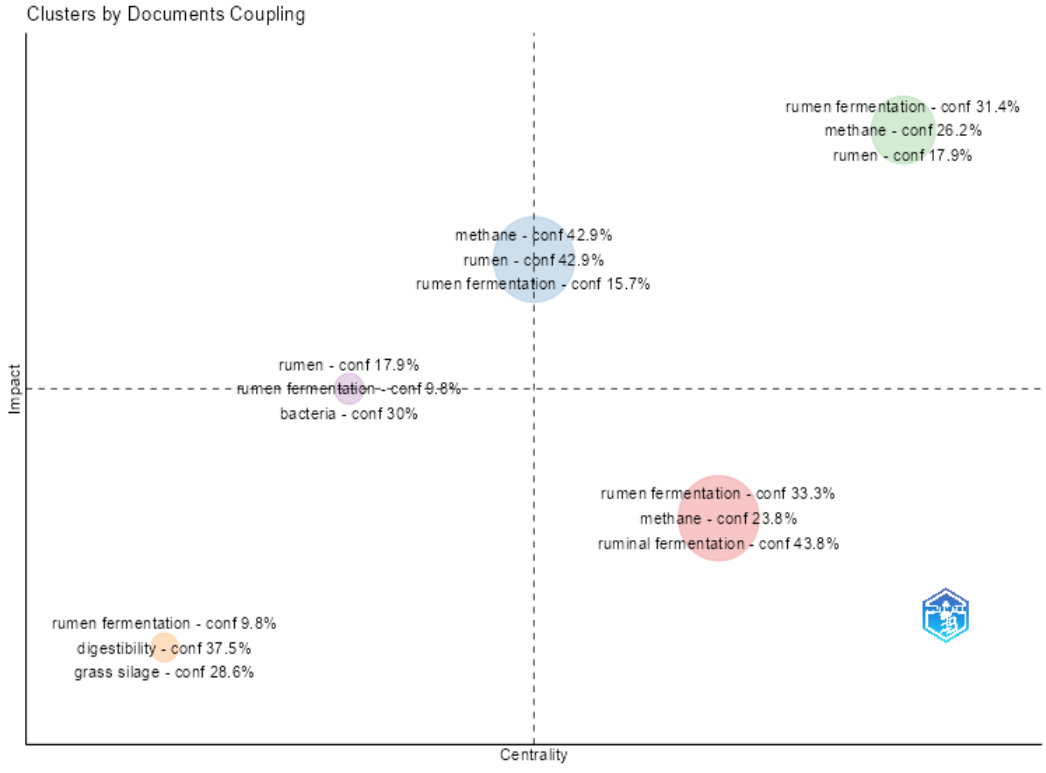


Figure 11. Cluster by documents coupling

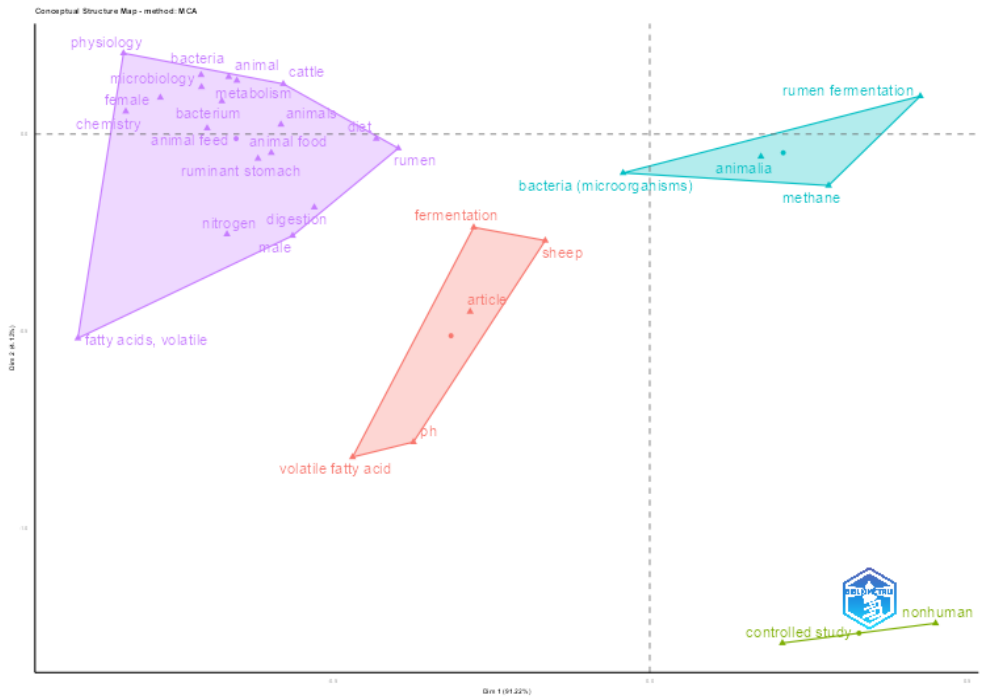


Figure 12. Conceptual structure map

The subsequent conceptual structure map further elucidates the thematic organization of this field by distinguishing foundational concepts in rumen physiology and microbiology from research streams oriented toward environmental outcomes. Core terms related to rumen physiology, microbiology, metabolism, and volatile fatty acids form a stable foundational cluster, underscoring their role as the scientific bedrock for understanding fermentation processes and host–microbe interactions. In contrast, a distinct cluster centered on methane and rumen fermentation emerges as a specialized and high-impact research frontier, suggesting that methane mitigation remains relatively segregated from broader nutritional and physiological frameworks (Zhu et al., 2022).

Table 3. Trend analysis of research on fermented feeds in modulating rumen microbiota

| Word | Dim1 | Dim2 | word | Dim1 | Dim2 |
|---|---|---|---|---|---|
| Rumen | -0.4 | -0.04 | digestion | -0.53 | -0.19 |
| Fermentation | -0.28 | -0.24 | Bacteria (microorganisms) | -0.04 | -0.1 |
| Animals | -0.58 | 0.02 | Physiology | -0.83 | 0.21 |
| Article | -0.28 | -0.45 | Methane | 0.28 | -0.13 |
| Animal | -0.66 | 0.15 | Female | -0.77 | 0.09 |
| Metabolism | -0.65 | 0.14 | Volatile fatty acid | -0.47 | -0.82 |
| Animal food | -0.6 | -0.05 | Controlled study | 0.21 | -1.29 |
| Animal feed | -0.7 | 0.01 | Chemistry | -0.83 | 0.06 |
| Ruminant stomach | -0.62 | -0.06 | pH | -0.37 | -0.78 |
| Microbiology | -0.71 | 0.12 | Sheep | -0.16 | -0.27 |
| Cattle | -0.58 | 0.13 | Male | -0.56 | -0.26 |
| Bacteria | -0.71 | 0.15 | Fatty acids, volatile | -0.9 | -0.52 |
| Bacterium | -0.67 | 0.08 | Nitrogen | -0.67 | -0.25 |
| Diet | -0.43 | -0.01 | Animalia | 0.18 | -0.06 |
| Nonhuman | 0.45 | -1.24 | Rumen fermentation | 0.43 | 0.1 |

Note: Dm1= Dimension 1; Dm2= Dimension 2

These visual findings are quantitatively reinforced by the MCA-based dimensional analysis presented in Table 3 (Anggraeni et al., 2024; Cao et al., 2024) . Dimension 1 represents a conceptual gradient ranging from classical rumen physiology, microbial metabolism, and volatile fatty acid production toward more application-oriented and environmentally focused research emphasizing methane mitigation and controlled experimental designs (Dai et al., 2022; Harahap et al., 2018). Dimension 2, in contrast, differentiates in vivo physiological studies from controlled experimental approaches, reflecting methodological diversification within the field (Vargas et al., 2024). Collectively, these results indicate a clear paradigm shift from traditional research centered on digestion and feed evaluation toward integrative studies that combine microbiome modulation, fermentation dynamics, and environmental sustainability. The partial conceptual separation between methane-focused research and core physiological themes highlights a critical research gap, underscoring the need for integrative approaches that link fermented feed interventions with rumen function and livestock productivity.

**Limitations**

This study has several limitations that should be acknowledged. First, the analysis is based solely on bibliometric metadata, including titles, abstracts, keywords, citations, and authorship information. Consequently, the findings reflect research patterns, thematic structures, and collaboration dynamics rather than the biological effectiveness or technological performance of specific fermented feed interventions. Second, as with most bibliometric studies, the results are influenced by database coverage and indexing practices, which may lead to the underrepresentation of non-indexed publications or region-specific studies. Finally, the interpretative nature of bibliometric analysis means that the identified trends and emerging themes indicate directions of scholarly attention, not empirical validation or future research recommendations. These limitations should be considered when interpreting the results, while the study remains valuable for mapping research development and guiding future investigations.

## CONCLUSION

This bibliometric study provides a comprehensive overview of the global development of research on fermented feeds for rumen microbiota modulation, revealing a clear transition from classical physiological and nutritional studies toward more integrative research approaches that link the rumen microbiome, fermentation processes, and environmental sustainability. Rumen fermentation, microbial community dynamics, and methane mitigation have emerged as the core themes shaping contemporary research, reflecting increasing scientific and future research attention to feed efficiency and enteric methane emissions.

The thematic and conceptual structure analyses indicate that, although physiology-based research remains central to the field, methane mitigation has developed into a high-impact research frontier that is still relatively weakly integrated with core rumen physiological frameworks. These patterns highlight the importance of future research efforts that more closely connect fermented feed interventions with rumen function, animal performance, and environmental outcomes.

By systematically mapping research trends, thematic evolution, and collaboration structures, this study contributes to the existing literature by clarifying the intellectual structure and research gaps within fermented feed and rumen microbiota studies. The findings provide strategic insights to guide future research directions, particularly for developing countries such as Indonesia, where strengthened molecular-based approaches and expanded international collaboration offer significant

potential to enhance research impact and global relevance. For developing countries, including Indonesia, there is considerable potential to strengthen research development in this field, particularly through increased research integration and expanded international collaboration.

## CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this article.

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