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Unfolding the Global Biogas Economy: A Bibliometric and Science-Mapping Analysis of Business, Accounting, and Economic Research (1980–2025)

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Abstract

Biogas plays an increasingly important role in renewable energy transitions due to its capacity to integrate waste management, energy production, and circular economy objectives. While a substantial body of literature has examined biogas from technical and engineering perspectives, a systematic understanding of its evolution within business, economic, and accounting research remains limited. This study addresses this gap through a comprehensive bibliometric and science-mapping analysis of 182 peer-reviewed journal articles indexed in Scopus between 1980 and 2025. Using performance indicators and keyword co-occurrence network analysis, the study examines publication trends, leading contributors, geographic distribution, subject area composition, and the thematic development of the biogas economy literature. The results reveal a marked increase in research activity after the mid-2010s, accompanied by a shift in themes from waste management and technical utilization toward circular economy frameworks, market-oriented analyses, rural economic development, and value creation from biogas by-products, such as digestate. Despite this progression, accounting-related perspectives, including long-term cost–benefit assessment, sustainability reporting, ESG-aligned measurement, and investment risk evaluation, remain weakly integrated within the field. By clarifying the intellectual structure and identifying persistent gaps, this study provides an integrative foundation for future interdisciplinary research and offers policy-relevant insights to support more transparent, accountable, and economically viable biogas development strategies for policymakers, practitioners, and investors.

Introduction

Biogas has emerged as a strategically important component of the global renewable energy portfolio due to its multifaceted contributions to the energy transition, the implementation of

the circular economy, and rural development [1], [2], [3]. As a renewable energy carrier generated through the anaerobic processing of organic waste [4], [5], biogas offers dual benefits by simultaneously addressing energy supply challenges and waste management pressures [6]. Within waste-to-energy frameworks, biogas is increasingly recognized as a systemic solution for enhancing energy security [7], reducing environmental externalities [8], [9], and supporting resource efficiency [10].

Beyond its technical function, biogas systems are increasingly characterized by expanding economic and institutional dimensions. The diversification of biogas-related business models, including digestate valorization [11], [12], nutrient recovery [13], and carbon-related mechanisms [14], indicates that biogas is no longer viewed solely as an energy technology. Instead, it is progressively understood as a value-creating system embedded within broader economic, environmental, and governance structures.

In parallel with global sustainability agendas, recent years have witnessed a notable increase in academic attention to the economic and governance aspects of biogas [15], [16]. This trend aligns with broader policy and market-driven demands for low-carbon energy solutions that deliver measurable environmental, social, and economic value. For developing and emerging economies, biogas holds particular relevance as a decentralized energy option capable of strengthening rural livelihoods, improving waste governance, and supporting inclusive growth [17].

Within this context, accounting-based perspectives become increasingly salient. Accounting provides analytical tools necessary to measure, allocate, and communicate value creation beyond conventional energy output. Issues such as waste-based asset recognition, life-cycle costing, sustainability performance measurement, and ESG-related disclosures are central to understanding the full economic implications of biogas deployment. These perspectives are particularly important where environmental and social benefits are expected to inform investment decisions, policy evaluation, and accountability mechanisms.

Despite the growing prominence of biogas within sustainability-oriented research, existing literature addressing its economic, business, and accounting dimensions remains fragmented. A substantial proportion of biogas-related studies continue to prioritize technical efficiency, process optimization, and engineering performance, while offering limited integration with economic valuation frameworks or accounting-based assessment. As a result, critical questions related to long-term economic performance, environmental benefit valuation, risk exposure, and accountability mechanisms remain insufficiently explored. Moreover, the absence of a structured synthesis that connects biogas research with ESG reporting, sustainability assurance, and governance mechanisms limits decision-makers' ability to evaluate biogas systems as integrated socio-economic infrastructures rather than isolated energy technologies.

From an ESG and sustainability assurance perspective, biogas presents a particularly compelling case. Its potential contributions to emissions mitigation, waste reduction, and rural socio-economic development position biogas systems at the intersection of environmental performance, social impact, and governance accountability. However, translating these contributions into decision-useful information requires robust accounting frameworks capable of capturing avoided emissions, recovered nutrients, and circular value creation. The limited visibility of such accounting-oriented analyses within the existing biogas literature highlights

a structural gap between sustainability objectives and the measurement systems used to assess their achievement.

In response to these challenges, this study aims to systematically map the global research landscape of the biogas economy through a bibliometric and science-mapping approach, with explicit attention to business, economic, and accounting perspectives. Using peer-reviewed journal articles indexed in Scopus between 1980 and 2025, the study analyzes publication trends, influential authors and institutions, geographic distribution of research, and thematic evolution. Keyword co-occurrence network analysis is employed to uncover the intellectual structure of the field and to examine how concepts related to markets, policy, accounting, and sustainability have evolved. This approach enables the identification of underexplored areas, particularly those related to accountability, sustainability reporting, and data-driven economic evaluation within biogas systems.

The principal contribution of this study is to offer the first comprehensive bibliometric synthesis of biogas research that explicitly integrates business, economic, and accounting lenses. By combining performance-based bibliometric indicators with science-mapping techniques, the study provides a structured understanding of how the biogas economy has evolved and how it interfaces with ESG-oriented measurement and assurance concerns. In doing so, the study not only advances academic discourse on renewable energy systems but also supports RSER's broader objective of fostering interdisciplinary insights that inform policy design, investment decisions, and sustainability-oriented governance in the transition toward low-carbon, circular energy systems.

Methodology

This study adopts a bibliometric and science-mapping approach to systematically examine the evolution of research on the biogas economy from business, economic, and accounting perspectives. The methodological procedures were designed to ensure transparency, reproducibility, and consistency with the study objective of mapping the global knowledge structure of biogas-related economic research.

Data Source and Search Strategy

Data were retrieved from the Scopus database, which was selected due to its extensive coverage of peer-reviewed international journals [18] and its provision of standardized bibliographic metadata suitable for bibliometric analysis [19]. The final search query was formulated to capture publications explicitly addressing biogas within an economic context and was applied to titles, abstracts, and keywords as follows: TITLE-ABS-KEY (biogas AND economy) AND (LIMIT-TO (SUBJAREA, "BUSI") OR LIMIT-TO (SUBJAREA, "ECON")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (LANGUAGE, "English")).

The application of these criteria resulted in a final dataset of 182 English-language journal articles. No manual modifications or post-hoc adjustments were applied to the search results, and the dataset reflects the output directly obtained from the database under the specified conditions.

Inclusion and Exclusion Criteria

To ensure thematic relevance and methodological consistency, the analysis included only peer-reviewed journal articles published in their final form [20]. Conference proceedings,

non-relevant review articles, and studies focusing exclusively on technical or engineering aspects of biogas without explicit economic, business, policy, or accounting dimensions were excluded. These criteria were applied to maintain alignment between the dataset and the study's analytical focus on the biogas economy.

Data Extraction and Pre-Processing

Bibliographic metadata were exported from Scopus, including information on authors, institutional affiliations, citation counts, author keywords, countries of origin, and source journals [21]. Before analysis, the dataset underwent a data cleaning process to address inconsistencies in keyword spelling, merge synonymous terms, and consolidate conceptually equivalent expressions. This preprocessing step was necessary to reduce semantic noise and to ensure that network visualizations accurately reflected the underlying structure of the literature rather than variations in terminology.

Bibliometric Tools and Analytical Procedures

Bibliometric analyses were conducted using a combination of specialized software tools. VOSviewer was employed to generate network visualizations, including co-authorship networks, keyword co-occurrence maps, and overlay visualizations illustrating thematic evolution over time [22], [23]. These visualizations facilitated the identification of collaboration patterns, conceptual linkages, and dominant research themes within the biogas economy literature. In parallel, Microsoft Excel and built-in Scopus analytical functions were used to compute descriptive indicators, including annual publication trends, citation distributions, and author and institutional productivity.

Analytical Framework

The analytical framework comprised two complementary components. First, descriptive performance analysis was applied to examine publication growth, citation patterns, and geographic and institutional distributions. Second, science-mapping techniques were used to explore the field's intellectual structure through keyword clustering, author networks, and thematic relationships. Together, these approaches provide a comprehensive overview of the evolution, structure, and research dynamics of the biogas economy literature from 1980 to 2025.

Methodological Limitations

Several methodological limitations should be acknowledged. First, this study relies exclusively on the Scopus database. Although Scopus offers broad coverage and high-quality metadata, relevant publications indexed in other databases, such as Web of Science or regional indexing platforms, may not be captured. Consequently, the findings should be interpreted as representative of the Scopus-indexed literature rather than the entirety of global biogas economy research.

Second, the analysis is based on a single primary search query combining the terms' biogas' and 'economy'. While this query was intentionally designed to ensure conceptual focus and thematic consistency, it may exclude studies that address economic, accounting, or business aspects of biogas using alternative terminology not explicitly captured by the search string. As a result, some relevant contributions may fall outside the dataset's scope.

Finally, bibliometric and science-mapping methods emphasize patterns in publication output, citation relationships, and keyword co-occurrence rather than the substantive quality

or empirical rigor of individual studies. Accordingly, the results provide insights into structural and thematic trends rather than evaluative judgments on specific research findings.

Despite these limitations, the methodological approach adopted in this study provides a transparent and systematic basis for mapping the intellectual landscape of biogas economy research and for identifying persistent gaps and future research opportunities.

Results and Discussion

Publication Trends (1980-2025)

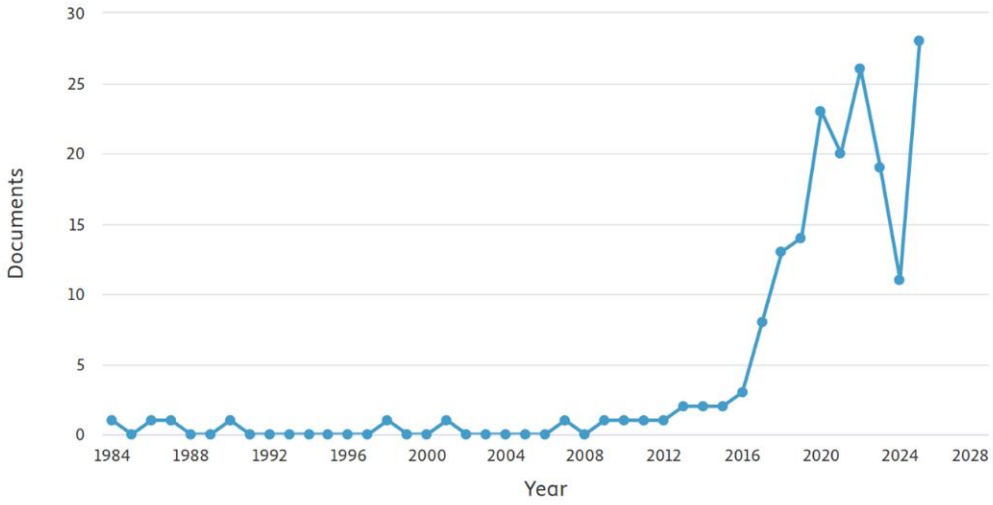

Figure 1. Annual Publication Trends (1980-2025)

Figure 1 presents the temporal evolution of publications on the biogas economy based on the Scopus dataset. Overall, the figure indicates that publication output remained low and relatively stable from the mid-1980s until approximately 2015. During this period, annual publication counts fluctuated within a narrow range and did not exhibit sustained growth, as reflected in the largely flat distribution of data points before 2016.

A more distinct change becomes apparent after 2016, when the publication curve shows a sharper increase than in earlier years. Although exact numerical values are not provided, the visual pattern suggests that publication output increased severalfold relative to the pre-2016 period. This upward trend continued until around 2020, during which several years recorded noticeably higher publication numbers than previously observed. After 2020, the trend shows greater variability, with alternating periods of higher and lower output, followed by another increase approaching 2025. This pattern reflects a more dynamic and active research landscape, although it does not indicate a stable linear growth trajectory.

Most Productive and Influential Authors

Figure 2 illustrates the authors with the highest publication output in the biogas economy literature. Several authors contribute comparable numbers of articles, with Barros R.M., D'Adamo I., and Feiz R. appearing as the most productive, each with four publications. A second group, including Cucchiella F., Gastaldi M., Gedminaitė Raudonė Ž., Metson G.S., and

Vilkė R., is represented by three publications, while Adani F. and Ammenberg J. each contribute two articles.

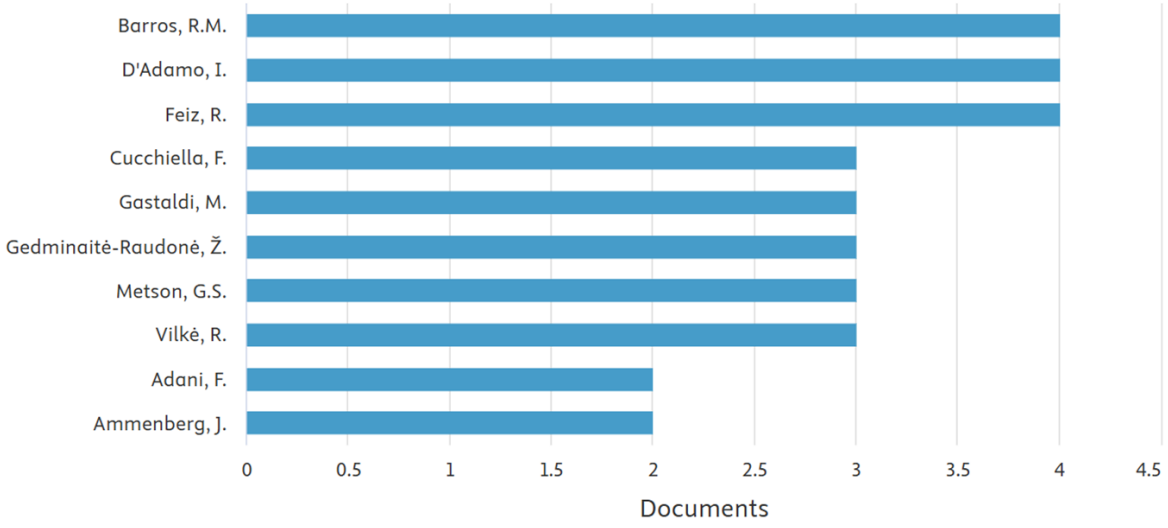

Figure 2. Most Productive Authors

The distribution suggests that no single author dominates the field. Instead, the literature is shaped by a group of researchers who have contributed consistently over time. The recurrence of these authors across related studies on circular economy, waste management, and energy economics, as indicated by thematic linkages in the keyword analysis, suggests sustained engagement with core topics of the biogas economy. This interpretation is limited to productivity patterns, as the figure does not provide information on citation impact or qualitative influence.

Leading Institutions

Figure 3 reports the most productive institutions in the dataset. Linköping University emerges as the leading contributor, followed by a group of institutions with similar publication counts, including Università degli Studi dell'Aquila, the Chinese Academy of Sciences, and Universidade Federal de Itajubá. Additional institutions with comparable output include the Institute of Technology and Business, Chalmers University of Technology, the Ministry of Education of the People's Republic of China, KTH Royal Institute of Technology, Wageningen University and Research, and the University of São Paulo.

Although the figure does not provide contextual information on institutional strategies or funding environments, the distribution indicates that leading contributions originate primarily from institutions located in countries with strong research capacity and sustained engagement in renewable energy and sustainability research.

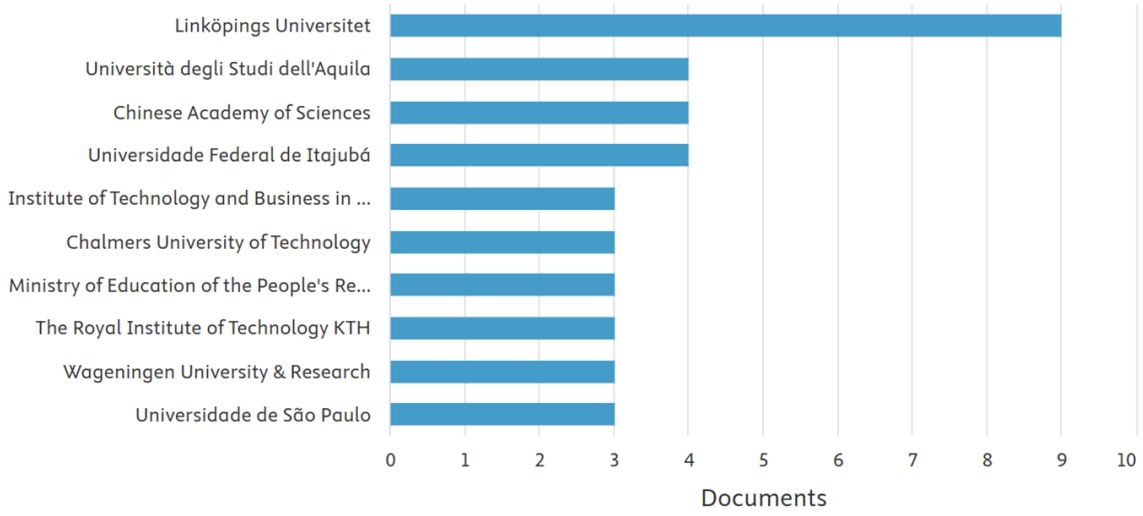

Figure 3. Leading Institutions

Geographic Distribution of Research

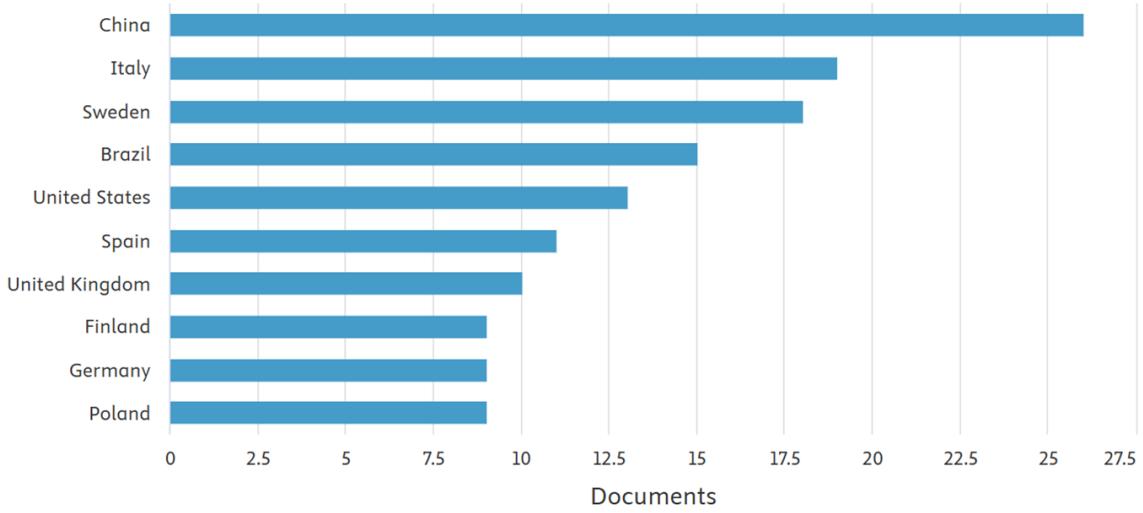

Figure 4. Most Leading Country

Figure 4 depicts the geographic distribution of publications by country. China appears as the most productive country, followed by several European nations, notably Italy and Sweden. Brazil also demonstrates a relatively high level of contribution, while the United States and Spain occupy intermediate positions. Other countries, including the United Kingdom, Finland, Germany, and Poland, contribute smaller but still visible shares of the literature.

Overall, the visualization indicates a concentration of biogas economy research in Europe and China, with additional focus on select countries in the Americas. African countries and Southeast Asian nations do not appear among the top contributors shown in the figure.

However, as the visualization is limited to the most productive countries, the absence of certain regions should not be interpreted as a complete lack of research activity.

Subject Area Distribution

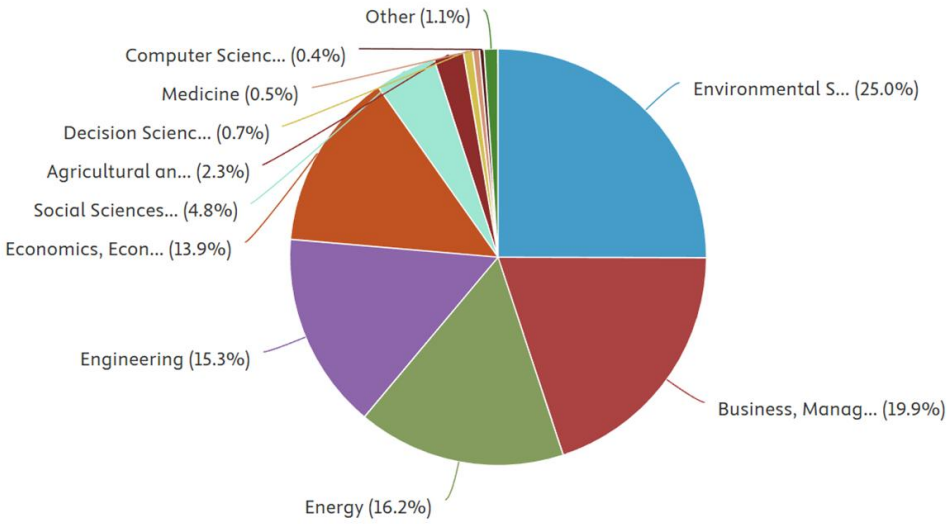

Figure 5. Subject Area Distribution

Figure 5 summarizes the composition of the biogas economy literature by subject area. Environmental Science accounts for the largest share, approximately one quarter of the total publications. This dominance reflects the strong linkage between biogas research and environmental issues such as waste management, sustainability, and the environmental impacts of energy systems.

Business, Management, and Accounting constitute a substantial proportion of the dataset, representing nearly one-fifth of the publications. This finding indicates that biogas is increasingly examined not only as an energy technology but also as an economic and organizational phenomenon involving managerial decision-making, economic evaluation, and accounting implications. Energy and Engineering also account for significant shares, underscoring the interdisciplinary nature of biogas economy research, where technical considerations provide an essential backdrop for economic and policy analysis. Economics, Econometrics, and Finance further contribute a notable share, reflecting engagement with formal economic analysis and policy evaluation.

Other subject areas, including Social Sciences and Agricultural and Biological Sciences, contribute smaller proportions, while Decision Sciences, Medicine, and Computer Science appear only marginally. Overall, the distribution confirms that the biogas economy literature is primarily anchored in environmental, business, economic, and energy disciplines, with other fields playing complementary roles.

Keyword Co-occurrence Network

The keyword co-occurrence network shown in Figure 6 reveals a multi-cluster thematic structure within the biogas economy literature. These clusters are identified by the frequency

with which keywords co-occur in the same documents, reflecting research topics commonly examined together.

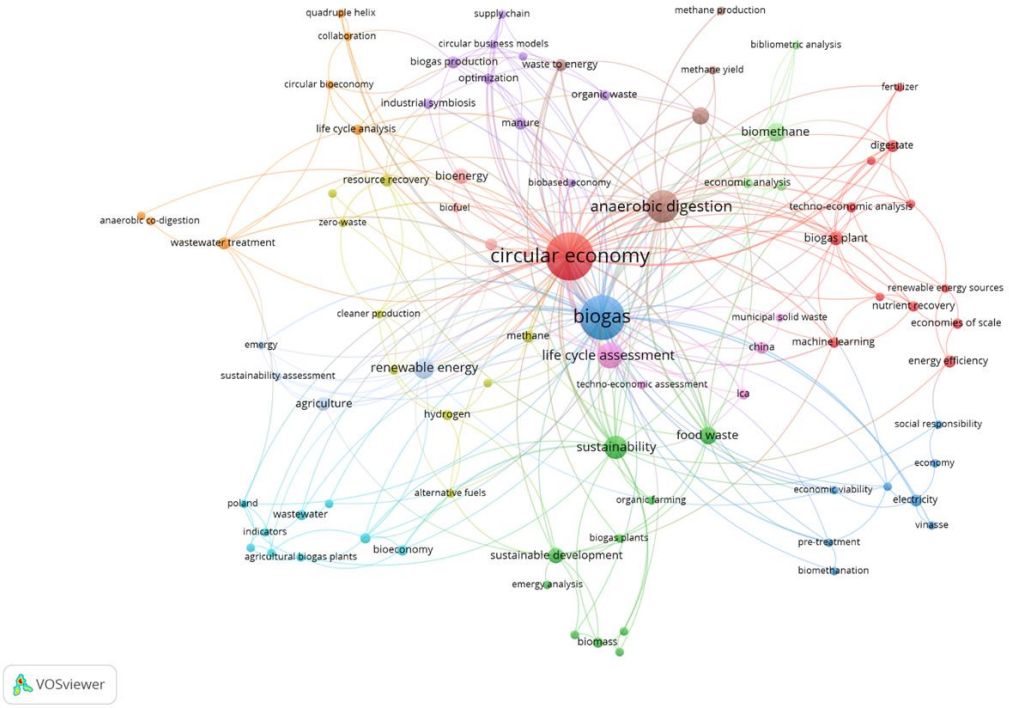

Figure 6. Author Keywords Network Visualization based on Occurrences

The first cluster relates to circular economy and waste valorization, emphasizing resource recovery, waste utilization, and sustainability-oriented economic frameworks. The second cluster focuses on rural energy economics and livestock waste utilization, highlighting the role of biogas in rural development, energy access, and local economic impacts. A third cluster centers on biogas markets, cost analysis, and profitability, reflecting research that treats biogas as an economic commodity evaluated through market mechanisms and financial performance metrics. The fourth cluster addresses digestate economy, nutrient cycling, and agricultural value chains, indicating growing attention to by-products and their integration into agronomic systems. The fifth cluster relates to policy, renewable energy governance, and Environmental Kuznets Curve analysis, situating biogas within broader debates on energy policy and environmental economics.

Overlay visualization in Figure 7 illustrates the temporal evolution of these themes. The color gradient suggests a gradual shift from early emphases on waste management toward circular economy concepts, followed by increased attention to biogas markets and broader economic analysis. In recent periods, keywords related to emissions reduction and carbon-centric economic considerations have become increasingly prominent. This interpretation is based solely on the visual progression displayed in the overlay map.

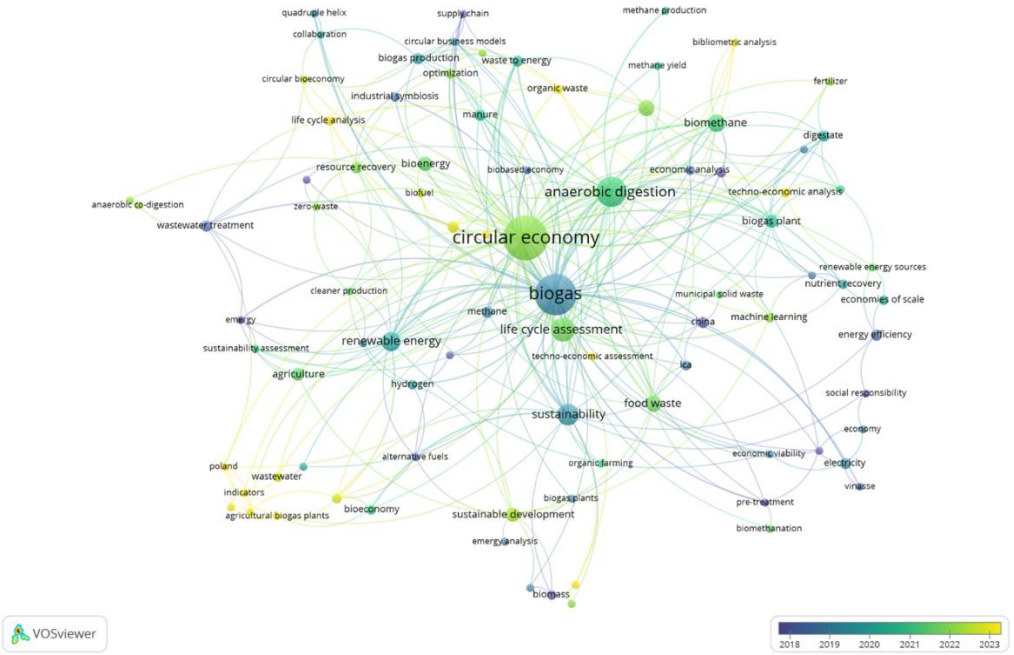

Figure 7. Author Keywords Overlay Visualization based on Occurrences

Evolution of the Biogas Economy Knowledge Landscape

Taken together, the bibliometric results indicate a gradual, discernible shift in the orientation of biogas-economy research. Early studies were largely embedded in technical and environmental problem-solving contexts, where biogas was primarily viewed as a waste-treatment or energy-conversion technology. Within this phase, economic considerations were often limited to basic cost comparisons, while accounting-related dimensions remained largely implicit or peripheral.

Following the expansion of publication activity after 2016, the literature increasingly adopted economic, market-oriented, and circular economy perspectives. This shift is reflected in both the distribution of subject areas and the emergence of thematically coherent keyword clusters related to markets, cost analysis, sustainability, and circular value creation. The growing presence of research in business, management, accounting, and economics suggests rising recognition of the need for systematic value measurement, performance evaluation, and accountability mechanisms within biogas systems.

However, the bibliometric patterns also reveal that accounting-related studies lag behind broader economic analyses. One plausible explanation is that economic research on biogas has largely focused on feasibility, market potential, and policy incentives, which can be addressed using conventional economic tools without requiring detailed accounting frameworks. In contrast, accounting research demands well-defined measurement standards, data availability, and institutional reporting requirements, which are often underdeveloped or inconsistent in biogas projects, particularly in decentralized or small-scale settings. As a result, accounting perspectives have been slower to be formalized in the biogas economy literature, despite their growing relevance.

Insights into Market, Accounting, Policy, and Value Chain Economics

The literature's thematic structure indicates that the biogas economy is underpinned by multiple, interrelated value dimensions, each with direct implications for accounting practice. The emergence of a distinct cluster focused on digestate reflects a conceptual shift toward recognizing by-products as economic outputs rather than residual waste. While economic studies increasingly acknowledge the market potential of digestate, accounting-oriented analyses addressing recognition, measurement, and reporting of by-product value remain limited. This gap highlights an unresolved tension between economic valuation and accounting treatment within biogas systems.

Clusters related to renewable energy policy and environmental economic analysis further suggest that biogas is frequently examined within governance and policy frameworks. Keywords associated with emissions, policy instruments, and economic–environmental relationships indicate that biogas is commonly framed as a mitigation instrument within broader energy transition strategies. From an accounting perspective, this framing raises questions regarding the measurement of environmental impacts, sustainability disclosure practices, and the incorporation of non-financial benefits into performance reporting. Nevertheless, such accounting-based inquiries appear fragmented and are rarely integrated into mainstream policy or market analyses.

The findings also indicate an emerging diversification of revenue models, encompassing energy production, by-products, and environmental benefits. Despite this diversification, the literature tends to address these value streams in isolation. Comprehensive accounting frameworks capable of integrating multiple revenue and benefit streams into coherent measurement, reporting, and assurance systems remain underdeveloped within the existing thematic structure.

Critical Gaps and Institutional Explanations

Despite the growth and diversification of the biogas economy literature, several research gaps remain evident. First, long-term cost–benefit analyses are relatively scarce, with most studies focusing on static or short-term economic evaluations. Accounting approaches that explicitly address cost dynamics, asset depreciation, and long-term value sustainability are still underrepresented. This limitation limits stakeholders' ability to assess biogas projects from an investment and risk management perspective.

Second, the geographic concentration of research in Europe and China reflects underlying institutional and policy factors. Both regions benefit from relatively mature renewable energy policy frameworks, dedicated funding mechanisms, and regulatory requirements that emphasize performance measurement and reporting. These conditions are conducive to economic and, to some extent, accounting-oriented research. In contrast, many developing regions face fragmented policy support, limited reporting mandates, and weaker research infrastructure, which may hinder the production and dissemination of accounting-focused studies. As a result, the observed geographic concentration likely reflects not only research capacity disparities but also differences in institutional demand for economic and accounting analyses.

Third, although business models and energy policy are often treated as distinct themes, their integration with accounting systems remains limited. Issues related to financial risk assessment, investment viability, and scalability barriers are only implicitly represented in

the keyword network. This suggests that management accounting and financial accounting perspectives, which are essential for supporting strategic decision-making and investment appraisal, have not yet been fully incorporated into the biogas economy research agenda.

Future Research Direction

Building on the bibliometric evidence and critical gaps identified, several future research directions can be articulated with explicit emphasis on accounting integration. First, future studies should develop long-term cost–benefit assessment frameworks that are explicitly aligned with accounting approaches, including life-cycle costing, asset valuation, and systematic treatment of by-products such as digestate.

Second, comparative research across developing economies is needed to examine how variations in institutional settings, policy regimes, and reporting requirements shape the measurement and disclosure of biogas performance. Such studies would enhance understanding of how accounting practices influence economic outcomes and sustainability performance under diverse conditions.

Third, future research should seek to integrate biogas business model innovation with energy policy analysis and sustainability accounting frameworks. Linking policy incentives, cost structures, and performance outcomes would provide more robust insights into the mechanisms that support or constrain biogas diffusion.

Finally, dedicated investigations into financial risk, investment viability, and scalability constraints remain essential. Applying management accounting and financial reporting tools to these issues would strengthen the analytical foundation for decision-making and support the positioning of biogas as a viable and accountable component of sustainable energy systems.

Overall, research informed by these directions can reinforce the role of accounting as a central discipline for understanding and supporting biogas development as a complex socio-economic system, rather than treating it solely as an energy technology.

Conclusion

This study provides a comprehensive bibliometric and science-mapping assessment of the global biogas economy research landscape, drawing on 182 Scopus-indexed journal articles in the domains of business, economics, and accounting. By systematically examining publication trends, geographic and institutional distributions, key scholarly contributors, subject area composition, and keyword co-occurrence networks, the analysis offers a structured overview of how knowledge on the biogas economy has evolved and how research priorities have shifted over time.

The findings reveal a pronounced increase in publication activity after the mid-2010s, reflecting growing academic attention to biogas not only as an energy technology but also as an integral component of the circular economy. The identified thematic structure indicates a transition from early emphases on waste management toward broader economic concerns, including circular economy frameworks, rural economic development, market analysis, and the valorization of by-products such as digestate. This evolution underscores an emerging understanding of biogas as a value-creating system that simultaneously encompasses energy production, nutrient recovery, and environmental benefits.

Geographic and institutional patterns show that biogas economy research remains concentrated in countries with strong research capacity, particularly in Europe and China, while contributions from other developing regions remain relatively limited. This imbalance points to unequal knowledge development and highlights opportunities to expand research across diverse economic and institutional contexts.

From a disciplinary perspective, the prominence of environmental science, business, management and accounting, economics, energy, and engineering confirm the interdisciplinary nature of the biogas economy literature. At the same time, the results indicate that accounting perspectives remain underrepresented relative to economic and policy analyses. In particular, issues related to long-term value measurement, sustainability, and ESG-aligned reporting, financial risk assessment, and investment feasibility are not yet strongly integrated into the dominant thematic structure, despite their importance for informed decision-making.

Beyond its academic contributions, this study also offers several practical implications. For policymakers, the findings highlight the importance of aligning renewable energy policies with robust measurement and reporting frameworks that capture the full economic and sustainability value of biogas systems. For accounting and sustainability researchers, the identified gaps underscore the need to develop accounting methodologies capable of integrating multiple value streams, including energy output, by-products, and environmental benefits, into coherent performance and reporting systems. For renewable energy investors and project developers, the results emphasize the importance of accounting-based tools for assessing the long-term viability, risk exposure, and scalability of biogas projects in evolving policy and market environments.

Overall, this study emphasizes that future biogas economy research should advance more integrated business models, strengthen the alignment between policy frameworks and economic practice, and further develop accounting approaches capable of capturing the multidimensional value of biogas systems. Enhanced cross-country and cross-disciplinary collaboration will be essential to enrich analytical perspectives and extend the empirical relevance of biogas economy research, particularly in developing-country contexts. By clarifying the existing knowledge structure and identifying key research gaps, this study provides a solid conceptual foundation for more inclusive, accountable, and sustainability-oriented advances in biogas economy research.

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