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Review

Systematic and Bibliometric Review of Biomethane Production from Biomass-Based Residues: Technologies, Economics and Environmental Impact

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Abstract: Fossil fuels drive global warming, necessitating renewable alternatives such as biomethane (or renewable natural gas). Biomethane, primarily produced through anaerobic digestion (AD), offers a cleaner energy solution but is limited by the slow AD process. Biomass gasification followed by syngas methanation has emerged as a faster alternative. This review examines advancements in these processes over the last decade (2015–2024), focusing on techno-economic and life cycle assessment (LCA) studies. Techno-economic analyses reveal that biomethane production costs are influenced by several factors, including process complexity, feedstock type and the scale of production. Smaller gasification units tend to exhibit higher capital costs (CAPEX) per MW capacity, while feedstock choice and process efficiency play significant roles in determining overall production costs. LCA studies highlight higher impacts for gasification and methanation due to energy demands and associated emissions. However, integrating renewable hydrogen production through electrolysis, along with innovations such as sorption-enhanced gasification (SEG), can enhance overall system efficiency and reduce environmental impacts. This review critically evaluates the technical and economic challenges, along with the opportunities for optimizing biomethane production, and discusses the potential for these technologies to contribute to sustainable bioenergy solutions in the transition to a low-carbon economy.

Keywords: biomethane production; biomass gasification; syngas methanation; techno-economic analysis; life cycle assessment

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1. Introduction

As the world's population grows, so does its energy demand, projected to increase by 21% by 2040 [1]. Currently, fossil fuels (natural gas, coal, crude oil and derivatives) supply over 80% of global energy needs [2], contributing significantly to greenhouse gas (GHG) emissions and climate change [3]. In response, there is a global push towards a low-carbon economy, with various technologies aimed at producing renewable alternatives to natural gas (NG) [4].

Biomass stands out as the only renewable carbon source on Earth. Extensive research has focused on converting biomass into biofuels, including biomethane (renewable natural gas, or RNG), biodiesel, renewable diesel and bioalcohols [5]. The biomethane market has seen substantial growth, with the potential to cover up to 30% of the European Union's current gas demand by 2040, reflecting its crucial role in achieving energy security and decarbonization goals [6]. Globally, the biomethane market is expected to expand significantly, driven by advancements in production technologies, supportive policies and increasing adoption in sectors such as transportation and power generation. Its value is expected to increase from 1.95 M$ to 3.22 M$ between 2023 and 2031 [7]. Furthermore, a detailed study underscores biomethane's economic and environmental benefits, highlighting its capacity to reduce greenhouse gas emissions and support circular economies through the utilization of organic waste. The EU is currently the major biomethane producer, with France and Germany being the main producers [8]. These developments position biomethane as a cornerstone in the renewable energy landscape, aligning with global sustainability objectives.

The most widely used and viable method for producing biomethane is anaerobic digestion (AD) of biomass waste followed by biogas upgrading [9]. Biogas, a versatile carbon source, is a gaseous mixture produced by AD, containing methane, carbon dioxide and trace gases [10]. AD is a biological process comprising four stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis. Hydrolysis, the rate-limiting step, involves the breakdown of organic matter into monomers by hydrolases. Acidogenesis ferments these monomers, while acetogenesis produces acetic acid and hydrogen from intermediates. Finally, methanogenesis converts organic matter into methane from acetic acid [11]. Despite its efficiency, AD alone cannot meet the growing global energy demands. It also has drawbacks, such as being slow and limited by feedstock availability. As a promising alternative, biomethane synthesis via biomass gasification and syngas methanation is gaining attention. Research studies on using solid wastes as feedstock for biomethane production through gasification and syngas methanation report final methane contents of up to 96% [12].

Apart from biomass gasification and methanation, there are examples in the literature of utilizing solar energy for biofuel production, including biodiesel, bioethanol, biohydrogen and biomethane. These approaches are significant in reducing dependence on fossil fuels [13]. Specifically, in the case of biomethane, yields of up to 96% have been reported when using concentrated solar power collectors at high temperatures.

Despite the promising advancements, the economic and environmental viability of biomethane production via gasification and methanation remains uncertain, primarily due to the limited research available on this technology. The European Commission-funded HYFUELUP project, https://hyfuelup.eu/ (accessed on 18 November 2024), aims to address this by developing advanced technology for biomethane production, combining gasification and methanation with renewable hydrogen, and then the produced biomethane is liquified and used for decarbonization of long-distance road freight transport and maritime transportation.

A more in-depth analysis of trends and recent findings is essential to identify pathways for optimizing processes to achieve efficiency and cost reductions. This paper addresses this gap by reviewing advancements in biomethane production from biomass waste gasification and methanation over the past decade. It focuses on the economic and environmental aspects, structuring the discussion around the following research questions (RQ):

- RQ1: What are the recent advancements in biomass gasification and syngas methanation technologies for biomethane production, and how do these compare with traditional AD methods in terms of efficiency, costs and environmental impacts?
- RQ2: What techno-economic factors influence the viability and scalability of biomethane production from biomass gasification and methanation?
- RQ3: How do LCAs of biomethane production from gasification and methanation compare to other renewable energy alternatives?

- RQ4: What are the emerging feedstock options for biomethane production, and how do they impact overall process sustainability?

Section 2 details the methodology used for the systematic literature review and bibliometric analysis. Section 3 provides an overview of feedstocks, production technologies and research trends in biomethane synthesis. It also presents the results of the bibliometric analysis of the retrieved documents, followed by a discussion on the latest advancements in gasification and methanation technologies, including technical aspects, techno-economic data and environmental impacts.

Overall, this review aims to serve as a comprehensive guide to understanding the profitability and environmental potential of biomass waste gasification and methanation for biomethane production, supporting the decision-making on processes and feedstocks to meet global energy needs.

2. Materials and Methods

2.1. Systematic Literature Review

The search for publications was conducted using the Web of Science™ (WoS) Core Collection database. The retrieved datasets were then categorized by topic, covering the period from 2014 to 2024. Specifically, the Web of Science™ Core Collection (covering publications from 1900 to the present) was used to identify papers written in English between 1 January 2014 and 31 May 2024. The search was performed based on "Topic" (including title, abstract or author keywords) and "Publication Date". The following search query was used to gather a comprehensive overview of the literature:

TS = (("pyrolysis" OR "upgrad" OR "gasification" OR "methana*" OR "biomethanation" OR "bio-methanation") AND ("life cycle ass*" OR "economic* ass*" OR "life cycle ana*" OR "economic* ana*" OR "life cycle evaluation" OR "environmental ana*" OR "environmental ass*" OR "economic* evaluation methanol") AND ("biomethane" OR "bio-methane" OR "bio methane" OR "bio* CH4") NOT ("methanol" OR "succinic" OR "socio-economic" OR "hydrogen production from biogas" OR "calcination" OR "hydrogen from natural" OR "solar thermal" OR ("upgrading" NEAR/2 "performance"))).*

The systematic literature review followed the PRISMA 2020 process flowchart represented in Figure 1 [14,15]. It was conducted to identify technological parameters from the retrieved studies based on the search query. These parameters include:

- Technological parameters: such as feedstock type, location, technology setup, data source and biomethane production rates.
- Economic parameters: including capital (CAPEX) and operational (OPEX) expenditures, minimum selling price of biomethane and production costs; biomethane production costs (in €/MWh) were calculated assuming 7920 h of operation per year, when not specified in the documents. CAPEX was also normalized per biomethane plant capacity (in €/MW).
- Environmental parameters: such as the scope of the assessment, functional unit, software and databases used, life cycle impact assessment methods and environmental impacts.

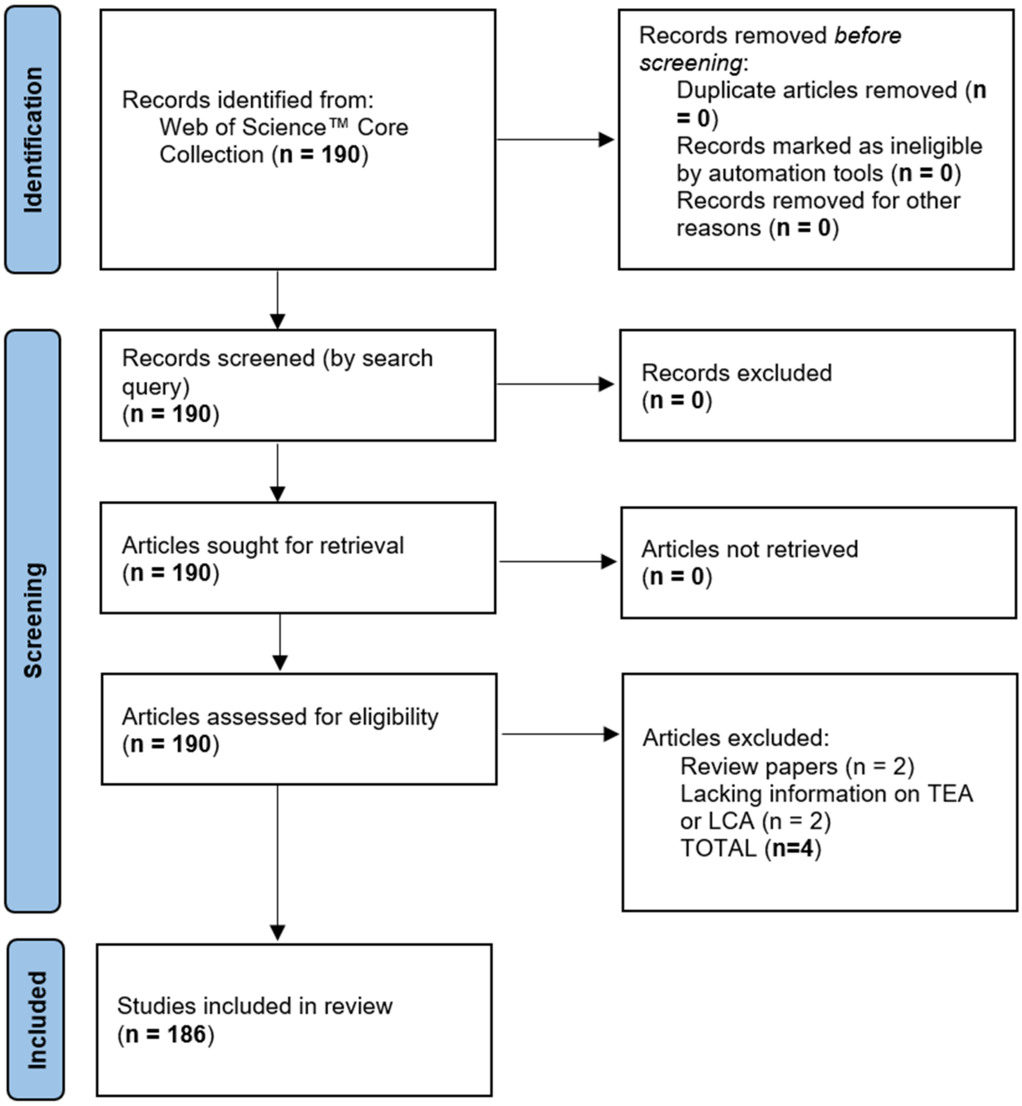

Figure 1. Flow diagram for new systematic reviews that included searches of databases and registers only (adapted from PRISMA 2020 [14,15]).

2.2. *Bibliometric Analysis Methodology*

To gain insights into the research trends and patterns in the field of TEA and LCA studies of biomethane production systems, a bibliometric analysis was conducted. Each paper was meticulously examined to extract bibliometric data, including the number of citations, publication year, authorship and the journals in which the studies were published.

For a comprehensive analysis, the open-source *bibliometrix* R-package (version 4.3.0) [16] was employed using the exported BibTeX file from the query. After a deeper analysis to identify and discard papers outside the scope, this tool facilitated the extraction and visualization of key metrics. Specifically, the keyword co-occurrence network was used to identify prevalent keywords and their relationships, thus highlighting core research themes and emerging topics. Trend topics provide valuable insights into the shifting focus of research and current hot topics. Additionally, bibliographic coupling allows one to identify influential works and common research foundations. The analysis also encompassed identifying prolific authors, influential publications and dominant research themes. By leveraging these methodologies, the bibliometric analysis provides a macroscopic view of the scholarly landscape, offering insights into the evolution, emerging trends and future directions of biomethane research.

3. Results and Discussion

3.1. Overview of Feedstock, Production Technologies and Research Trends in Biomethane Synthesis

The analysis shows that different authors use a variety of biomass feedstock types and technologies for biomethane production. As shown in Figure 2, agricultural residues and organic waste are the most used feedstocks, representing 31.9% and 28.1% of the total, respectively—together accounting for 60% of all feedstocks used over the last decade. Other feedstock types, such as energy crops, sewage sludge, industrial waste, forestry residues, aquatic biomass and industrial flue gases, are also employed, though less frequently. Notably, over 20% of the publications did not specify the feedstock used. These findings indicate that biomethane has significant potential and versatility due to the wide range of available feedstocks.

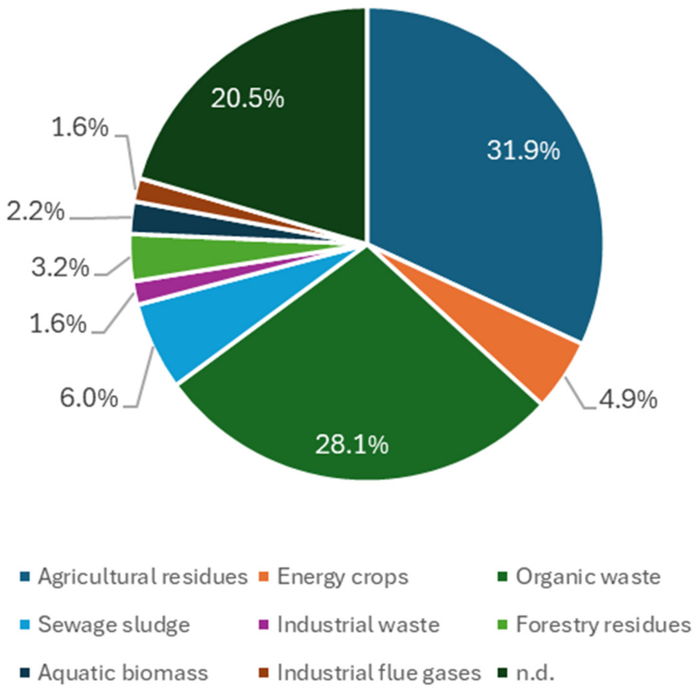

Figure 2. Distribution of types of feedstocks commonly used in the synthesis of biomethane, as retrieved by the assessed documents.

As shown in Figure 3, the combination of anaerobic digestion followed by biogas upgrading (AD + BU) is the most used technology for biomethane production, appearing in 110 publications and accounting for more than 60% of the studies. The next most reported process is biogas upgrading (BU), regardless of the biogas source, found in 31 publications, followed by anaerobic digestion and methanation (AD + M) with 15 publications. Meanwhile, the combination of gasification and methanation (G + M) accounts for only 6.1% of the studies (12 publications in the past decade), indicating that this biomethane production approach is still an emerging technology. Additionally, a few studies have focused only on chemical (CM) or biological methanation (BM). Notably, three publications did not specify the technology used for biomethane production.

Analyzing the number of publications between 2015 and 2024 (Figure 4), the annual production has been quite constant, but some events might have influenced or shifted the amounts of biomethane-related studies produced. For instance, during the COVID-19 pandemic (2019–2022), the annual production was clearly higher in comparison with the remaining periods, which is a cross-sectoral event in terms of higher scientific productivity due to the increase in remote work, which allowed researchers to produce more papers and not run new experiments. In general, approximately half of such publications involve

TEA studies. The number of publications regarding LCA is also considerable (almost 30%). However, the number of papers dealing with both TEA and LCA is lower, accounting only for 18.9%. Moreover, there are very few studies regarding social life cycle assessment (S-LCA), ca. 1.5%, which is still a very understudied pillar of sustainability, namely when it comes to bio-based products or biorefineries.

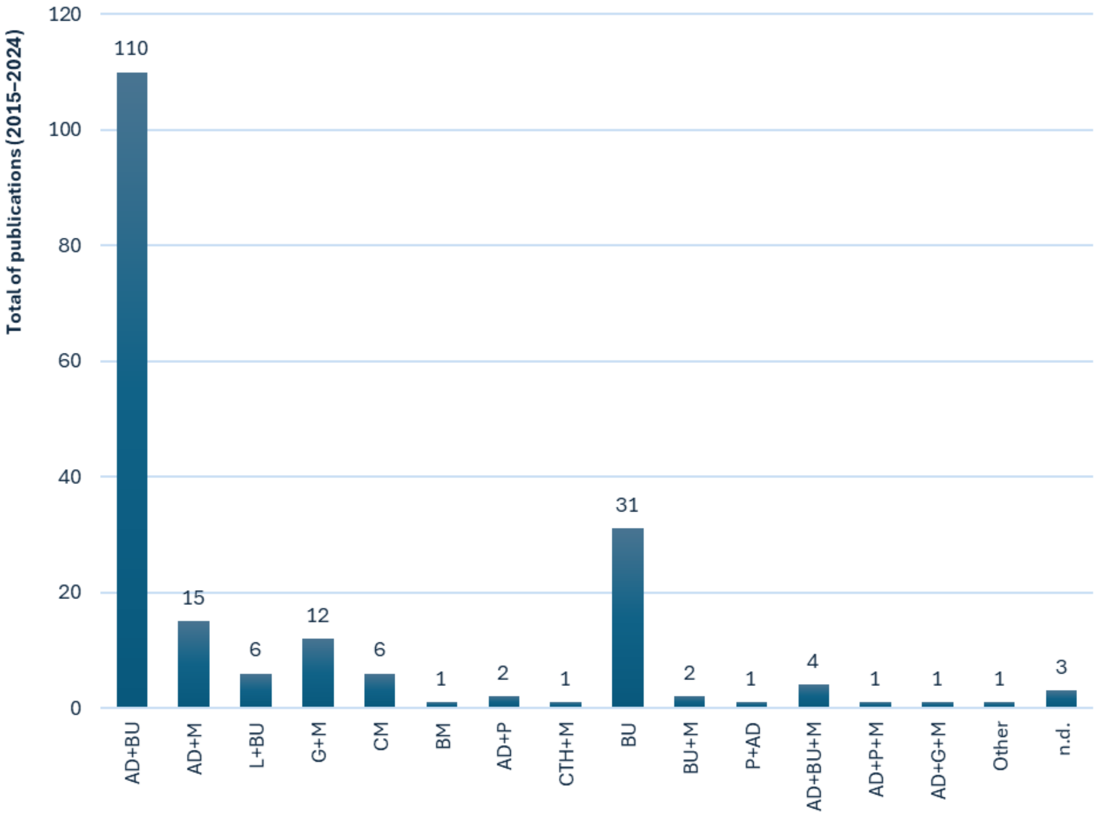

Figure 3. Number of publications reporting different technologies of biomethane production. (AD = anaerobic digestion; BU = biogas upgrading; M = methanation; L = landfill; G = gasification; P = pyrolysis; U = upgrading; CM = chemical methanation; BM = biological methanation; CTH = catalytic transfer hydrogenolysis; n.d. = not defined).

The trends in biomethane-related studies might also have been influenced by the public policies published throughout the last decade. Between 2018 and 2023, the European Commission (EC) published important regulations in respect of the usage and distribution of biomethane. In May 2018, with the Clean Mobility Package, the objective was to encourage Europe to reduce emissions in transportation and to stay competitive [17]. The European Green Deal (December 2019) aimed at controlling the global warming threat, referring to biomethane to achieve that goal [18]. By May 2022, with the publication of the REPowerEU Plan, the EC intended to eliminate fossil fuel imports from Russia by addressing the following objectives: (i) save energy, (ii) diversify energy supplies and (iii) produce clean energy [19]. The Renewable Energy Directive (RED II), published in June 2018, required 32% of the energy consumed in the European Union to be renewable by 2030 [20]. Later, the revised RED II also called RED III (October 2023) updated this requirement to 42.5% of renewable energy [21]. It is thus expected that the upcoming years will be of high interest in biomethane and, therefore, with an increased number of scientific publications being produced.

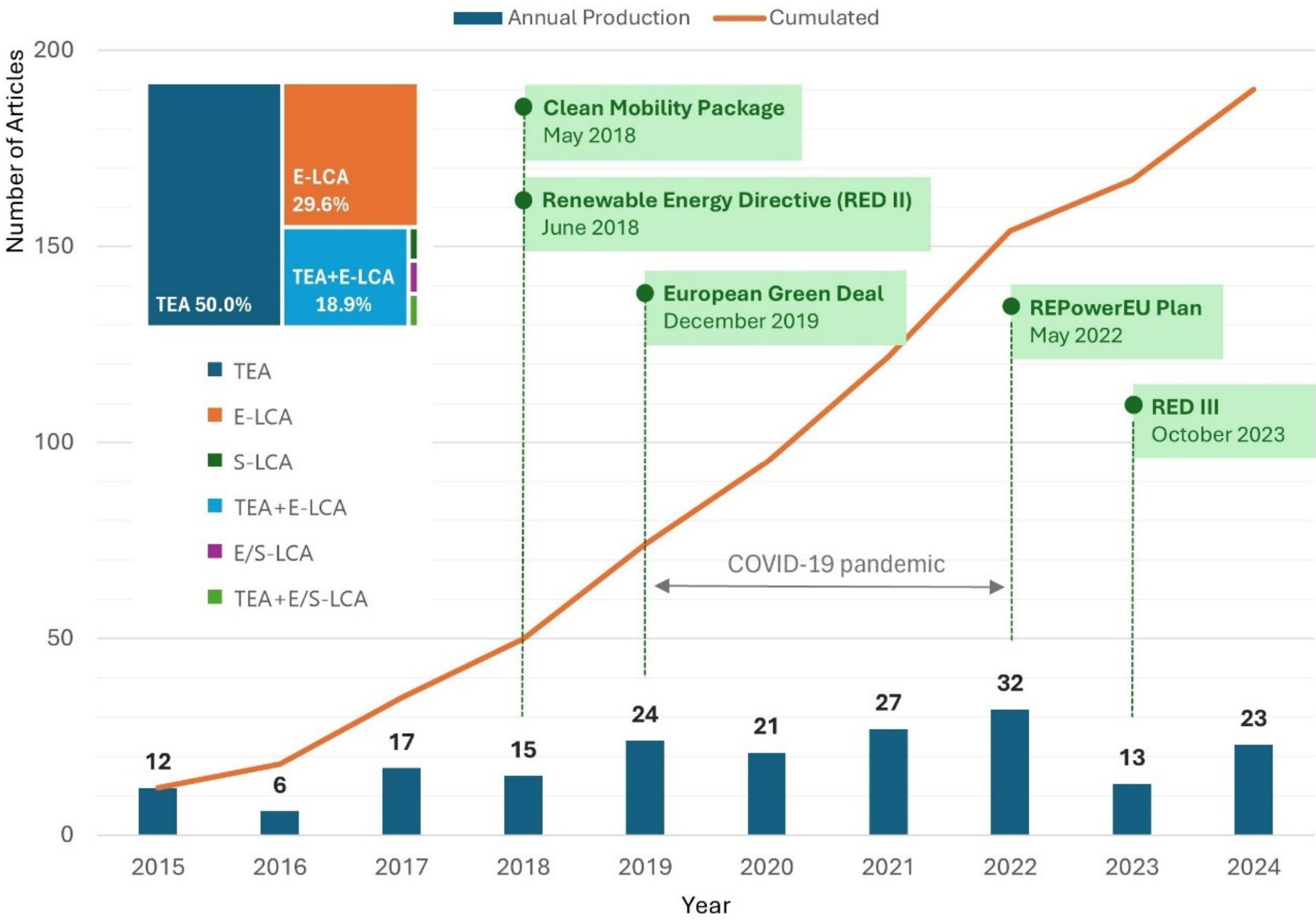

Figure 4. Number of publications over the years, evidencing the type of analysis performed. The distribution of type of study is included in each reference assessed (TEA—techno-economic analysis, E-LCA—environmental life cycle assessment, S-LCA—social life cycle assessment).

3.2. Bibliometric Analysis

3.2.1. Analysis of the Most Cited Documents

Figure 5 displays the top 10 most cited documents both globally and within the set of publications retrieved using the query, as analyzed through *bibliometrix*. While there is no clear trend regarding the number of citations over time, the data indicate a noticeable peak in citations between 2015 and 2018. This period saw a higher frequency of citations, suggesting increased attention to the topics discussed in these key documents during that time. These most relevant studies have explored both the environmental sustainability and economic feasibility of biomethane production from various waste sources, including the organic fraction of municipal solid waste (OFMSW) and animal residues. Ardolino et al. conducted an LCA comparing biomethane production from OFMSW for road transportation with energy generation from OFMSW via a combined heat and power (CHP) unit, this being the most cited work [22]. Their findings indicated that biomethane production is more environmentally sustainable, with lower global warming potential and reduced consumption of non-renewable energy. Ravina and Genon supported these conclusions, showing that biomethane offers a better carbon footprint and reduced air pollution compared to biogas combustion in CHP units [23]. Despite these environmental benefits, the economic viability of biomethane production is sensitive to several factors, including plant size, substrate type, capital investment and the availability of government incentives.

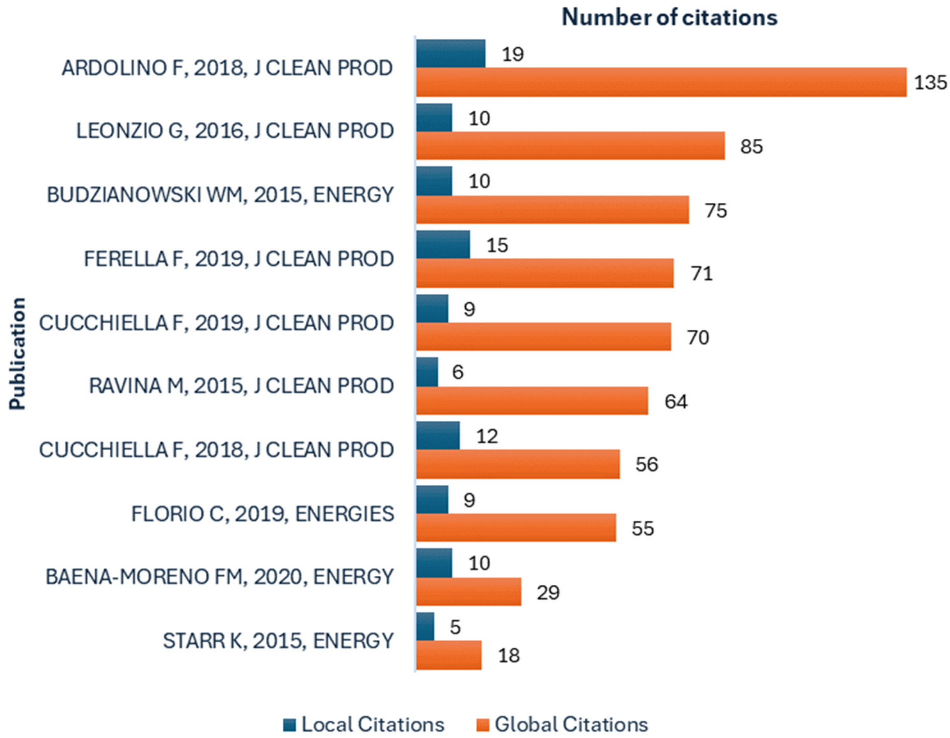

Figure 5. Top 10 of most locally (within the universe of retrieved documents) and globally cited documents, obtained using *bibliometrix*.

Cucchiella et al. [24] and Baena-Moreno et al. [25] examined the economic feasibility of small-scale biomethane plants (less than 150 m^3/h) and found that they are generally not profitable without government subsidies. Starr et al. reached similar conclusions in Spain, where a biogas upgrading plant using alkaline with regeneration (AwR) technology with a capacity of 250 Nm^3/h was deemed economically unviable due to high operational costs [26]. These studies emphasize the critical role that policy support and financing mechanisms play in making biomethane production financially feasible. Budzianowski et al. [27] and Ferella et al. [28] also acknowledged the importance of government subsidies in making biomethane production economically viable.

Technological integration has been proposed as a strategy to improve both the sustainability and cost-effectiveness of biomethane production. Leonzio's techno-economic analysis of a power-to-gas (PtG) process integrated with anaerobic digestion suggested that this approach could be economically viable while also delivering environmental benefits [29]. Florio et al. focused on the environmental advantages of biogas upgrading, pointing out that it contributes to greenhouse gas emission reductions and the preservation of fossil resources [30]. However, they stressed the importance of conducting comprehensive LCA studies to capture the full environmental impact of biomethane production systems.

Overall, the research highlights biomethane's potential as a renewable energy source with significant environmental benefits. Nevertheless, economic and policy challenges remain barriers to its large-scale adoption. Further research into cost-effective biogas upgrading technologies, alongside supportive policy frameworks, will be essential to realizing biomethane's role in the transition to a low-carbon economy.

Among these studies, Ardolino et al.'s work stands out (135 global citations and 19 local citations, as per July 2024) for its detailed LCA and use of real-world data from Italian plants [22]. By directly comparing biomethane production for transportation to energy production from OFMSW, Ardolino et al. analysis provided key insights, particularly regarding fleet composition, biomethane consumption and methane slip, which are crucial for policymakers and stakeholders in the field. In contrast, studies such as the ones performed by Cucchiella et al. [24,31], Baena-Moreno et al. [25] and Starr et al. [26] focused more narrowly on economic factors, while Leonzio's study [29] on PtG integration addressed only one aspect of the broader biomethane production landscape. Florio et al.'s [30] broader scope on biogas upgrading also lacked the direct comparison to energy pathways seen in Ardolino's work. This comprehensive data-driven approach makes Ardolino's research especially influential, offering a robust foundation for future decision-making in the biomethane sector, being this the main reason why it leads both global and local citations among the analyzed documents in this work.

3.2.2. Trend Topics, Authors and Documents

A three-field plot diagram is visually represented in Figure 6, containing the relationships between cited references (CR), authors (AU) and keywords (DE). The leftmost column (CR) shows the most frequently cited documents in the dataset. Cited documents such as Ardolino et al. [22] (as previously highlighted), Budzianowski et al. [32], Ferella et al. [28] or Vo et al. [33] serve as cornerstones for the field, often referenced by influential researchers. These studies likely focus on various aspects of biomethane production, such as life cycle assessments, economic analysis and technological innovations in biomethane systems.

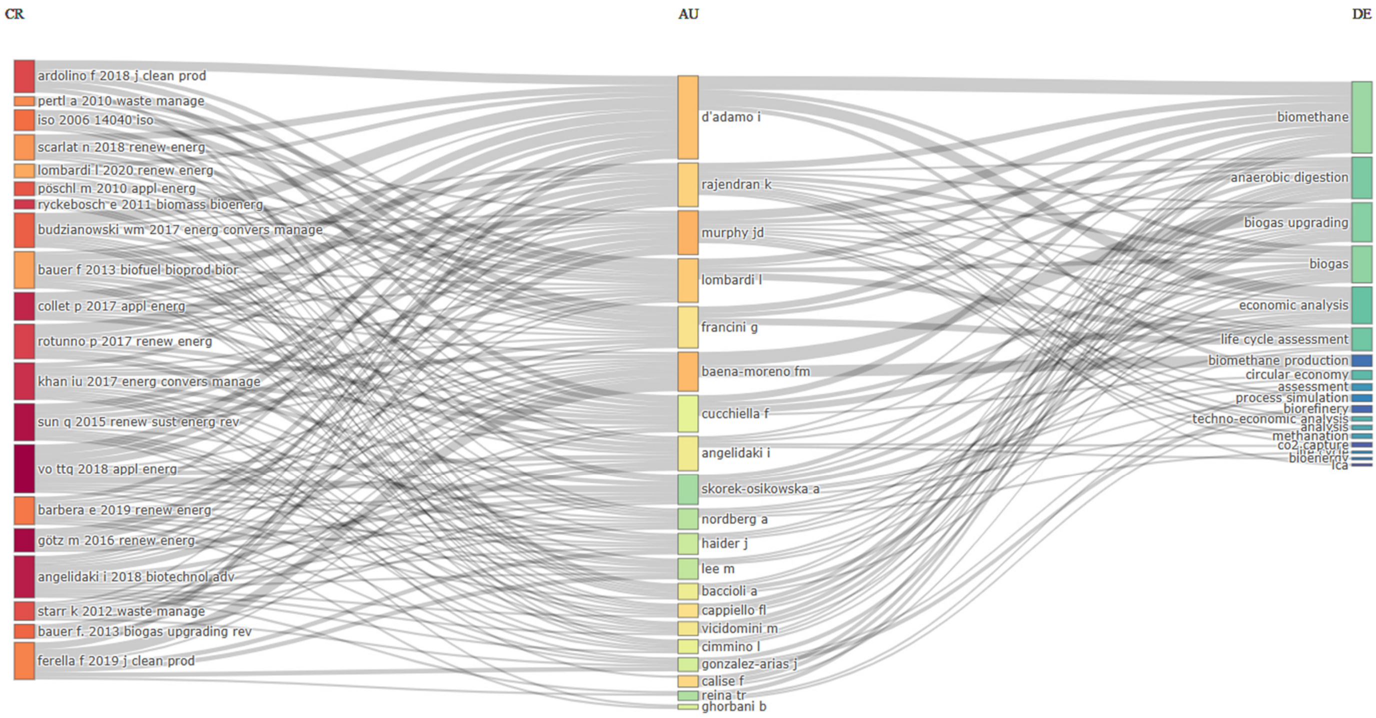

Figure 6. Three-field plot illustrating the correlation between the most frequently cited documents (CR), the most relevant authors who commonly cite those documents (AU) and the most frequently occurring keywords (DE) in research on biomethane production, retrieved using *bibliometrix*.

The middle column features the authors who frequently cited the documents on the left. Authors such as D'Adamo I. and Lombardi L. frequently cited foundational works to explore innovative approaches to biomethane production, focusing on areas such as techno-economic assessments and process integration with technologies such as anaerobic digestion and biogas upgrading.

The keywords on the right represent the central themes of the research conducted by these authors. The diagram highlights "biomethane", "anaerobic digestion" and "biogas upgrading", as well as "life cycle assessment" and "economic analysis" as core themes in the research. This emphasizes the dual focus on both the environmental and economic dimensions of biomethane production. Keywords such as "circular economy" and "CO_2 capture" indicate that the field is increasingly concerned with integrating biomethane into broader sustainability frameworks.

The co-occurrence network of keywords, generated with *bibliometrix* and depicted in Figure 7, highlights the dominant research themes within the field of biomethane production and its associated processes. At the center of the network, anaerobic digestion, biomethane and energy are the most prominent keywords, indicating their pivotal role in the scientific discourse. These terms are closely linked with other key topics such as biogas production, waste management and greenhouse gas emissions, underscoring the focus on sustainable energy generation from organic waste sources. The network also reveals a strong connection between techno-economic analysis and environmental considerations such as emissions and LCA, reflecting the ongoing efforts to balance environmental sustainability with economic feasibility.

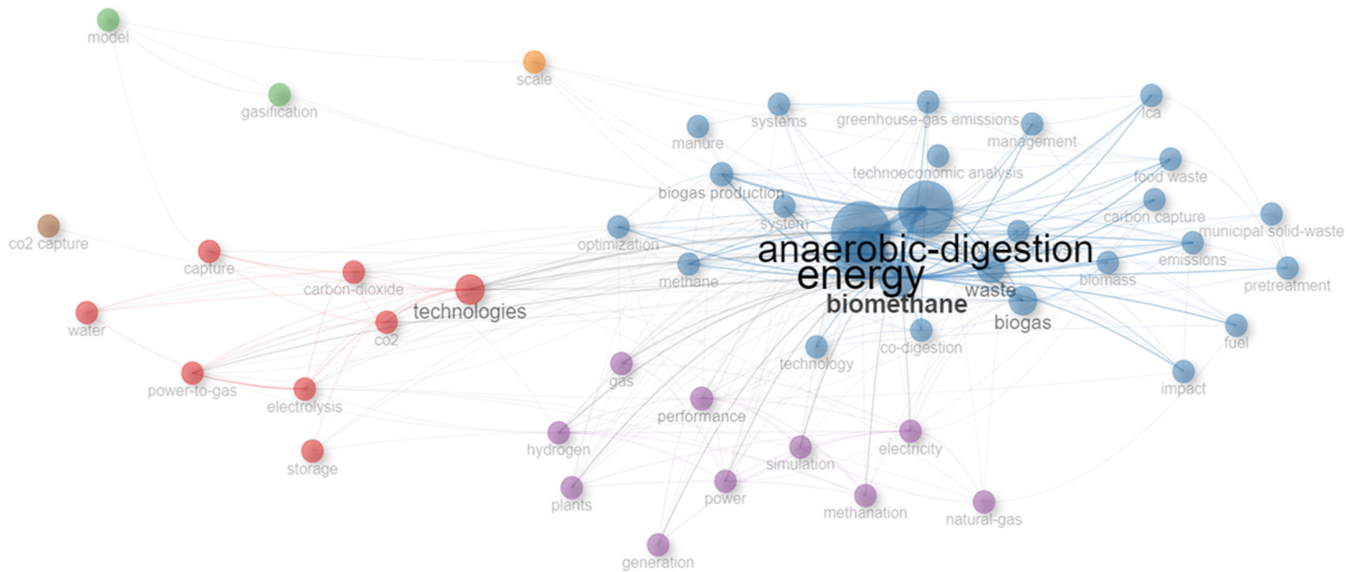

Figure 7. Co-occurrence network of keywords from the retrieved documents related to biomethane production, generated using *bibliometrix*.

Another notable cluster involves technologies such as gasification, methanation and electrolysis, which are gaining attention as complementary or alternative pathways for biomethane synthesis. These topics often link to terms such as CO_2 capture and carbon dioxide, highlighting the integration of carbon management strategies into biomethane research. Additionally, terms related to system optimization and performance, such as simulation and power generation, show a growing interest in improving the efficiency of energy systems. The network also includes emerging keywords such as hydrogen and power-to-gas, signaling an interest in innovative approaches that combine biomethane production with hydrogen technology to meet future energy demands. Overall, the network indicates a comprehensive approach in the field, combining technological innovation with sustainability goals.

3.3. Advancements in Biomethane Production via Gasification and Methanation

Although biomethane production via AD of waste followed by biogas upgrading is both efficient and profitable, its capacity is limited and cannot meet the growing energy demand. To address this limitation, alternative processes such as biomass gasification and methanation have been explored. A general and simplified schematic of these stages is shown in Figure 8. The process begins with the *gasification* of biomass residues, where they are converted into a syngas primarily composed of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2) and some methane (CH_4). The syngas produced is then subjected to *gas cleaning*, which removes impurities such as tar, particulates and sulfur compounds to ensure that the gas is suitable for the next stages of processing [34]. Once purified, the syngas undergoes *methanation*, a catalytic reaction where hydrogen is added to carbon monoxide to produce methane, which can be upgraded to biomethane (renewable natural gas) [34].

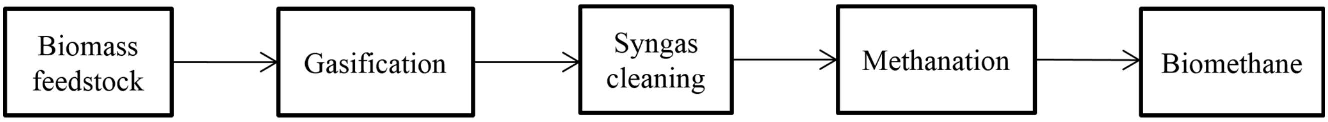

Figure 8. Stages of biomethane synthesis by gasification and methanation of biomass, adapted from [34].

However, not all studies integrate both gasification and methanation in a single process. Many focus on either the gasification step alone or the methanation of biogas derived from AD rather than syngas from biomass gasification. This distinction is important as the overall efficiency and economic feasibility of the integrated process depend on the optimization of both stages. While gasification and methanation provide a promising route for producing high-purity biomethane, these processes are energy-intensive and require significant capital investment. Nevertheless, advancements in catalyst development and syngas conditioning technologies are improving the efficiency of methanation, making this integrated approach more viable for large-scale biomethane production [34].

This section highlights the technological advancements in these areas, emphasizing their potential to contribute to a sustainable bioenergy future by addressing the energy demands and reducing greenhouse gas emissions.

3.3.1. Technical Aspects

The integration of AD with the gasification process has shown potential for enhancing biomethane production efficiency. Li et al. reported significant gains when wood pellets were used as feedstock [35], with similar results observed for forest residues [36]. Zhang et al. achieved yields up to 520 mL CH_4 per gram of volatile solids using plastic-containing food waste, showcasing flexibility in feedstock use while raising environmental concerns [37]. Gasification of waste biomass, such as wood chips, sawdust and paper, has performed well under high temperatures, with optimal results above 900 °C as noted by Safarian et al. [38]. Advanced techniques such as chemical looping gasification (CLG) demonstrated higher syngas yields, especially when coupled with electrolysis, improving carbon efficiency [39]. Polluzzi et al. [40] explored sorption-enhanced gasification (SEG) with in-situ CO_2 capture, achieving cost reductions while addressing emission challenges [41,42]. The syngas produced during biomass gasification often contains tar, which needs to be removed. Harb et al. used mixtures of fluoranthene, naphthalene, indene, phenol and toluene as tar representatives and cooled the mixture to allow for tar condensation [43].

Catalytic methanation, dominated by nickel-based catalysts, has achieved CH_4 contents exceeding 99%. Studies by Gaikwad et al. converted the CO_2 present in biogas into biomethane using four fixed-bed reactors and a nickel catalyst, achieving CO_2 conversions greater than 90%, while coupling the process with electrolysis [44]. Catalysts based on nickel supported on calcium aluminate have also been used, reaching a methane content of 99.2% when processing lignocellulosic biomass as feedstock [45]. González-Arias et al. demonstrated that nickel supported on ceria-alumina structures delivered a promising methane yield (above 50%) and selectivity (between 96 and 100%) [46]. Lanni et al. used a nickel-alumina catalyst in a catalytic methanation process coupled with electrolysis, achieving an annual production of 3.0×10^6 Nm^3 of biomethane [47]. Furthermore, Atzori et al. employed NiO-CeO_2 nanomaterials in catalytic methanation, achieving CO_2 conversions above 80% and selectivity greater than 99.5%, being a more efficient technology than the one studied by González-Arias et al. [48]. A nickel catalyst containing magnesium supported on carbon nanotubes (CNT) and silica reached a CH_4 content of 95% in the biomethane stream [49]. Ruthenium catalysts have also been explored, either supported on alumina [50] or titania [51], with promising results.

Biological methanation (or bio-methanation) is also often performed on syngas. Andreides et al. reached a CH_4 content of 94.7% in a two-step bio-methanation process following anaerobic digestion of sewage sludge [52]. Asimakopoulos et al. demonstrated that scaling up syngas bio-methanation in a trickle-bed reactor at a semi-pilot scale significantly improved CH_4 productivity compared to lab-scale results [53]. In situ bio-methanation of food waste achieved CH_4 content above 95% [54], while ex situ bio-methanation also showed high methane content (98%) [55]. It is important to note that methane yield is limited to thermodynamic equilibrium, so parameters such as pressure and hydrogen content are often adjusted to optimize results [56,57].

Several studies have explored the integration of gasification and methanation in a single process, demonstrating significant advancements. For example, Molino et al. implemented a water-gas shift (WGS) stage between gasification and methanation, increasing methane purity from 65 to 80% [58]. Ahlström et al. aimed to replace fossil fuels with biomethane by gasifying sawmill residues, followed by methanation of the cleaned gas, achieving a 9% reduction in fossil fuel usage [59]. A nickel-alumina catalyst has been shown to promote high conversion rates at around 300 °C during combined gasification and methanation of biomass [60]. Bartik et al. achieved complete conversions of biogenic residues by combining sorption-enhanced reforming (SER) with gasification and using a fluidized bed reactor for methanation [61]. More recently, Akbari et al. achieved methane purity of 84% in RNG using various biomass feedstocks subjected to gasification and methanation [62].

Despite these advancements, comparing systems is challenging due to inconsistent efficiency metrics. Some studies emphasize methane purity, while others highlight CO or CO_2 conversion rates, catalyst selectivity or methane yield. These parameters are crucial and should be consistently reported to facilitate a robust and accurate comparison of production technologies. Standardizing evaluation criteria will help to identify the most efficient systems for biomethane production.

3.3.2. Techno-Economic Analysis

There are still many doubts regarding the economic viability of current biomethane production processes. Today, the anaerobic digestion of waste followed by biogas upgrading presents the most economical method of RNG production. This fact alone suggests a more intensive study and optimization of the economic viability of waste gasification and syngas methanation for biomethane synthesis to fulfill the necessities of our society. Depending on the study, different economic indicators are presented. The most common ones are CAPEX and OPEX. CAPEX comprises the equipment purchase and installation, control and instrumentation, piping, electric systems and services. On the other hand, the OPEX is defined as the operational costs per year and comprises labor salaries, maintenance, insurance, marketing, logistics, utilities and raw materials. Other indicators are often considered, such as net present value (NPV), internal rate of return (IRR), payback period (PBP) and minimum selling price (MSP). NPV is defined as the difference between the discounted present value of future cash flows at a given interest rate and the initial investment, meaning that the project is acceptable if the NPV is positive [63]. IRR is the discount rate at which the NPV of a project is equal to zero [64], measuring the viability of a project considering the time value of money. PBP is the time needed to recover the initial investment; the lower, the better. MSP means the minimum price at which the fuel must be sold for the project to be viable; in other words, it is the selling price at which the revenues are equal to the costs.

According to a recent publication, the cost of biomass gasification ranges from 60 to 105 €/MWh, highlighting a cost disadvantage for this process. In comparison, biological methanation incurs a CAPEX of approximately 20–200 €/MWh and an OPEX of about 13 €/MWh. On the other hand, catalytic methanation offers a CAPEX between 35 and 70 €/MWh, presenting a cost advantage over biological methanation [65].

Table 1 presents the CAPEX, production costs and MSP for various biomethane production technologies, feedstocks, plant locations and capacities. Costs reported in American Dollar (USD) or British Pound (GBP) were converted to Euro (EUR) for a proper comparison. Additionally, electrolysis CAPEX was also included for those works that considered this technology for hydrogen generation to be used in the methanation reactor. The data reveal a wide range of economic performances across different technological setups and geographical contexts. Factors such as plant scale, feedstock type and the integration of processes such as anaerobic digestion (AD), gasification (G), biogas upgrading (BU), methanation (M) and electrolysis for hydrogen production significantly influence both CAPEX and operating costs.

CAPEX plays a crucial role in determining the economic feasibility of biomethane production facilities. Across the table, CAPEX values show substantial variation depending on the specific technology and feedstock. Smaller-scale plants generally exhibit higher CAPEX per MW of installed capacity. For instance, the plant in Lithuania using wood chips (Striugas et al. [66]) shows a CAPEX of 4253 k€/MW, which is among the highest for a G + M technology. This may reflect the relatively high complexity of handling solid biomass and the added costs of gasification. Similarly, the study on manure in Spain (Skorek-Osikowska et al. [67]) reports a CAPEX of 3871 k€/MW, which is a value relatively close to the one obtained in the previously mentioned work, with the same technology and plant capacity. Larger plants, benefiting from economies of scale, show significantly lower CAPEX per MW. For example, woody biomass in Sweden (Thunman et al. [68]) shows a strikingly low CAPEX of 1039 k€/MW, largely due to the plant's capacity of 20 MW (significantly higher than the previous ones), highlighting the cost-efficiency of scaling up operations. The integration of different processes, as in Michailos et al.'s study on sewage sludge in England, combines AD with gasification and methanation (AD + G + M), resulting in a CAPEX of 2816 k€/MW. This reflects the higher initial investment associated with the increased complexity of the integrated system [69]. Similarly, Carmo-Calado et al.'s work presents an even higher CAPEX of 11,709 k€/MW, the highest among all analyzed studies, attributed to the small scale of the system (only 0.475 MW), which significantly influences capital cost efficiency [70]. Additionally, pyrolysis has been explored in combination with gasification and methanation. However, detailed capital and operational cost data for this configuration remain unavailable [71].

Production costs (€/MWh) are another critical factor determining the financial viability of biomethane plants. These costs are influenced by several variables, including the feedstock type, technology used and plant location. The study in Lithuania (Striugas et al. [66]), using wood chips, reports a production cost of 418.94 €/MWh, the highest in the table. This can be attributed to the complex nature of wood gasification and the higher processing requirements. Additionally, smaller plants, such as the crude glycerol plant in Canada (Okolie et al. [72]), show relatively high production costs of 231.83 €/MWh, likely reflecting the difficulties in managing and converting glycerol, a byproduct of biodiesel production, although they are not as high as Striugas et al.'s work due to the higher plant capacity (16.1 MW). In contrast, woody biomass in Sweden (Thunman et al., 2019a) stands out with a production cost of only 9.13 €/MWh, one of the lowest [68]. This highlights the cost advantages of large-scale operations and optimized processes, especially when abundant local biomass resources are utilized. The plant's efficiency likely benefits from low transportation costs and optimized technology. Similarly, the manure-based biomethane plant in Spain has a production cost of 105.58 €/MWh, demonstrating a reasonable cost for a small-scale facility [67]. Apart from CAPEX, economies of scale also impact OPEX, as shown in a recent study where the production cost of biomethane decreased from 84 to 54 €/MWh when plant capacity increased from 5.5 MW to over 14 MW [65]. However, gasification and methanation of manure in Spain left to lower production costs than the same processes for crude glycerol, despite having a lower plant capacity (1 MW for the former and 16.1 MW for the latter). This can be explained by the much higher annual biomethane production for the latter, which is 128,800 MWh/year, while in the former only 8000 MWh/year is produced. This suggests that the annual production may also influence the production costs.

Feedstock choice is a key determinant of both CAPEX and production costs. Different types of feedstocks require varying levels of pretreatment and handling, which impacts the overall cost structure. Organic waste and manure are commonly used feedstocks due to their availability and ease of digestion. For example, in Italy, an organic waste plant shows a CAPEX of 1592 k€/MW (Leonzio et al. [29]), which is relatively low, reflecting the mature technology of anaerobic digestion. The production cost here is unspecified but would likely be lower due to the ease of processing. Woody biomass tends to involve more complex processing, often involving gasification, which can drive up both CAPEX and operational costs. However, as seen in Sweden, when managed at scale, woody biomass can be extremely cost-effective [68]. On the other hand, wood chips in Lithuania show high CAPEX and production costs, likely due to smaller plant capacity and potentially higher local feedstock costs. The study by Michailos et al. on sewage sludge in England shows the potential of integrating various technologies (AD + BU + M) for biomethane production [69]. With a CAPEX of 2125 k€/MW and a production cost of 148.01 €/MWh, this setup demonstrates the trade-offs between capital investment and operating costs, where integration improves efficiency but comes with higher upfront investment [69].

The integration of multiple technologies, such as anaerobic digestion, gasification, methanation and biogas upgrading, presents a complex but promising approach to enhance biomethane yield and efficiency. Combining processes, as seen in Michailos et al. (AD + G + M) and Skorek-Osikowska et al. (G + M), often results in higher CAPEX due to the additional infrastructure required [67,69]. However, these setups tend to offer better efficiency and higher biomethane yields. For example, the integration of gasification and electrolysis in Sweden has shown significantly low production costs, despite the higher complexity of the process. Advanced methods such as sorption-enhanced gasification (SEG) and chemical looping gasification (CLG) offer promising cost reductions by improving carbon capture and biofuel yield, but these technologies are still emerging, and their long-term economic feasibility remains to be fully validated.

MSP represents the minimum price at which biomethane must be sold to cover production costs and generate a profit. The MSP varies significantly based on location, feedstock and technology. In regions with higher production costs, such as England (Michailos et al.)

and Ireland (Vo et al.), MSPs are 185.82 €/MWh and 143.80 €/MWh, respectively [69,73]. These higher MSPs may reflect a combination of higher operational costs and more favorable market conditions, potentially due to government subsidies or local energy demand. In contrast, Spain shows a lower MSP of 92.86 €/MWh for a manure-based plant, likely due to lower local production costs and less reliance on expensive technologies [67]. A similar trend is seen in Sweden, where the large-scale woody biomass plant (Thunman et al.) reports a very low MSP of 51.64 €/MWh, reflecting the advantages of large-scale production and possibly lower feedstock costs [68].

The data indicate that location plays a significant role in both CAPEX and MSP. Differences in labor, energy markets and government policies contribute to the variability in costs across different countries. Countries such as Ireland and England have higher production costs and MSPs, likely due to more stringent regulations and higher labor costs, but they may also benefit from stronger government incentives to support renewable energy. In Sweden, despite the complexity of technologies such as gasification and methanation, large-scale operations and favorable local conditions result in much lower CAPEX, production costs and MSP, demonstrating how geographical factors can make biomethane production more competitive.

Figure 9 presents the distribution of CAPEX (a) and production costs (b) across various biomethane production technologies, derived from Table 1. More complex processes such as gasification (G), methanation (M), chemical methanation (CM) or biological methanation (BM) exhibit significantly higher CAPEX and production costs than simpler options such as anaerobic digestion (AD) and biogas upgrading (BU). This is due to the technical requirements for gasification and methanation, such as high-temperature reactors and advanced gas cleaning systems.

AD, utilizing widely available feedstocks such as organic waste and manure, exhibits the lowest CAPEX and production costs, making it ideal for smaller-scale operations. Biogas upgrading shows moderate costs due to simpler purification technologies. Chemical and biological methanation fall between these extremes, highlighting their intermediate complexity and potential for cost reductions through further process optimization.

The analysis reveals a trade-off between cost and complexity, with gasification and methanation offering greater flexibility and higher biomethane yields but at increased expense. Technological advances, especially in methanation, could reduce this cost gap, improving economic viability for larger-scale applications.

Despite many studies providing valuable comparisons of plant costs related to size, location, technology and feedstock type, some fail to detail these parameters—a notable limitation. To enable a more comprehensive economic analysis, metrics such as net present value (NPV) and payback period (PBP) should also be evaluated to assess profitability.

Table 1. Capital expenditure and production costs reported in the reviewed documents for biomethane production via gasification and/or methanation, including feedstock type, location and annual biomethane production.

Technology	Feedstock	Location	Plant Capacity (MW)	Production [1] (MWh/Year)	CAPEX (M€)	CAPEX (k€/MW)				Production Cost (€/MWh)	MSP [2] (€/MWh)	Ref.
						Total	G	M	E			
AD + M	Organic waste	Italy	1	7920	1.59	1592	-	-	-	212.37	-	[29]
	Manure	Spain	1	8000	3.39	3391	-	840	1382	86.49	116.94	[67]
	Manure (80%) + other biowaste (20%)	Denmark	4.6	38,385	5.68	-	-	-	-	47.67	66.37	[74]
	Grass silage (80%) and dairy manure (20%)	Ireland	5	39,600	7.80	1560	-	938	-	217.17	143.80	[73]
	Sewage sludge	England	10.6	84,800	22.53	2125	-	761	1462	148.01	185.82	[69]
AD + BU + M	Grass silage (80%) and dairy manure (20%)	Ireland	5	39,600	8.81	1762	-	938	-	226.77	150.84	[73]
AD + G + M	Forestry biomass and sludge	Portugal	0.475	3040	7.49	11,709	8661	42	2659	110.22	182.30 [3]	[70]
	Sewage sludge	England	12.8	102,080	35.93	2816	277	761	1462	145.20	191.43	[69]
AD + P + M	OFMSW	Sweden	n.d.	3080	-	-	-	-	-	24.17	147.82	[75]
G + M	Manure	Spain	1	8000	3.87	3871	608	955	1663	105.58	92.86	[76]
	Wood chips	Lithuania	1	8000	4.25	4253	295	246	63	418.94	-	[66]
	Crude glycerol	Canada	16.1	128,800		6679	498	899	1408	231.83	147.44	[72]
	Woody biomass	Sweden	20	160,000	139.39	6970	149	98	-	60.6	-	[68]
	n.d.	Sweden	48	-	-	-	-	-	-	-	141.12	[77]
G + P + M	n.d.	Sweden	170	4634	-	-	-	-	1000	-	-	[71]
CM	n.d.	Switzerland	1	7920	3.16	3161	-	-	-	126.01	-	[78]
		Hungary	1	8000	4.98	4984	-	600	1100	123.75	56.31	[79]
	Landfill biogas	France	n.d.	35,665	-	-	-	-	-	-	80.00	[80]
	CO_2 from flue gases	Spain	7000	58,100,000	64.30	9186	-	-	-	46.82	-	[81]
BM	Biogas from an anaerobic digester	Denmark	2.67	21,146	2.62	981	-	55	752	132.83	135.34	[82]

AD—Anaerobic Digestion; BU—Biogas upgrading; M—Methanation; G—Gasification; P—Pyrolysis; CM—Chemical methanation; BM—Biological methanation; E—electrolysis; n.d. — not defined. [1] For annual biomethane production, 7920 h of operation per year (330 days) were considered whenever not disclosed in the assessed documents; [2] MSP—Minimum selling price; [3] Average.

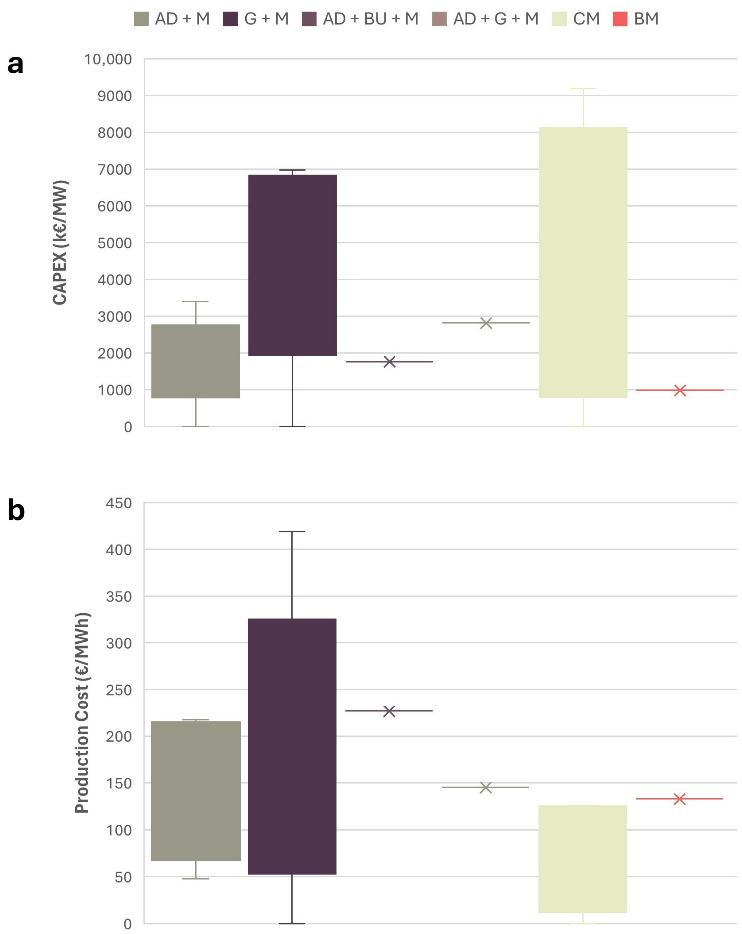

Figure 9. Distribution of CAPEX (**a**) and Production Costs (**b**) per type of technology used in biomethane production. AD—Anaerobic Digestion; BU—Biogas upgrading; M—Methanation; G—Gasification; CM—Chemical methanation; BM—Biological methanation.

3.3.3. Life Cycle Assessment

In terms of the environmental assessment of biomethane production systems, there are still relatively few studies in the literature that report environmental impacts for systems utilizing gasification and/or methanation technologies. Table 2 provides a summary of these studies, outlining the technology used, feedstock type, scope, functional unit, LCA software and impact assessment method applied in each case. This overview highlights the limited but growing body of research focused on evaluating the environmental performance of advanced biomethane production processes. Each study applied different impact categories for LCA characterization, depending on the chosen impact assessment method. However, several categories are commonly used across studies. One of the most frequently reported is global warming potential (GWP—kg CO_2 eq.), which quantifies the increase in global temperature due to GHG emissions. Another common category is acidification potential (AP—kg SO_2 eq.), caused by emissions of NO_x, NH_3 and SO_x into the air, water and soil, leading to ecosystem damage. Freshwater eutrophication (FE—kg P eq.) is also widely reported, which measures the release of phosphorus-containing substances, causing excessive algae growth and reduced oxygen levels in water bodies. Other frequently calculated categories include marine eutrophication (ME—kg N eq.), resulting from nitrogen emissions into water, which can harm aquatic ecosystems, and stratospheric ozone depletion (SOD—kg CFC-11 eq.), caused by chlorofluorocarbons (CFCs) from refrigerants and aerosols. Ionizing radiation (IR—kg U-235 eq.), linked to exposure to radioactive substances, is also commonly assessed in these studies.

Table 2. Life cycle assessment studies found in the literature for biomethane production systems with gasification and/or methanation.

Technology	**Anaerobic Digestion + Methanation**			**Gasification + Methanation**		**Methanation**
Feedstock	Manure	Pig manure (66.7%wt) and green waste (33.3%wt)	Biogas from a WWTP	Manure	Wood chips	CO_2 from flue gases
Functional Unit (FU)	1 MWh biomethane	1 m^3 biomethane	1 kWh biomethane	1 MWh biomethane	1 MJ biomethane	1 kg biomethane
Database	Ecoinvent v3	Ecoinvent v3	Ecoinvent	Ecoinvent v3	n.d.	Ecoinvent v3.5
Software	SimaPro	SimaPro	OpenLCA v1.10.2	SimaPro	SimaPro 8.3	n.d.
Method	CML	ReCiPe Midpoint (H)	ReCiPe 2016 Midpoint (H)	CML	ReCiPe Midpoint (H) v1.13	EF 2.0
Scope	Cradle-to-gate					
Ref.	[67]	[83]	[84]	[67]	[85]	[81]
	Impacts normalized to 1 MWh of biomethane					
GWP (kgCO_2, e)	98.4 [a]	484.0	3.3 [c]	47.1 [b]	446.4	17.0
AP (SO_2, e)	0.0718 [a]	2.10	0.13 [c]	0.15 [b]	2.52	0.0086
FE (kg Pe)	0.2210 [a]	0.1140	0.0210 [c]	0.0281 [b]	0.0468	5.66×10^{-5}
ME (kg Ne)	-	-	-	-	0.11	157.86
SOD (kg CFC-11e)	-	1.35×10^{-4}	1.40×10^{-5} [c]	-	3.17×10^{-5}	2.44×10^{-7}
IR (kg U-235e)	-	-	-	-	36	1.23

[a]—AD + M; [b]—G + M; [c]—Spain. n.d. — not defined.

To enable meaningful comparison across studies with varying functional units, the values have been normalized to 1 MWh of biomethane production. Table 2 demonstrates notable differences in the environmental impacts of biomethane production systems using gasification and/or methanation technologies. GWP shows significant variability, with the highest impacts observed in systems processing pig manure and green waste (484 kg CO_2 eq.) [83], while biogas methanation from wastewater treatment plants (WWTP) has the lowest GWP (3.3 kg CO_2 eq.) [84]. Acidification Potential (AP) and freshwater eutrophication (FE) are substantially higher in gasification systems, reflecting the emissions of phosphorus and sulfur compounds from these energy-intensive processes, such as in wood chip gasification and methanation (2.52 kg SO_2 eq. and 0.0468 kg P eq.) [85]. In contrast, systems utilizing CO_2 from flue gases for methanation show lower GWP (17 kg CO_2 eq.) but have elevated marine eutrophication (ME) (157.86 kg N eq.), suggesting increased nitrogen emissions [81]. Observing Skorek-Osikowska et al. [67]'s work, it is noticeable that, when the technology exchanges from AD to gasification, the climate change drops to less than one half (from 98.4 to 47.1 kg CO_2 eq.) and the freshwater eutrophication loses one order of magnitude, meaning that this is a promising alternative to reduce environmental damage. Nevertheless, acidification increased, but this increase is not as significant as the decrease of GWP and FE. In addition, when only methanation is used, the impact categories tend to be lower due to the simplicity of the process, mainly AP, FE, SOD and IR, with ME being the only category in which an increase is observed.

Overall, systems involving gasification and methanation exhibit higher environmental burdens compared to simpler processes such as anaerobic digestion and biogas upgrading (as verified in Skorek-Osikowska et al.'s work [67]), primarily due to their greater energy demands and emissions. However, the ability of some systems, such as those using CO_2 or biogas from WWTPs, to recycle waste streams offers the potential for reducing specific impacts, highlighting the trade-offs between technology complexity and environmental performance.

Although these studies provide a preliminary comparison of the environmental impact of biomethane production based on feedstock types and technologies, the analysis is limited due to the narrow range of impact categories considered. A more comprehensive evaluation should include additional categories such as human toxicity, particulate matter formation and resource use (water, metals and fossils). The limited number of LCAs on gasification and methanation further highlights the need for expanded research in this area.

Furthermore, discrepancies in software tools (e.g., openLCA vs. SimaPro) complicate direct comparisons, as different platforms apply varying calculation methods and different databases [86]. Expanding the scope to a cradle-to-grave analysis (or well-to-wheel) would provide a more holistic understanding of the environmental impacts across the entire lifecycle of the final product, enabling more accurate and meaningful assessments.

4. Conclusions and Future Prospects

Recent advancements in biomethane production through biomass gasification and (bio)methanation underline their potential to address global energy demands sustainably. Biomass waste remains a key renewable feedstock, aligning with circular economy principles. While AD is the predominant method for biomethane production, its slow processing and feedstock limitations have stimulated interest in alternatives such as gasification and methanation.

The bibliometric analysis highlights an increasing research focus on these technologies, driven by policies such as the European Green Deal and Renewable Energy Directives. Integrated approaches—such as combining gasification with methanation, with or without biogas upgrading—have shown significant potential to enhance biomethane yields and improve overall system efficiency. Feedstocks such as agricultural waste, organic residue and industrial byproducts have been successfully applied, emphasizing their versatility and availability.

This review highlights key findings that address critical aspects of biomethane production, namely:

- Gasification and methanation systems exhibit higher CAPEX and OPEX compared to AD and biogas upgrading, primarily due to technical complexity. Economies of scale can mitigate costs, but smaller plants face economic challenges.
- Advanced technologies such as SEG and CLG show promise for cost reduction and carbon efficiency but require further development.
- Environmental assessments highlight higher impacts for gasification and methanation systems compared to AD, attributed to greater energy demands. However, integrating CO_2 from flue gases or using wastewater biogas can mitigate some environmental burdens.

It provides a unique synthesis of technical, economic and environmental data across diverse biomethane production pathways, also offering a bibliometric analysis of research trends, identifying gaps in literature and opportunities for technological integration. By combining systematic review insights with bibliometric trends, the paper highlights key areas for innovation, supporting the transition to scalable and sustainable biomethane production.

To further advance biomethane production, future research should focus on:

- Advancing gasification and methanation processes to improve energy efficiency and lower costs.
- Developing more robust and efficient catalysts for methanation, targeting durability and cost-effectiveness.
- Addressing gaps in LCA studies by evaluating diverse feedstocks, functional units, more impact categories and regional contexts to identify environmental hotspots.
- Assessing policy frameworks and market incentives to promote large-scale adoption, ensuring economic feasibility and alignment with decarbonization goals.

By addressing these priorities, biomethane production via gasification and methanation can become a cornerstone of the low-carbon energy transition, contributing to energy security and sustainability.

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