Article

Bibliometric Analysis of Renewable Natural Gas (Biomethane) and Overview of Application in Brazil

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Abstract: In view of the increasing demand for clean energy and the growing awareness of environmental sustainability, a bibliometric study examines the various facets of renewable natural gas (biomethane). Sustainable fuels are gaining importance as an alternative to fossil fuels because they are renewable and can reduce greenhouse gas emissions. In addition, an overview of the use of biomethane was compiled for Brazil. The country was chosen because it is the authors’ home country. These emerging energy sources have the potential to play a critical role in the transition to a cleaner, more sustainable and cost-effective energy landscape, thereby reducing environmental impact and strengthening the resilience of our energy future.

Keywords: biomethane; renewable natural gas; renewable energy sources

1. Introduction

In recent decades, there has been a significant increase in human population and, at the same time, new industrial layouts; thus, the use of conventional fossil fuels has developed greatly. Resource depletion and climate change due to human activities and the excessive burning of fossil fuels are the driving forces for research into alternative clean energy sources [1]. The depletion of fossil fuels, the increasing concerns about climate change and the need to reduce greenhouse gas emissions, in addition to the desire for energy independence and security, have led to the development of various biogas upgrading techniques that can provide a reliable and sustainable source of energy [2]. Increasing pollution and strict emission regulations have increased the demand for alternative green fuels as a sustainable energy source for engines and general industrial applications, which include manufacturing processes, power generation, material handling, transport and other activities that contribute to industrial production and operations [3].

Biogas (upgraded to biomethane) and natural gas (methane) are taking center stage among renewable fuels due to their environmental compatibility; these gaseous fuels have significant environmental advantages over conventional petroleum-based or fossil fuels [4]. A large number of scientific publications with a wide variety of topics has increased the need for review articles in the last decade [5]. In the last twenty years, there has been a large amount of literature on how to improve methane production performance, but few systematic reviews have been conducted [6]. However, there is a lack of practical research on new standards, engine performance and costs for low carbon intensity [7]. The overview of limitations and perspectives highlights a number of opportunities for research areas that can further contribute to increasing sustainability in biofuel production and thus achieving the SDGs (sustainable development goals), since there is little work assessing the actual impact of biofuels on sustainable development [8]. Renewable energy gases such as biomethane are expected to replace natural gas, provided they strictly comply with the quality standards for natural gas, which prescribe maximum levels for various trace chemicals [9].
Biogas is considered one of the most promising alternative renewable fuels, but the raw biogas must be upgraded before it can be used in vehicles or injected into the natural gas grid, and the resulting biomethane must be liquefied to be transported to distant locations [10]. However, in order to sustainably integrate these gases into the current energy mix, their quality must be controlled in terms of their major, minor and trace components in order to maintain the integrity of the infrastructure in which they are burned, transported or stored [11].

An article evaluated a series of coupled computational physics and fluid dynamics models developed with the aim of assessing the feasibility of producing photothermal synthetic fuel from mixtures of biogas (biomethane) and water vapor using plasmonic Ag/TiO$_2$ substrate nanostructures (each 0.1 µm thick) within a boundary layer for heat, momentum and mass transport in a microreactor [12]. The biochemical methane potential (BMP), biodegradability index (BI), competitiveness index (IC), physicochemical properties and elemental composition of cassava vinasse (CV) derived from an ethanol distillery were investigated by experimental analysis and instrumentation [13].

Biomethane (BM) is a highly competitive bioenergy alternative to reduce dependence on fossil fuels worldwide [14]. Biogas is a cornerstone of a clean and sustainable energy portfolio, while hydrogen production from biogas is a key enabler for methane conversion and carbon dioxide valorization to mitigate greenhouse gas emissions stove [14].

The anaerobic digestion (AD) of different organic wastes is a promising technique to increase the production of clean energy (bioenergy) and manure (slurry), reducing stress on the environment [15,16].

Anaerobic digestion is one of the routes available to recover energy from waste through the production of biogas, while reducing organic load and pollutants in the environment [17]. It has attracted the scientific community for its simplicity and ease of handling, and has the potential to use any type of organic waste to produce a mixture of combustible gases, that is, biogas and digested leachate, which has other applications in agriculture, solid biofuels and purification [18].

A study investigates the effect of the specially designed adsorptive packed column system (APCS) on improving biogas quality up to biomethane purity [19]. The production of biogas from food waste with the AD process and co-digestion process achieved high purity of biogas [20].

A study points to the need for the complete cleaning of Renewable Natural Gas (RNG) before its injection into the Natural Gas (NG) network [21].

For the purpose of achieving a flexible and economical energy storage, a transcritical energy cycle study combining CO$_2$ was added to biomethane plants to form a liquefied biomethane storage system [22].

The expected increase in the proportion of biomethane in NG networks could increase fluctuations in the composition of the NG–biomethane mixture in amplitude and frequency [23].

The degree of substitutability of current impure fuels and the net greenhouse gas emissions avoided by using this biomethane is assessed for three different end-use scenarios: electricity production, cooking and road transport [24].

The injection of biomethane into the existing gas infrastructure is a fundamental opportunity to be promoted, but one that leads to increasing complexity in the management of natural gas networks [25]. The same study evaluated the role of line-pack in determining the absorption capacity of the gas network and tested the smart management of pressure set points and injection flow to minimize the reduction in biomethane.

For data from 2021 onwards, the methodology for reporting the main activity of producing CHP plants has been updated to include biomethane that is injected into the natural gas network; in 2018, a new biomethane plant was installed, leading to increases in the blending of biogas with natural gas; and 2017 is the first year that biogas was mixed with natural gas [26].
Biomethane can be used as an environmentally friendly substitute for natural gas for various applications such as transportation, heating and electricity generation [27,28]. The composition of biogas and biomethane is well known in terms of main compounds, which include methane, carbon dioxide and hydrogen sulfide; also, the metal concentrations of natural gas and treated biomethane were compared [29].

Work was carried out in a pilot plant to clean and recover real biogas from anaerobic digestion using the chemical absorption method [30]. A 29-month stability study of reference gas mixtures of 10 µmol mol\(^{-1}\) ammonia in methane and synthetic biogas is also reported [31]. Research carried out the processing of a mixed stream of gases with a typical biogas composition using a gas separation membrane with the aim of producing a stream of purified biomethane [32].

An effective model was developed that takes into account both the molecular chemistry of the solvent with the partition coefficient of CO\(_2\) and methane in the mono-ethanolamine (MEA), and the process parameters to upgrade the biomethane for use as a renewable fuel, as well as sustainable waste management. In order to optimize the process, several sensitivity analyses were carried out with variations in the number of absorption and removal stages [33].

A study investigated the performance of a multi-cylinder SI engine using 10%, 20% (ethanol, methanol, methyl acetate) and 100% compressed biomethane gas (CBG) as alternative fuels. The minimum average gas emission was found in CBG at RPM minimum and maximum, indicating that CBG offers the best emission result with engine performance compared to all alternative fuels [34].

A comparison of the operational performance of biomethane with natural gas and gasoline was carried out in a small pickup truck. Three different purity levels were used for biomethane, with the lowest having a methane concentration of 83%. The study compares the performance of a biomethane-powered vehicle by measuring its power, torque, emissions, fuel efficiency and cost to examine the benefits and problems of using biomethane [35].

The composition of biomethane was studied in an experimental pilot plant that treats organic waste through dry anaerobic digestion, using a solid ash matrix obtained from a wood-fired central heating plant. European limits were considered and respected for the injection of biomethane into the gas network [36].

The selective removal of CO\(_2\) during biogas upgrading and subsequent sequestration can transform the biomethane produced from a carbon-neutral energy source to a carbon-negative energy source. Such technology can be considered as bioenergy with carbon capture and storage (BECCS), that is, as a negative emission technology (NET) [37].

Biomethane is more suitable to become an engine fuel than other gaseous fuels due to its bioderived nature and burning characteristics [38].

The technical feasibility of a small-scale, environmentally sustainable system is lacking in the literature [39]. Circular economy concepts for electricity production could be adopted for the transition to green energy [36].

The scarcity of studies on the effects of heat transfer on the rupture curves and bed temperature profile of the biomethane upgrading process in the literature leads us to investigate these effects in more detail [40].

As mentioned, biomethane is a renewable and clean energy source which can be used to reduce greenhouse gas emissions and support sustainable development; it is used in the production of electricity, for heating purposes and as fuel for vehicles that have engines [20,41,42].

Several studies were carried out to reduce biogas from waste, aiming to make full use of residual biomass in a circular economy context [43]. The waste and biomass used in research for biomethane production were the following: slaughterhouse waste as substrates with high organic content [44]; different percentages of fats, oils and grease in anaerobic co-digestion with slaughterhouse wastewater [45]; waste from the agri-food sector, such as chestnut shells [46]; co-digested sheep manure and kitchen waste [47]; effluents from E. coli
fermenters through anaerobic fermentation using wastewater treatment sludge [48]; straw corn coupled with disk refining to increase biomethane production [49]; and avocado oil and wastewater, which can potentially be digested anaerobically to produce biomethane [50] from pine sawdust [51], okra waste and pig manure [52]; however, landfills and ETEs are more viable sources of biomethane production in terms of cost efficiency [53].

In detail, by-products represent a cheap, renewable and abundant raw material, useful for several new products, including biochemicals, biomaterials and, above all, biogas, which are taking on an increasing role [54].

The potential for biomethane production through anaerobic digestion depends not only on the availability of resources in the territory considered, but also on their physico-chemical characteristics [55].

Most biomethane production is obtained through the anaerobic digestion process, which is an important tool for sustainable energy production [44]. It can be used with different organic waste and is a promising technique to increase the production of clean energy (bioenergy), thus reducing stress on the environment [15,56,57]. Another technique that can also be used is the gasification of biomass, which generates a gas mixture (synthesis gas) that constitutes a rich source of carbon and energy for the production of second-generation renewable fuels, such as biomethane [58]. A new approach for the production of CH$_4$ with high yield and biomass selectivity using a pressurized fixed two-stage bed reactor system incorporating hydropyrolysis and gas-phase hydrotreatment is also considered [51].

Still in the context of biomethane production, some research has evaluated a green route for biomethane and green hydrogen production by integrating pressure swing adsorption with steam methane reforming using low-grade biogas mixture as feedstock [14] and the performance of a custom optical feedback cavity enhancing absorption spectroscopy (OFCEAS) instrument for determining the composition of energetic gases [59]. A proposal for the simultaneous decarburization, desulfurization and dehydration of biogas with deep eutectic solvent (DES) based on quaternary ammonium salt was also developed [59].

2. Bibliometric Search Analysis

2.1. Bibliometric Database Training

The analysis of blends of renewable natural gas and biomethane is a promising approach to improve the quality of fuels used in different sectors such as transport, industry and power generation. Considering that blends of these renewable gases with natural gas, which are currently widely used in industrial processes and generally in many other activities, may be present in different proportions, the opportunity arises to adapt their properties to the specific needs of each application. In this sense, continuous advances in production, storage and distribution technologies are essential to realize synergies between renewable gases. To start building a database, it was important to clearly define the scope of the topic. In this case, the research focused on finding studies dealing with technical, production and configuration data relevant to this field. In addition, the prospects in the consumer market for renewable natural gas or biomethane were investigated. The research began with a search for the most important keywords on the Scopus platform. A bibliometric analysis was carried out in the Scopus database, searching for the keywords “renewable natural gas” or “biomethane” in the titles and articles. Initially, 1376 references were found that contained the selected keywords. However, the search gave articles published since 1988 (Figure 1). Considering that the main objective is to show current scenarios, new filters were applied to improve and select articles according to the expected perspectives. We first included the words “mixture” or “blend” in the search to select articles specifically dealing with these topics, as one of the objectives of this research is also the analysis of blends containing renewable natural gas/biomethane, and then the following filters were selected, to obtain a result with a high search relevance selection of the last 10 years of publication, as seen in Figure 2. Then, topics were selected from the
subjective area of publication, type of documents, articles or literature reviews, disregarding books or conferences, and finally we restricted to articles published in English.

Figure 1. Number of publications per year considering the first stage of researched articles, based on data from the Scopus platform, until July 2023 (source: the authors).

Figure 2. Number of publications per year considering the last 10 years, based on data from the Scopus platform, until July 2023 (source: the authors).

These documents were ordered chronologically according to the most recent year of publication, taking into account the last 10 years, since articles with more than 30 years of publication appeared in this study and the current scenarios are very different, whereupon the articles with the highest number of citations but more recent publications were also taken into account. This information was essential for carrying out several bibliometric analyses. The information contained in these articles was extracted in CSV format (comma-separated values) from the Scopus database. To ensure the quality of this information, records with inconsistent data were removed from the current analysis.

The bibliometric searches were carried out using chains linking topics across the title field of articles published up to July 2023. After applying these filters, 269 articles were selected for a more detailed reading selection and the start of the research, initially considering the most recent and most cited for conducting this bibliometric analysis.

2.2. Results

From here onwards, the entire discussion of bibliometric analysis is based on the 269 selected articles. The number of articles published by the authors were analysed, and the 10 authors with the highest number of publications were selected. These are shown in Figure 3. Then, an analysis was carried out containing the highest number of citations of the authors with the highest number of publications (Figure 4). This article argues that the relevance of a publication is associated with the timeliness of the publications and the significant numbers of citations it receives. Therefore, the year of publication and number of citations were used as an important weighted indicator of relevance.
Highly cited publications can be considered as references to provide perspective on a topic or provide a solution to a problem.

According to this analysis, in the last 10 years, the topic with renewable fuels, especially blends between natural gas and biomethane, has gained considerable attention, as the large number of publications has increased, especially since 2019 (Figure 2).

It is also important to highlight the thematic areas of Energy, Chemistry, Environmental Sciences, Engineering and Chemical Engineering, which are areas that are directly correlated to the development of techniques that allow the use of renewable gases or biomethane in industrial processes, or even areas that are linked to sustainable development, as shown in Figure 5.
One of the selection topics was determined by the type of publication, with only works published in an article format and in a review format being selected, considering the last 10 years of research on the topic. The majority of works were published in article form, representing a total of 92% of the results presented by the Scopus platform, and only 8% were reviews, as shown in Figure 6.

In terms of circulation, these articles can be found in more than 140 different journals. However, 19% of the published articles are found in 10 of these journals, with the journal of Anna University of India being the one that published the most articles in the 10-year period, with 7 articles. The journals Chiang Mai University, from Thailand, Universiti Sains Malaysia, from Malaysia, Jiangsu University and Beijing University of Chemical Technology, both from China, Universitas Riau, from Indonesia and Al-Qasim Green University, from Iraq, appear in succession with 6 publications each, as shown in Figure 7; the other journals contain between 5 and 4 publications.
These results demonstrate that on all continents, there is broad interest in research on renewable natural gas/biomethane, and this research is being published in large university centers. The largest numbers of publications are concentrated in China, India, the United States and Brazil, as seen in Figure 8, which facilitates access to a reasonable number of researchers, and there is still a lot to be researched in this area, since mixtures containing this type of fuel can be applied in many commercial, industrial and domestic sectors.

The countries that feature the most publications on the topic are China first with 16%, followed by Italy with 15%, the United States with 10%, India with 9% and finally Brazil with 4%, as shown in Figure 9. These five countries represent 54% of the publications on the selected topic.
A network graph containing the main highlights of keywords was constructed to identify trends in the use of biomethane and to understand the relationship between the techniques developed for gas mixtures using fuels produced from renewable sources. To build this map, as seen in Figure 10, a dictionary of keywords extracted from articles in the Scopus database was applied, and the pre-treatment of these data was carried out so that there were no repetitions of keywords with the same meaning (for example: gas and gases, fuel and fuels) which were written in slightly different ways.

After the necessary executions of this pre-treatment, four main keyword network clusters were created: red, green, blue and yellow. As expected, biogas, biomethane, methane, biofuels, biofuel production, biogas production and carbon dioxide are the keywords that are most prominent, as shown in Figure 11. The four clusters substantially present the highlighted keywords of this study. The focus of the research is that biomethane is interconnected with the other clusters, interacting mainly with the production of biofuels, biomass, biogas production, biogas, sustainable development, fuels and carbon dioxide, among others.
Figure 11. Details of the keyword co-occurrence network (minimum of five occurrences) showing the links between the keyword biomethane and the other clusters, information based on the selection of articles carried out in the Scopus database and VOSviewer as bibliometric mapping software. Period considered 2013–2023. Source: the authors.

3. Biomethane in Brazil

3.1. Overview

Brazil has historical concerns with renewable energy sources, mainly because it is the largest tropical country in the world, receiving intense solar radiation, which is the basis for biomass production [60].

Several technologies have been disseminated to digest organic waste, capture biogas and provide energy. Despite numerous efforts to finance biogas technology in Brazil, uptake remains slow. This may be due to the low recognition among key actors supporting technology with resources in a broader innovation system [61].

The Brazilian Association of Biogas and Biomethane (ABiogás) reports a biogas production potential of 41.4 billion m³ per year in the sugar-energy sector. However, less than 2% of this value is a success, reducing the fact that biogas is still chemically, economically and politically invisible [62].

Biogas production in Brazil provides three main categories of substrates, as described in Table 1 [63].

Table 1. Three main categories of substrates for biogas production in Brazil [63].

<table>
<thead>
<tr>
<th>Source</th>
<th>Description</th>
<th>Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>It involves animal husbandry activities such as poultry, cattle, pig and sheep farming, among others</td>
<td>Animal manure, effluent from waste management (urine, feces, washing water, etc.), feed remains, carcasses of dead animals that have not been slaughtered, among others.</td>
</tr>
<tr>
<td>Industry</td>
<td>Includes slaughterhouses and slaughter houses, sugar and ethanol plants, starch and starch factories, breweries, vegetable oil, gelatine, among others.</td>
<td>Industrial effluent and other organic waste from the industrial process.</td>
</tr>
<tr>
<td>Sanitation</td>
<td>It includes sanitary landfills, organic waste treatment plants and sewage treatment plants.</td>
<td>Urban solid waste (MSW) deposited in landfill, MSW segregated at source (organic fraction), fruit and vegetable waste, food waste, supermarket sanitary sewage.</td>
</tr>
</tbody>
</table>
In Brazil, biogas is used mainly in three ways: in the generation of thermal energy, in the production of electrical energy and in the production of biomethane [64]. Although biogas technologies in Brazil have enormous potential and a long history, few studies have examined biogas in Brazil as a technological field [64], even though it contains a thriving agricultural sector and has high potential for using agricultural waste in the production of biogas and, consequently, high potential for energy generation, as indicated by data from the Biogas Panorama in Brazil Ciobiogas, as seen in Figure 12.

Agricultural, animal, industrial and food waste are excellent substrates used for the production of clean and sustainable energy in a circular economy context [64].

Of the volume of biogas produced in these units, the sanitation sector was responsible for 74% of the total volume produced, followed by the industrial (16%) and agricultural (10%) sectors.

Due to relatively low investment, operating costs and technical requirements, landfills are still a more widespread alternative for the final provision of municipal solid waste. The biogas produced in the landfill, a renewable energy source, can be an important alternative for generating electricity. Brazil has a significant number of landfills in operation, which receive most of the MSW collected. However, the country has only 17 landfill biogas power plants [65].

In terms of the volume of biogas for energy purposes, the increase in annual production was very representative, with an increase of 22% compared to the previous year, going from 2.3 billion cubic meters in 2021 to 2.8 billion Nm$^3$ in 2022. The growth rate of biogas production in plants in operation from 2022 was higher than the average recorded in the previous three years (average growth of 17% per year) [65].

Research evaluated the performance of a custom Optical Feedback Cavity Enhancing Absorption Spectroscopy (OFCEAS) instrument for determining the composition of energetic gases [66].

A work was prepared with a proposal for the simultaneous decarburization, desulfurization and dehydration of biogas with a deep eutectic solvent (DES) based on quaternary ammonium salt [59].

Biomethane specifications in Brazil are regulated by the following resolutions [67,68]:

![Figure 12. Accumulated volume; biogas (Nm$^3$) [63].](image-url)
• ANP Resolution No. 886/2022—Establishes the specification and rules for approving the quality control of biomethane from landfills and sewage treatment plants intended for vehicular use and residential, industrial and commercial installations, to be sold in national territory.

• ANP Resolution No. 906/2022—Provides for the specifications of biomethane from agroforestry and commercial organic products and waste intended for vehicular use and residential and commercial installations to be sold throughout the national territory.

3.2. Economic Aspects

In mid-2023, the price of biomethane in Brazil was USD 0.774/m$^3$ (m$^3$ at 1 atm and 20 °C). At the same time, the price of natural gas for consumers using more than 2 million m$^3$/month was USD 0.708/m$^3$. The average lower heating values (LHV) of Brazilian biomethane and natural gas are 34.25 and 39.66 MJ/Nm$^3$, respectively.

Biomethane is supplied by trucks with a capacity of 10,000 m$^3$/day, which would replace 8636 m$^3$/day of natural gas (8636 = 34.25/39.66 × 10,000). At a cost of USD 7740/day compared to USD 6114/day, this leads to a cost increase of USD 1626/day per 10,000 m$^3$/day of biomethane.

This cost increase is not mitigated by carbon credits, because in Brazil these credits belong to the landfill that supplies the biogas for upgrading.

Biomethane is therefore currently more expensive for consumers than natural gas. However, this scenario could change over the years, as the price of natural gas, a fossil fuel with no unlimited reserves, is expected to rise. If carbon credits are allowed for end users, the carbon credits can also be used to reduce the cost of biomethane.

4. Conclusions

This article presents a bibliometric study on the various facets of renewable natural gas (biomethane). An overview of the use of biomethane in Brazil was also given, along with a brief analysis of the costs compared to natural gas, in figures from 2023.

The idea was to create a guide for authors interested in compiling the main publications in this area. The main points discussed in the bibliometric study were the following:

• Number of publications per year considering the first level of articles researched;
• The increase in the number of publications per year over the last 10 years;
• Number of documents published per author;
• Number of citations per author;
• Distribution of scientific publications by subject area;
• Number of publications by journal with more than four publications;
• Number of publications by country;
• Percentage of publications by country;
• Co-occurrence network of keywords (at least five occurrences);
• Details of the network of keywords (at least five occurrences) showing the links between the keyword biomethane and the other clusters.

Finally, an overview of the situation of biomethane in Brazil was given. The cost of the renewable fuel is not offset by carbon credits in Brazil, as these credits are linked to the landfill that supplies the biogas for upgrading. Biomethane is currently more expensive for consumers than natural gas. However, this situation could change in the coming years as the price of natural gas—a finite fossil fuel resource—is expected to rise. Should end users be allowed to utilize carbon credits, these credits could potentially help to reduce the costs associated with biomethane.

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