International Journal of Design & Nature and Ecodynamics
Vol. 18, No. 3, June, 2023, pp. 565-572
Journal homepage: http://iieta.org/journals/ijdne

Trend in Publications Related to Biomethane Using a Bibliometric Approach

Donaji Jiménez-Islas[1], Miriam E. Pérez-Romero[2,3], José Álvarez García[4*], Ignacio Ventura-Cruz[5]

[1] Renewable Energy Division, Higher Technological Institute of Huichapan, TecNM/campus Huichapan, 42411, Mexico
[2] International Doctoral School of the UEx, Universidad de Extremadura, Badajoz 06006, Spain
[3] Business Management Division, Higher Technological Institute of Huichapan, TecNM/campus Huichapan, 42411, Mexico
[4] Department of Financial Economic and Accounting, University Research Institute for Sustainable Territorial Development (INTERRA), Faculty of Business, Finance and Tourism, Universidad de Extremadura, Cáceres 10071, Spain
[5] Mechatronic Division, Higher Technological Institute of Huichapan, TecNM/Campus Huichapan, 42411, Mexico

Corresponding Author Email: pepealvarez@unex.es

https://doi.org/10.18280/ijdne.180308

Received: 3 January 2023
Accepted: 28 March 2023

Keywords:
biogas, methane, Scopus, biofuels, Gompertz

ABSTRACT

The emission of greenhouse gases emitted into the atmosphere by the burning of fossil fuels has allowed the development of biofuels such as biomethane. The aim of this research was to explore the characteristics of biomethane literature from 1978 to 2020 based on the database of Scopus and its implications using indicators bibliometrics. The information in the database was analyzed through the Gompertz model to determine the specific growth rate over the years. Also, maps were elaborated with the VOSviewer software to show in a visual way the collaboration between authors and keywords related to the topic of study. Documents were examined in a variety of aspects of the publication characteristics such as document type, language, authorship, countries, institutions, journals, high-cited papers. Results showed that the evolution of publications grew exponentially from 2006 to 2020, the specific speed of growth determined with the Gompertz model was 0.4 0.095 years^{-1} (R^2>0.99). 52% of publications are concentrated in five countries (Italy, India, China, the United States and Spain). Bioresource Technology is the journal with the highest number of publications and citations, the authors publish in quartile 1 and 2 journals. The biomethane topic has a growing number of publications and citations due to the collaboration between researchers from different countries. The present work can be contrasted with the analysis of bibliographic indicators with other databases to determine the level of collaboration with other journals with different index.

1. INTRODUCTION

Global energy demands for conventional fossil fuels have risen as a result of population growth and urbanization [1]. This would raise global temperatures, resulting in more heatwaves, droughts, and floods, posing serious health and economic risks, because each country has its own policies and socioeconomic characteristics [2]. As society, with the introduction of oil the balance was lost due the development of new synthetic products of fossil origin [3] and we need to reduce global greenhouse gas emissions where the use of biofuels can be an option to improving energy security also bring an increase in food production [4-6]. Biofuels can be defined as fuels from biomass, that offer different types of biofuel such as liquid, solid and gaseous.

Liquid biofuels play an important role in the global transition to renewable and sustainable energy sources [6], such as forest residues [7], agricultural material related to food crops [8], no compete with food, such as switchgrass [9], eucalyptus [10] and solid biogenic waste [6]. Also, the liquid biofuels from biomass have become a natural complement for gasoline (as an additive) in the transport sector [11], nowadays, the most common liquids biofuel are bioethanol, biodiesel and biomethanol. Solid plant biofuels, such as wood and agricultural residues, play an important role within the biomass groups while having no negative impact on the food industry; similarly, wood pellets are the only solid biofuels with a global market that is continuously expanding [12]. The gaseous biofuels are biogas, hydrogen and syngas, which could be used as a source of electricity, heating, and transportation fuel [13]. Nevertheless, bio-hydrogen and biogas are the most important gaseous biofuels, it can be generated from lignocellulosic biomass hydrolysates or food waste via anaerobic fermentation [14, 15].

Biogas is an appealing energy source for reducing greenhouse gas emissions, containing approximately 40 to 75 percent CH_4 and an unavoidable volume of CO_2 depending on the feedstock; waste landfills, agricultural waste treatment plants, sewage end-treatment plants, and animal manure treatment plants are the primary sources of biogas [16, 17].

Biogas technologies (with biomethane upgrade) are clearly capable of generating advanced gaseous fuels from these feedstocks [18]. Also, biomethane development and use will open up new doors for society for reducing greenhouse gas emissions and promote human health [16, 19]. Some authors have reported lignocellulosic biomass pretreatment processes for biomethane production, among them we can mention: the size reduction [20], chemical (acid, alkali and oxidisin agents), thermal (explosion of steam), biological (fungi) and hybrid combinations [21, 22].

In Europe with the economic incentives have fostered that from 6227 in 2009 to 17432 in 2017, the number of biogas production plants has increased, in Germany and Italy the number of biogas plants was 10971 and 1655, respectively [23]. And as a considerable fact in the biogas sector we can mention that in 2017, the global biomethane market was estimated at USD 0.62 billion.

By 2026, $4.96 billion industry is expected to have grown at a rate of 26% per year (8 times the growth compared to 2017), several countries have set ambitious targets for biomethane as natural gas replacement for household consumption, such as France and UK [24].

Biomethane derived from by-products or agricultural residues, as well as biodegradable household waste, are commonly preferred over biomethane derived from energy crops; increased awareness and information will assist consumers in making more informed decisions about biomethane derived products [25].

At present, knowing the development of scientific publications allows to identify the contributions of authors in different areas of knowledge, the need to establish a starting point of the literature of biofuels and specifically biomethane allows to discover the interaction of authors, countries and emerging areas in the subject of study.

1.1 Theoretical framework of bibliometric analysis

Some of the publications relating to biomethane were published using a bibliometric analysis of biomass, thus, several research teams have been studying how to improve biogas for biomethane processing. A study of the 100 to cited papers in the field of biogas was carried out using the Web of Science database, with the majority of documents released between 2006 and 2011 [26].

The biomethane field is receiving a rising number of papers and scientific interest, necessitating the development of a quantitative method to examine scientific output and study trends in this field. The bibliometric analysis is a quantitative analysis to assess the amount of research work in a topic [26-28].

In general, the bibliometric analysis can be used to describe the development of biomethane research, this method is systematic and requires a wide variety of statistical techniques of bibliography counting to evaluate and quantify the growth of global research trends from different perspectives [29-31].

There is no bibliometric analysis of trends on biomethane, and this research uses the Scopus database to perform bibliometric analysis of the key patterns in order to fill this research void. In addition, the study adds to our understanding of biofuel liquid biomethane and its connections to various topics, which will aid researchers in conducting new research on the topic.

2. MATERIALS AND METHODS

From 1978 to 2020, the literature was retrieved using the following search terms in the Scopus database “biomethan*” OR “bio-methan*” AND “digest*” AND “biogas” options, with “title”, “abstract”, and “keywords” to achieve the research production that has been examined on a global scale. The sign (*) in the search box was used to obtain both singular and plural versions of a keyword, and the marks (" ") were used for exact phrases search. The number of documents found under the search criteria was 1477. The data were analyzed using Microsoft Excel. Bibliometric indicators were extracted and analyzed both quantitatively and qualitatively.

The time trend of the publications was analyzed by fitting mathematical models with the solver-function. The Gompertz growth model (1) and normalization equation (2) were used to adjust the profile of documents in the field.

$$P(y) = ae^{-be^{-\mu t}} \quad (1)$$

$$\left(P_{(y)Scopus} - P_{(y)model}\right)^2 \quad (2)$$

where, the symbol P(y) represents the cumulative volume of documents by year, “μ” the specific growth rate of publications, “a” the asymptotic publications, “b” an integration constant related to initial publications, “t” is time, P(y) Scopus publications reported on Scopus database and P(y) model estimated publications by model.

The data of Scopus was fitted to determine the value of specific growth rate (μ), the results of Scopus and the generate by model were analyzed using regression curve fitting with statistical significance set at p=0.05 with data analysis of Microsoft Excel and it was estimated the determination coefficient (R^2) . Also, the data download from Scopus database was imported into Microsoft Excel and VOSViewer software which was used to create network maps. The instructions are the next: Create a map based on bibliographic data, read data from bibliometric database, files, type analysis Co-authorship-countries (unit of analysis), full counting, maximum number of countries per document (25), minimum number of documents of a country (10). To ensure that the results were reliable and correct, the Microsoft Excel program was used to eliminate any possible duplicates [32].

3. RESULTS AND DISCUSSION

3.1 Document type and publication language

Of the 1477 documents found in the database, 78.19% are articles, 11.87% conference paper, 6.17% review articles and the remaining 3.77% are Book, book chapter, notes and conference review.

As English is a global language, most research papers in our database were published in English [33]. Of 1477 research documents, 97.77% were written in English (n=1444 of the total documents), followed by Chinese (n=11), French (n=11), Portuguese (n=3) and Spanish (n=2). The less frequently used languages were Finnish (n=1), Polish (n=1), Russian (n=1), and Slovenian (n=1). The most researchers will publish the research results in English language types in order to facilitate communication and improve the influence of their research [34].

3.2 Trends of publications

Figure 1 illustrates the trends in the number of scientific publications published from 1978 to 2020. As can be observed, the research trends can be concretely divided into three stages: i) In the first stage from 1978 to 2002, it was a stage which slowly increased and few documents were published on biomethane topics. ii) The second stage from 2005 to 2010, the number of publications on the topic quickly increased. iii) the third stage, the number of biomethane related publications significantly increased from 2010 onwards.

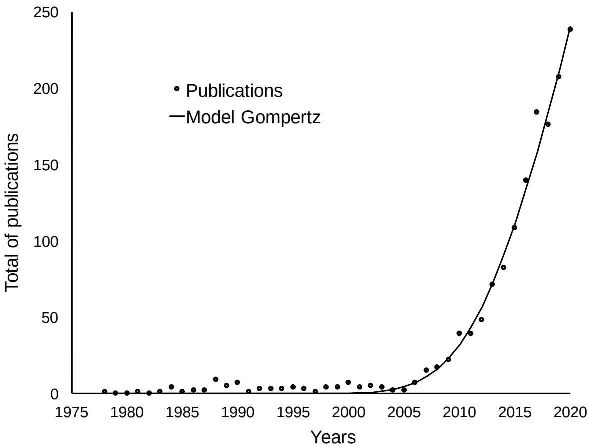

Figure 1. Total number of publications for biomethane research

In this work, we observe that the volume of publications covering grows exponentially and for this reason, the Gompertz model to fit the data. As can be seen in Figure 1, a lag phase was observed during the first 28 years. The Gompertz model fitted the data very well (coefficient of determination R^2>0.99) and a rate of growth 0.095 $year^{-1}$. A recent study examined the rate of publications of biofuels in Latin America, where the logistic model was used with a rate of growth of 0.19 to 0.21 ($year^{-1}$) [35]. In the same way, it was analyzed quantitatively the growth of publications research with Web of Science (WoS) and Scopus database, the results indicated that WoS and Scopus had a rate of 0.29 y 0.31 $year^{-1}$ in the topic of bioethanol [36]. The Logistic model can be used to determine the evolution in the next years in the field of biomethane or biofuels in general.

3.3 Most publications countries

The research results show that Italy, India, China, USA, Spain are the five biggest contributing countries on biomethane with more than 100 total publications, Table 1. Of the top 20 countries, two were from America, six from Asia, eleven from Europe, one from Oceania, while no countries were from Africa. Italy had the largest number of total publications (13.8%), followed by India (12.8%), China (10.2%), the United States (8.3%) and Spain (7%), in this case, the top 5 countries concentrate more than 50% of the publications of the biomethane field.

The total number of publications (TP) and total number of citations (TC) are the two basic metrics used to assess the amount and quality of scientific publications in general. The most active authors, organizations, and countries are represented by the indicator TP [37]. The number of citations, on the other hand, is a clear indicator of the content of a paper. As a result, the TC indicator aids in determining the accuracy of scientific articles [37]. Spain and Italy are leading in the TC, however to our TC/TP (number of citations/ number of publications) relationship in Table 1, Belgium with 63.81 citations/documents is the most cited country, followed by Ireland (55.20).

These country level contributions can be visualized using a co-authors network map between countries (Figure 2), the nodes (frames) represent the countries that collaborate on biomethane topics, and their dimensions are proportional to the number of documents they contain. The lines that interconnect these nodes show the strength of the collaboration [38]. A remarkable link can be seen in this field between Italy and Germany, India and South Korea, China and Sweden, United States and Spain, Spain with Chile and Brazil, Figure 2.

Table 1. Top 20 most productive countries on biomethane

Ranking of countries	TP	% of total publications	TC	TC/TP
Italy	203	13.8%	4832	23.80
India	189	12.8%	2444	12.93
China	150	10.2%	2386	15.91
United States	122	8.3%	2611	21.40
Spain	103	7.0%	4944	48.00
Germany	99	6.7%	3285	33.18
United Kingdom	65	4.4%	2123	32.66
Ireland	60	4.1%	3312	55.20
Sweden	53	3.6%	1469	27.72
Denmark	46	3.1%	2343	50.93
France	46	3.1%	1359	29.54
Malaysia	44	3.0%	546	12.41
Belgium	37	2.5%	2361	63.81
Brazil	34	2.3%	388	11.41
South Korea	34	2.3%	506	14.88
Poland	33	2.2%	365	11.06
Thailand	33	2.2%	200	6.06
Iran	29	2.0%	475	16.38
Australia	28	1.9%	794	28.36
Netherlands	27	1.8%	1947	72.11

TP, Total number of publications; TC, Total number of citations

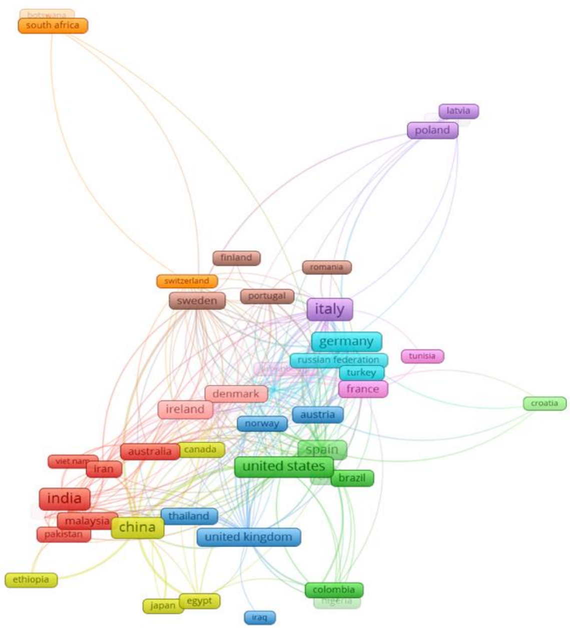

Figure 2. Collaborative network map between countries in biomethane research

There were 11 clusters (54 items) with different colors, the authors in the same cluster almost always indicated that they studied in the same area and collaborated closely [39]. The largest cluster consisted of nine countries (red color); the second cluster consisted of seven countries (green color); see Figure 2. According to network centrality, India, China, Italy, and the United States occupied the core of the international cooperation network of these 20 most active countries.

3.4 Institutions

The affiliation of at least one author was used to estimate the contribution of various organizations to a publication [40]. Table 2 lists the top ten most profitable institutions. First is the University College Cork (47), followed by Danmarks Tekniske Universitet (29), Leibniz-Institut für Agrartechnik und Biookonomie e.V. ATB (23), Beijing University of Chemical Technology (20) and others with less than 20 TP.

The degree of interaction through international collaboration tends to receive more citations than those obtained by individual countries [41].

Table 2. Top 10 most productive institutions/organizations on publications from biomethane

Ranking of organization	TP	Country
University College Cork	47	Ireland
Danmarks Tekniske Universitet	29	Denmark
Leibniz-Institut für Agrartechnik und Biookonomie e.V. ATB	23	Germany
Beijing University of Chemical Technology	20	China
Isfahan University of Technology	17	Iran
Politecnico di Torino	16	Italy
Universitá degli Studi di Milano	16	Italy
China Agricultural University	15	China
Universidad de Valladolid	15	Spain
Ministry of Agriculture of the People´s Republic of China	15	China

The global distributions of institutions that published documents for biomethane show a broad geographical coverage classified into seven groups. The first group with three institutions of China (Beijing University of Chemical Technology, China Agricultural University and Ministry of Agriculture of the People´s Republic of China); the second group with two institutions of Italy (Politecnico di Torino, Universitá degli Studi di Milano); and other countries with one institution, Table 2.

3.5 Publications distribution in the biomethane subject areas

The analysis of the documents allows obtaining an overview of the biomethane topic in the various academic fields. On Figure 3, it can be shown that "Environmental Science" is the most highly populated research area, followed by "Energy", "Chemical Engineering", "Engineering", "Agricultural and Biological Sciences" and "Immunology and Microbiology"; the areas described above represent 90.32% of the total found in the Scopus database on the subject of biomethane.

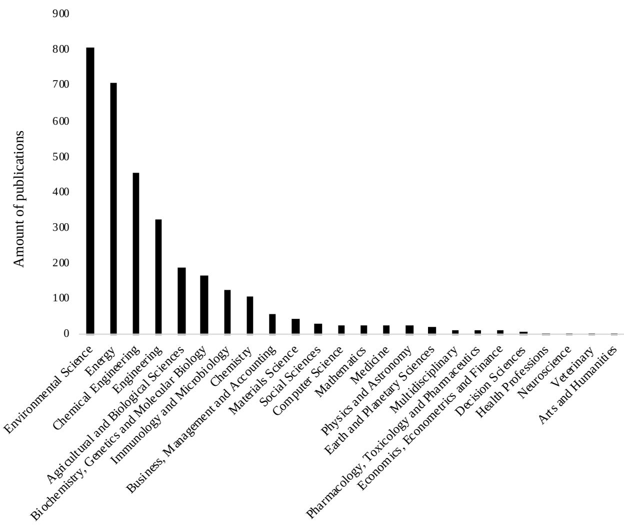

Figure 3. Distribution of publications of biomethane by subject areas

3.6 Journals participation

As show in Table 3, "Bioresource Technology" It has been discovered that has the most publications in this area (167), followed by "Applied Energy" (55); similar result in the rank of journals to the one reported in the field of thermal energy storage using latent heat. In terms of Quart (quartile), of top 20 journals, they are 14 classifieds into Q1, 3 are Q2, 1 is Q3 and two no-determined quartiles, characteristic relevant to determine the quality of journals.

Table 3. Top 10 most productive journal by biomethane topic

Journal	TP	TC	TC/TP	IF	(Q)
Bioresource Technology	167	7512	44.98	2.43	Q1
Applied Energy	55	2418	43.96	3.61	Q1
Journal of Cleaner Production	46	999	21.72	1.89	Q1
Renewable Energy	38	905	23.82	2.05	Q1
Renewable and Sustainable Energy Reviews	31	1174	37.87	3.63	Q1
Energy Procedia	30	229	7.63	0.55	-
Waste Management	28	794	28.36	1.63	Q1
Biomass and Bioenergy	26	1582	60.85	1.11	Q1
Waste and Biomass Valorization	23	359	15.61	0.57	Q2
Energies	22	159	7.23	0.64	Q2
Science of the Total Environment	21	358	17.05	1.66	Q1
European Biomass Conference and Exhibition Proceedings	20	5	0.25	0.16	-
Chemical Engineering Transactions	17	108	6.35	0.32	Q3
Water Research	17	575	33.82	2.93	Q1
Water Science and Technology	17	1695	99.71	0.47	Q2
Energy Conversion and Management	16	570	35.63	2.92	Q1
Energy	15	402	26.80	2.17	Q1
Fuel	15	564	37.60	1.8	Q1
Chemical Engineering Journal	13	203	15.62	2.32	Q1
Biofuels Bioproducts and Biorefining	12	500	41.67	1.14	Q1

IF, Impact factor (2019); Q, Quartile

Table 4. Top 10 most cited documents by biomethane topic

Title	Source title (TC)	University (corresponding author or first author)
Biogas production: Current state and perspectives [42]	Applied Microbiology and Biotechnology (1556)	Johann Heinrich von Thünen Institute
Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives [43]	Bioresource Technology (1261)	Universitat de Barcelona
Defining the biomethane potential (BMP) of solid organic wastes and energy crops: A proposed protocol for batch assays [44]	Water Science and Technology (1062)	Danmarks Tekniske Universitet
Techniques for transformation of biogas to biomethane [45]	Biomass and Bioenergy (697)	Katholieke Universiteit Leuven and Science, Engineering and Technology
Evaluation of energy efficiency of various biogas production and utilization pathways [46]	Applied Energy (509)	University College Dublin
Methanosarcina: The rediscovered methanogen for heavy duty biomethanation [47]	Bioresource Technology (413)	Ghent University
A meta-analysis of the microbial diversity observed in anaerobic digesters [48]	Bioresource Technology (286)	The Ohio State University
Towards a standardization of biomethane potential tests [49]	Water Science and Technology (241)	Ecole Polytechnique Federale de Lausanne
A review on the state-of-the-art of physical/chemical and biological technologies for biogas upgrading [50]	Reviews in Environmental Science and Biotechnology (237)	University of Valladolid; University of La Frontera
Lignocellulosic materials into biohydrogen and biomethane: Impact of structural features and pretreatment [51]	Critical Reviews in Environmental Science and Technology (235)	Laboratoire of Biotechnologie de Lenvironment

In addition, the journal “Renewable and Sustainable Energy Reviews" has the highest impact factor (3.63) among all these journals, followed by the journals “Applied Energy” (3.61) and “Energy Conversion and Management” (2.92). In terms of TC/TP ratio, “Water Science and Technology” ranks first (99.71), followed by Biomass and Bioenergy (60.85) and Bioresource Technology (44.98).

3.7 The most frequently cited documents

It is worth noting that the text chosen for citation by an author must be important to the work in which it's cited [35]. Table 4 shows a number of authors have been considered the most influential in the publications of biomethane field (with more than 1000 cites), the first most cited author is Weiland [42] with 1556 TC.

The author describes in the review the current state and prospective of biogas production, including the feedstocks and parameters that determine the efficiency and ratability of the microbial conversion and gas yield [42].

The second most cited author(s) are Mata-Alvarez [43], with 1261 cites to the review “Anaerobic digestion of organic solid wastes. The third document most cites (1062) is a protocol for batch assay to provide important experimental guidelines for the reliable and reproducible assessment of the anaerobic biodegradability of any compound or undefined material to methane and carbon dioxide [45].

The literature output concerning biomethane has shown a strong increase in recent years. With the most publications in the region, Europe is at the forefront of science.

4. CONCLUSIONS

In this study was used the literature on the biomethane published between 1978 to 2020, the main conclusions were as follows:

-The number of publications and rate of growth related to biomethane has significantly increased in the past 15 years by interest in renewable energy and the policy internationally in the countries.

-According to the number of publications on the topic of biomethane, Italy, India, and China were found to be the top three countries.

-In terms of total publications, University College Cork is the leader and Weiland is the author more influential with respect to the number of cites (TC).

-In terms of publications, the top three journals that published on this topic were “Bioresource Technology”, “Applied Energy and Journal of Cleaner Production" with high impact factors that highlights the evident scientific interest in this field.

-The application of the Gompertz model to the biomethane publication data allowed the determination of the specific growth rate with a coefficient of determination close to 1.

ACKNOWLEDGMENT

This publication has been made possible thanks to funding from the Regional Ministry of Economy, Science and Digital Agenda of the Regional Government of Extremadura and the European Regional Development Fund of the European Union through grant reference GR21161, and the authors are grateful to the Universidad de Extremadura (UNEX) Spain and the Higher Technological Institute of Huichapan, (TecNM) Mexico, for providing the research facilities for this study.

REFERENCES

[1] Sharma, S., Kundu, A., Basu, S., Shetti, N.P., Aminabhavi, T.M. (2020). Sustainable environmental management and related biofuel technologies. Journal of Environmental Management, 273: 111096. https://doi.org/10.1016/j.jenvman.2020.111096

[2] Subramaniam, Y., Masron, T.A. (2021). The impact of economic globalization on biofuel in developing countries. Energy Conversion and Management: X, 10: 100064. https://doi.org/10.1016/j.ecmx.2020.100064

[3] Gomes, J., Dewes, H. (2017). Disciplinary dimensions and social relevance in the scientific communications on biofuels. Scientometrics, 110(3): 1173-1189. https://doi.org/10.1007/s11192-016-2233-6
[4] Subramaniam, Y., Masron, T.A., Azman, N.H.N. (2020). Biofuels, environmental sustainability, and food security: A review of 51 countries. Energy Research & Social Science, 68: 101549. https://doi.org/10.1016/j.erss.2020.101549
[5] Chang, T.H., Su, H.M. (2010). The substitutive effect of biofuels on fossil fuels in the lower and higher crude oil price periods. Energy, 35(7): 2807-2813. https://doi.org/10.1016/j.energy.2010.03.006
[6] Sandesh, K., Ujwal, P. (2021). Trends and perspectives of liquid biofuel-Process and industrial viability. Energy Conversion and Management: X, 10: 100075. https://doi.org/10.1016/j.ecmx.2020.100075
[7] Buford, M., Neary, D. (2010). Sustainable Biofuels from forest: Meeting the challenge. Biofuels and Sustainability Report. Ecological Society of America, 9: 1-11.
[8] Barr, M.R., Volpe, R., Kandiyoti, R. (2021). Liquid biofuels from food crops in transportation-A balance sheet of outcomes. Chemical Engineering Science: X, 10: 100090. https://doi.org/10.1016/j.cesx.2021.100090
[9] Li, C., Tanjore, D., He, W., Wong, J., Gardner, J.L., Sale, K.L., Simmons, B.A., Singh, S. (2013). Scale-up and evaluation of high solid ionic liquid pretreatment and enzymatic hydrolysis of switchgrass. Biotechnology for Biofuels, 6(1): 154. https://doi.org/10.1186/1754-6834-6-154
[10] Healey, A.L., Lee, D.J., Furtado, A., Simmons, B.A., Henry, R.J. (2015). Efficient eucalypt cell wall deconstruction and conversion for sustainable lignocellulosic biofuels. Frontiers in Bioengineering and Biotechnology, 3: 190. https://doi.org/10.3389/fbioe.2015.00190
[11] Paredes-Cervantes, Samantha A., Barahona-Pérez, Luis Felipe, Barroso-Tanoira, Francisco G., Ponce-Marbán, D.V. (2020). Biofuels and their potential in the Mexican energy market. Revista de Economía, 37(94): 35-56.
[12] Arshanitsa, A., Akishin, Y., Zile, E., Dizhbite, T., Solodovnik, V., Telysheva, G. (2016). Microwave treatment combined with conventional heating of plant biomass pellets in a rotated reactor as a high rate process for solid biofuel manufacture. Renewable Energy, 91: 386-396. https://doi.org/10.1016/j.renene.2016.01.080
[13] Padilla-Rivera, A., Paredes, M.G., Güereca, L.P. (2019). A systematic review of the sustainability assessment of bioenergy: The case of gaseous biofuels. Biomass and Bioenergy, 125: 79-94. https://doi.org/10.1016/j.biombioe.2019.03.014
[14] Kucharska, K., Hołowacz, I., Konopacka-Łyskawa, D., Rybarczyk, P., Kamiński, M. (2018). Key issues in modeling and optimization of lignocellulosic biomass fermentative conversion to gaseous biofuels. Renewable Energy, 129: 384-408. https://doi.org/10.1016/j.renene.2018.06.018
[15] Menon, A., Ren, F., Wang, J.Y., Giannis, A. (2015). Effect of pretreatment techniques on food waste solubilization and biogas production during thermophilic batch anaerobic digestion. Journal of Material Cycles and Waste Management, 18(2): 222-230. https://doi.org/10.1007/s10163-015-0395-6
[16] Lee, S., Yi, U.H., Jang, H., Park, C., Kim, C. (2021). Evaluation of emission characteristics of a stoichiometric natural gas engine fueled with compressed natural gas and biomethane. Energy, 220: 119766. https://doi.org/10.1016/j.energy.2021.119766
[17] Andreides, D., Bautista Quispe, J.I., Bartackova, J., Pokorna, D., Zabranska, J. (2021). A novel two-stage process for biological conversion of syngas to biomethane. Bioresource Technology, 327: 124811. https://doi.org/10.1016/j.biortech.2021.124811
[18] Prussi, M., Julea, A., Lonza, L., Thiel, C. (2021). Biomethane as alternative fuel for the EU road sector: analysis of existing and planned infrastructure. Energy Strategy Reviews, 33: 100612. https://doi.org/10.1016/j.esr.2020.100612
[19] D'Adamo, I., Falcone, P.M., Huisingh, D., Morone, P. (2021). A circular economy model based on biomethane: What are the opportunities for the municipality of Rome and beyond? Renewable Energy, 163: 1660-1672. https://doi.org/10.1016/j.renene.2020.10.072
[20] Abraham, A., Mathew, A.K., Park, H., Choi, O., Sindhu, R., Parameswaran, B., Pandey, A., Park, J.H., Sang, B.I. (2020). Pretreatment strategies for enhanced biogas production from lignocellulosic biomass. Bioresource Technology, 301: 122725. https://doi.org/10.1016/j.biortech.2019.122725
[21] Paul, S., Dutta, A. (2018). Challenges and opportunities of lignocellulosic biomass for anaerobic digestion. Resources, Conservation and Recycling, 130: 164-174. https://doi.org/10.1016/j.resconrec.2017.12.005
[22] Mirko, C., Daniela, P., Chiara, T., Giovanni, G. (2021). Pretreatments for enhanced biomethane production from buckwheat hull: Effects on organic matter degradation and process sustainability. Journal of Environmental Management, 285: 112098. https://doi.org/10.1016/j.jenvman.2021.112098
[23] Baena-Moreno, F.M., Malico, I., Rodríguez-Galán, M., Serrano, A., Fermoso, F.G., Navarrete, B. (2020). The importance of governmental incentives for small biomethane plants in South Spain. Energy, 206: 118158. https://doi.org/10.1016/j.energy.2020.118158
[24] Nguyen, L.N., Kumar, J., Vu, M.T., Mohammed, J.A.H., Pathak, N., Commault, A.S., Sutherland, D., Zdarta, J., Tyagi, V.K., Nghiem, L.D. (2021). Biomethane production from anaerobic co-digestion at wastewater treatment plants: A critical review on development and innovations in biogas upgrading techniques. Science of The Total Environment, 765: 142753. https://doi.org/10.1016/j.scitotenv.2020.142753
[25] Hoo, P.Y., Hashim, H., Ho, W.S. (2020). Towards circular economy: Economic feasibility of waste to biomethane injection through proposed feed-in tariff. Journal of Cleaner Production, 270: 122160. https://doi.org/10.1016/j.jclepro.2020.122160
[26] Rai, S., Singh, K., Varma, A.K. (2020). A Bibliometric Analysis of Deep Web Research during 1997 to 2019. DESIDOC Journal of Library & Amp; Information Technology, 40(02): 452-460. https://doi.org/10.14429/djlit.40.02.15461
[27] Merigó, J.M., Yang, J.B. (2017). A bibliometric analysis of operations research and management science. Omega, 73: 37-48. https://doi.org/10.1016/j.omega.2016.12.004
[28] Coelho, M.S., Barbosa, F.G., da Rosa Andrade Zimmermann de Souza, M. (2019). A bibliometric

analysis of top-cited papers in the biogas field. Environmental Earth Sciences, 78: 1-7. https://doi.org/10.1007/s12665-019-8303-3
[29] Zhao, N., Liang, D., Meng, S., Li, X. (2020). Bibliometric and content analysis on emerging technologies of hydrogen production using microbial electrolysis cells. International Journal of Hydrogen Energy, 45(58): 33310-33324. https://doi.org/10.1016/j.ijhydene.2020.09.104
[30] Ren, Y., Yu, M., Wu, C., Wang, Q., Gao, M., Huang, Q., Liu, Y. (2018). A comprehensive review on food waste anaerobic digestion: Research updates and tendencies. Bioresource Technology, 247: 1069-1076. https://doi.org/10.1016/j.biortech.2017.09.109
[31] Tsay, M.Y. (2008). A bibliometric analysis of hydrogen energy literature, 1965–2005. Scientometrics, 75(3): 421-438. https://doi.org/10.1007/s11192-007-1785-x
[32] Mustapha, A.N., Onyeaka, H., Omoregbe, O., Ding, Y., Li, Y. (2021). Latent heat thermal energy storage: A bibliometric analysis explicating the paradigm from 2000-2019. Journal of Energy Storage, 33: 102027. https://doi.org/10.1016/j.est.2020.102027
[33] Zhao, Y., Jiang, Y., Zhou, Z., Yang, Z. (2021). Global trends in karst-related studies from 1990 to 2016: A bibliometric analysis. Alexandria Engineering Journal, 60(2): 2551-2562. https://doi.org/10.1016/j.aej.2020.12.052
[34] He, M., Zhang, Y., Gong, L., Zhou, Y., Song, X., Zhu, W., Zhang, M., Zhang, Z. (2019). Bibliometrical analysis of hydrogen storage. International Journal of Hydrogen Energy, 44: 28206-28226. https://doi.org/10.1016/j.ijhydene.2019.07.014
[35] Jiménez-Islas, D., Pérez-Romero, M.E., Aranzolo-Sánchez, A.P. (2021). The rate of production in scientific publications of biofuels in Latin America countrie. Prospectiva, (In Spanish) 19.
[36] Aranzolo-Sánchez, A.P., Pérez-Romero, M.E., Flores-Romero, M.B., Jiménez-Islas, D. (2020). "Bibliometric analysis of research on bioethanol" Conference Proceedings of the International Congress on Innovation and Sustainable, Leon-Mexico, 112-115.
[37] Hassan, W., Zafar, M., Hassan, H., Kamdem, J.P., Duarte, A.E., da Rocha, J.B.T. (2020). Ten years of Arabian Journal of Chemistry: A bibliometric analysis. Arabian Journal of Chemistry, 13(11): 7720-7743. https://doi.org/10.1016/j.arabjc.2020.09.007
[38] Briones-Bitar, J., Carrión-Mero, P., Montalván-Burbano, N., Morante-Carballo, F. (2020). Rockfall research: A bibliometric analysis and future trends. Geosciences, 10(10): 403. https://doi.org/10.3390/geosciences10100403
[39] Yuan, B.Z., Sun, J. (2019). Bibliometric and mapping of top papers in the subject category of green and sustainable science and technology based on ESI. COLLNET Journal of Scientometrics and Information Management, 13(2): 269-289. https://doi.org/10.1080/09737766.2020.1716643
[40] Magrí, A., Giovannini, F., Connan, R., Bridoux, G., Béline, F. (2017). Nutrient management from biogas digester effluents: a bibliometric-based analysis of publications and patents. International Journal of Environmental Science and Technology, 14(8): 1739-1756. https://doi.org/10.1007/s13762-017-1293-3
[41] Xu, Y.Y., Boeing, W.J. (2013). Mapping biofuel field: A bibliometric evaluation of research output. Renewable and Sustainable Energy Reviews, 28: 82-91. https://doi.org/10.1016/j.rser.2013.07.027
[42] Weiland, P. (2009). Biogas production: Current state and perspectives. Applied Microbiology and Biotechnology, 85(4): 849-860. https://doi.org/10.1007/s00253-009-2246-7
[43] Mata-Alvarez, J., Macé, S., Llabrés, P. (2000). Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives. Bioresource Technology, 74(1): 3-16. https://doi.org/10.1016/s0960-8524(00)00023-7
[44] Angelidaki, I., Alves, M., Bolzonella, D., Borzacconi, L., Campos, J.L., Guwy, A.J., Kalyuzhnyi, S., Jenicek, P., van Lier, J.B. (2009). Defining the biomethane potential (BMP) of solid organic wastes and energy crops: A proposed protocol for batch assays. Water Science and Technology, 59(5): 927-934. https://doi.org/10.2166/wst.2009.040
[45] Ryckebosch, E., Drouillon, M., Vervaeren, H. (2011). Techniques for transformation of biogas to biomethane. Biomass and Bioenergy, 35(5): 1633-1645. https://doi.org/10.1016/j.biombioe.2011.02.033
[46] Pöschl, M., Ward, S., Owende, P. (2010). Evaluation of energy efficiency of various biogas production and utilization pathways. Applied Energy, 87(11): 3305-3321. https://doi.org/10.1016/j.apenergy.2010.05.011
[47] De Vrieze, J., Hennebel, T., Boon, N., Verstraete, W. (2012). Methanosarcina: The rediscovered methanogen for heavy duty biomethanation. Bioresource Technology, 112: 1-9. https://doi.org/10.1016/j.biortech.2012.02.079
[48] Nelson, M.C., Morrison, M., Yu, Z. (2011). A meta-analysis of the microbial diversity observed in anaerobic digesters. Bioresource Technology, 102(4): 3730-3739. https://doi.org/10.1016/j.biortech.2010.11.119
[49] Holliger, C., Alves, M., Andrade, D., Angelidaki, I., Astals, S., Baier, U., Bougrier, C., Buffière, P., Carballa, M., de Wilde, V., Ebertseder, F., Fernández, B., Ficara, E., Fotidis, I., Frigon, J.C., de Laclos, H.F., Ghasimi, D.S.M., Hack, G., Hartel, M., Wierinck, I. (2016). Towards a standardization of biomethane potential tests. Water Science and Technology, 74(11): 2515-2522. https://doi.org/10.2166/wst.2016.336
[50] Muñoz, R., Meier, L., Diaz, I., Jeison, D. (2015). A review on the state-of-the-art of physical/chemical and biological technologies for biogas upgrading. Reviews in Environmental Science and Bio/Technology, 14(4): 727-759. https://doi.org/10.1007/s11157-015-9379-1
[51] Monlau, F., Barakat, A., Trably, E., Dumas, C., Steyer, J.P., Carrère, H. (2013). Lignocellulosic materials into biohydrogen and biomethane: Impact of structural features and pretreatment. Critical Reviews in Environmental Science and Technology, 43(3): 260-322. https://doi.org/10.1080/10643389.2011.604258

NOMENCLATURE

R^2	Determination coefficient
TP	Number of documents
TC	Total of citations
Q	Quartile
IF	Impact factor

Greek symbols

μ Specific growth rate, h^{-1}
β thermal expansion coefficient, K^{-1}

Subscripts

CO_2 Carbon dioxide