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Article

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Anaerobic Digestion in Biogas Production from Organic Matter: A Bibliometric Analysis from 2000 to 2021

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ABSTRACT

This work describes the contribution of researchers worldwide in the field of the biogas production in the period 2000-2021. A bibliometric approach was applied to analyze scientific publications in the area using the Scopus Elsevier database. From 2000 to 2021, there were 1198 articles developed by 4212 authors from 2789 research institutions distributed in 96 countries. Scientific articles come mainly from China, Italy, and the United States. The most productive journals, authors, institutions, and countries are Bioresource Technology, Irini Angelidaki, Danmarks Tekniske Universitet, and China. All this research is of supreme importance for the development of this line of research at the Universidad del Atlántico, where research projects are currently being developed that will contribute to the strengthening of the national and international scientific community.

Keywords: Biogas, Bibliometric, Scientometry, Production, Anaerobic Digestion, Organic Waste
JEL Classifications: Q16, Q20, Q42

1. INTRODUCTION

Fossil fuels promoted technological, economic, and social progress worldwide but had a negative impact on the environment, as evidenced by the consequences of climate change (Montt et al., 2018).

Reducing fossil fuels and using renewable energy resources has become an essential component of sustainable energy strategies worldwide (Chen et al., 2010).

Final energy consumption from renewable sources reached 19.73% in the European Union (IRENA, 2020). Globally, total final energy consumption from renewable sources has also increased and reached 10.6%. Nuclear energy and fossil fuels represented 2.2% and 79.7%, respectively; the remaining 7.5% of total final energy consumption was biomass (Renewables, 2021).

Regarding the use of biomass as a source of energy generation, biogas production can be used to produce heat and electricity (Wall et al., 2018; Dena et al., 2019), can be used to power vehicles, and can be transported through gas networks (Khan and Martin, 2016). Moreover, its production is very much in line with the circular bioeconomy, which can help manage biomass resources at the local level (Duque-Acevedo et al., 2020).

In 2020, the International Energy Agency published a report pointing out the vast unexploited potential of organic waste and sustainable biomass in clean energy production (International Energy Agency, 2020). However, although small-scale biogas plants have been implemented worldwide, few are in use due to insufficient knowledge of anaerobic digestion and the inadequate potential of installed plants (Kasinath et al., 2021). Poor understanding is a significant barrier to implementing and safely maintaining biogas plants in many developing countries. In addition, the high investment costs of anaerobic digestion systems, although operating costs are low, are considered critical factors affecting the implementation of biogas projects (Kamp and Bermúdez Forn, 2016; Garfí et al., 2016).

Anaerobic digestion of organic matter is a four-step process: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Syntrophic associations of bacterial consortia carry out these processes. During hydrolysis, bacteria excreted hydrolytic enzymes break down insoluble polymers, carbohydrates, lipids, and proteins into soluble mono- and oligomers, which are directly available to microorganisms (The Scientific World Journal, 2017). In acidogenesis (the second step), simple sugars, amino acids, and fatty acids are degraded into acetate, carbon dioxide, hydrogen, volatile fatty acids, and alcohols. In contrast, in acetogenesis (the third step), volatile fatty acids and alcohols are further degraded into H_2 and acetic acid. Finally, methanogenesis transforms the mixture of CO_2, H_2, formate, methanol, and acetate into the final product, methane. This last step is mainly carried out through acetoclastic, hydrogenotrophic, and methylotrophic ways (Costa and Leigh, 2014). This anaerobic process can be performed by the mesophilic or thermophilic treatment. Thermophilic treatment is optimally operated between 49°C and 57°C up to 70°C (Grübel and Suschka, 2015). Mesophilic treatment is optimally operated between 30°C and 35°C (Kougias and Angelidaki, 2018).

Bacterial communities that carry out anaerobic digestion are easily influenced by operational parameters such as substrate characteristics, temperature, pH, mixing ratios, additives, and other factors (Mao et al., 2017; 2015). Therefore, the study of biomass characteristics is relevant. First, the biomass must have a high nutritional value, which results in higher biogas production. Second, the moisture and pH of the biomass must be appropriate. Third, the amount of toxic substances must be limited. Fourth, the biogas produced from digestion should have more applications and be usable. Fifth, the digestion residue should be helpful as fertilizer (Alhraishawi and Alani, 2018).

A variety of substances are used in biogas production, such as wheat straw, corn stover, sugarcane bagasse, forest residues, switchgrass, energy cane, sorghum, food waste, sewage sludge, livestock waste, manure, source-sorted municipal waste, and wastewater with high organic content (Moraga et al., 2019). In developed countries, biogas is mainly produced in medium and large wastewater and farm or waste biogas plants (Scarlat et al., 2018), while rather small household digesters are used in developing countries. The system's complicated construction, complex operation, and high investment and maintenance costs have driven farmers to adopt cheaper and simpler anaerobic systems (Rajendran et al., 2012).

The advantage of biogas technology is its scalability. Biogas can be produced in large-scale installations requiring specialized knowledge in the design, construction, operation, and maintenance phases. Lack of this specialized knowledge in this area would lead to the failure of the biogas plant (Nevzorova and Kutcherov, 2019).

Implementing waste-to-energy technology is one of the best ways to achieve sustainable energy development. The most popular approach is the conversion of organic-rich compounds into clean and renewable products by anaerobic digestion (Kasinath et al., 2021). Biogas production can be improved by pretreatment, co-digestion, or new technologies to obtain various commercially essential products from biomass treated with anaerobic digestion (Kasinath et al., 2021).

Finally, the objective of this work is to study the evolution of biogas production from organic matter from 2000 to 2021. The geographical distribution of the papers, degrees of collaboration, list of authors, institutions and journals were studied. This work contributes to provide a general review of the scientific activities in this field.

2. METHODOLOGY

2.1. Bibliometric Method

Bibliometrics is a multifaceted endeavor that encompasses structural, dynamic, evaluative, and predictive scientometrics. Initially used in the library and information science field. It has extent to other areas to assess the impact of researchers and institutions (Mao et al., 2015). The bibliometric method, which contains the most extensive quantitative analysis of science, is an effective method of quantitative analysis to measure the contribution of different aspects within a given topic (Bjurström and Polk, 2011).

2.2. Characteristics of the Bibliographic Search

A comprehensive search was performed in the Scopus database using the compound word "biogas production" in the article title, abstract, or keywords "anaerobic digestion" and "organic waste" from the period between 2000 and 2021. The search results were filtered using the languages "English and Spanish," and the document type was limited to "articles, reviews, and conference proceedings," specifically using the search term: "biogas production." Finally, we obtained the complete data of 1198 documents that were analyzed in their entirety and 578 patents in the same search field. It is important to clarify that not all publications, conference proceedings, or technical reports are necessarily indexed in Scopus. Research can be disclosed on websites in languages other than English or Spanish. However, the peer-review process is an excellent filter for considering the thoroughness of the scientific work.

2.3. Indicators of Research Results

To analyze the influence of journals, authors, institutions and countries, the impact factor and h-index were chosen.

2.3.1. The impact factor

The quality of modern research is measured based on the impact factor. The impact factor of a journal in the nth year is the number of citations in the nth year divided by the number of publications in the same year. The impact factor was introduced by the Institute for Scientific Information (ISI) and is indexed in the Journal Citation Reports (JCR) annually (Amin and Michael, 2003).

2.3.2. The h-index

The h-index measures both the productivity and the citation impact of publications. The h-index is N if N publications, each of which has been cited in other articles at least N times (Vieira and Gomes, 2011).

Eight research output indicators were chosen: number of publications (TP), total citations (TC), h-index, impact factor (IF), numbers of productive authors, number of productive institutions, number of hot articles (HA), and number of citations of hot articles (HAC). These indicators were used to calculate the research percentage of each country (Imran et al., 2018). The standard research score is given by equation (1)

$$S_{pq} = \frac{x_{pq} - \bar{x}_q}{\bar{x}_q} + 1 \quad (1)$$

Where S_{pq} is the standard research score of indicator q in country p, x_{pq} is the original indicator q score in country p, and $\bar{x}_q$ are the average indicator q score. The sum of all standard research scores of a country is given by equation (2).

$$S_p = \sum_{q=1}^{n} S_{pq} \quad (2)$$

2.4. Degree of Collaboration

Three indicators were chosen to investigate the effect of research collaboration. These factors are the degree of authorial collaboration, the degree of institutional collaboration, and the degree of country collaboration shown in equations (3)-(5) (Imran et al., 2018).

$$D_a = \frac{\sum_{i=1}^{n} \alpha_i}{N} \quad (3)$$

$$D_i = \frac{\sum_{i=1}^{n} \beta_i}{N} \quad (4)$$

$$D_n = \frac{\sum_{i=1}^{n} \gamma_i}{N} \quad (5)$$

Where D_a, D_i, and D_n, are the auctorial collaboration degree, institutional collaboration degree, and national collaboration degree of country, respectively. α_i, β_i and γ_i, are the number of authors, countries, and institutions in each article. The parameter *N* represents the total number of articles. It should be noted that the number of countries is the sum of the countries of all authors and, similarly, the number of institutions is the sum of the institutions of all authors.

The performance of an author is described based on the productivity index (PI) with the following scenarios.

When the author's PI index equals zero, a small production author is considered (with only one paper).

When the author's PI index is greater than zero and less than one, a medium-production author is considered (between 2 and 9 papers).

When the author's PI index is greater than one, a large production author is considered (10 or more papers) (García-Villar and García-Santos, 2021). It is defined as the decimal logarithm of the number of published papers as described by equation (6).

$$PI = Log\ N \quad (6)$$

Where *PI* is the author's productivity index, and *N* is the number of articles.

3. RESULTS AND DISCUSSION

3.1. Distribution of Publications

Articles published from 2000 to 2021 related to the biogas production were analyzed. The total number of publications in Scopus indexed journals and conference proceedings was 1198. The timeline of biogas production publications from 2000 to 2021 is shown in Figure 1.

The publications of articles and patents increased from 2000 to 2013. A decrease in patents was observed between 2014 and 2018; meanwhile, for the same period, the number of publications increased remarkably.

The rapid increase in publications throughout the selected period can be attributed to the growing concern about the environmental impact and the need to decrease the use of fossil fuels. It is observed that the publication of articles and patents decreased in the last year. This may be related to the confinement and closure of institutions due to the pandemic (Covid-19).

An analysis of the type of publications suggests that "Original articles" represent the majority of the publications, about 76%, as shown in Figure 2.

3.2. Production by Country

The articles published come from more than 90 countries, as shown in Figure 3. Most of the publications come from countries with a high technological level.

Figure 1: Evolution of the articles and patents from 2000 to 2021

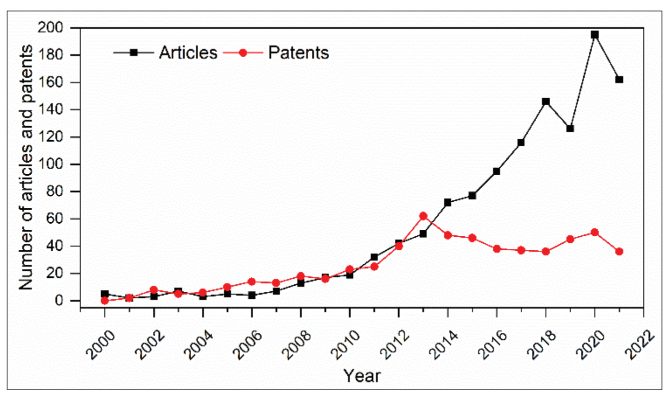
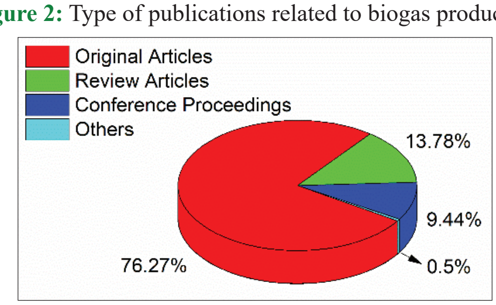


Figure 2: Type of publications related to biogas production



The most productive countries in terms of the number of publications are listed in Table 1. Approximately 70% of the publications come from the top 10 countries shown in Table 1. Publications related to biogas production originate mainly from China, Italy, USA, India, Spain, UK, Germany, Malaysia, France, and South Korea. The countries of China (12%) and Italy (12%) led the publications in biogas production from 2000 to 2021.

In addition, the results indicate that the highest number of publications originate from China, Italy, and the United States than all other countries combined, accounting for 34.89% of the total publications in biogas production. The research output from different countries is presented as a standard score of a single research indicator and also as a cumulative (the sum of the standard scores of all research indicators). The results are shown in Figure 4. The quantity of publications is not synonymous with quality; the h-index, citations, authors, and productive institutes, which are considered in the standard cumulative score, must be considered. The change of position of the countries China and Italy and others, where the characteristics of the h-index have made a difference. China, Italy, and the United States remain the leading countries in terms of numbers of publications and a standard score of research output.

Figure 3: Trend of publications during the period 2010-2019

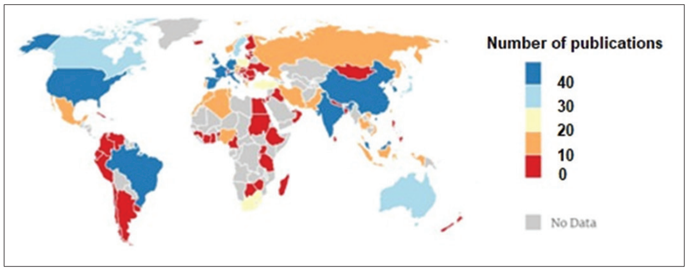
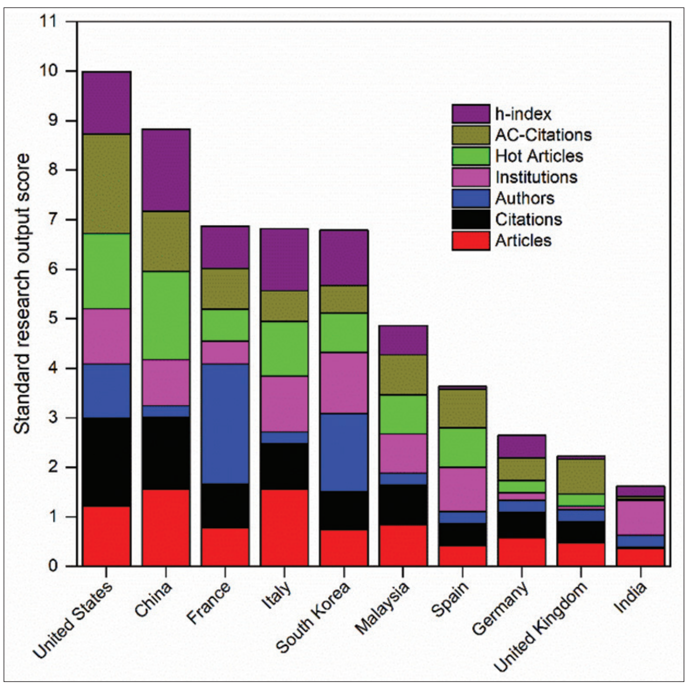


Figure 4: Standard research output score of the most productive countries



3.3. Journal Distribution

The source of publications was analyzed to identify the journals with the highest number of publications. The ten most productive journals/publishers in the field of biogas production are shown in Table 2. The journal Bioresource Technology has the highest number of publications and represents 8.10% of the total publications related to biogas production from 2000 to 2021.

The top 10 journals represent 34.73% of the total publications related to biogas production. Bioresource Technology, Waste Management, and Renewable and Sustainable Energy Reviews have more than 60 citations per publication and an h-index of more than 30. These three journals account for 19% of the total publications in the field of biogas production and 44% of the total citations. The percentage of articles, citations, and journal quality indicate that these journals are the leading journals in biogas production. The publishers of these journals are from two countries, the United States and the Netherlands.

3.4. Distribution by Research Areas

The Scopus search restricted the subject areas to chemical and environmental sciences. Figure 5 describes the research publications in biogas production according to the different categories.

Research work in biogas production falls mainly into environmental science, energy, engineering, and agricultural and biological sciences. It should be noted that a publication may be included in more than one thematic category.

3.5. Authorship Pattern

The authorship pattern results suggest that 4212 authors from 96 countries published these 1198 articles. This indicates that

Table 1: Top 10 countries with publications in the area of biogas production from 2000 to 2021

Country	Total		Number of Productive		Hot Articles		h-index
	Papers	Citations	Authors	Institutions	No. of Art.	Citations	
China	144	3200	160	160	20	1852	31
Italy	144	3874	160	153	25	2398	34
United States	130	4296	160	160	23	3118	31
India	97	1458	160	152	6	588	21
Spain	65	1996	160	94	12	1250	23
United Kingdom	60	2570	160	122	10	1930	21
Germany	56	1373	160	114	10	880	18
Malaysia	49	1051	160	75	6	782	13
France	48	888	160	136	7	548	15
South Korea	45	1012	160	91	6	560	17

46 authors are productive, i.e., authors who have published five or more articles. The productive authors represent 1.09% of the total authors, and their contribution to total publications related to biogas production is about 24.37%. The authorship pattern is shown in Figure 6.

The authorship pattern was also analyzed regarding the number of authors per publication. It is observed that as the years go by, the collaboration between authors is more evident. It can be seen in Figure 6 that articles with three authors constitute 18.28% of the total number of publications related to biogas production. The result indicates that the number of articles with two, three, four, and five authors constitute the maximum number of articles, representing 68.61% of the total number of publications in the area.

Figure 5: Distribution of publications according to topics classified by Scopus

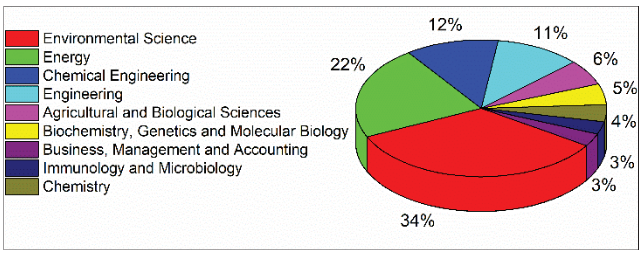
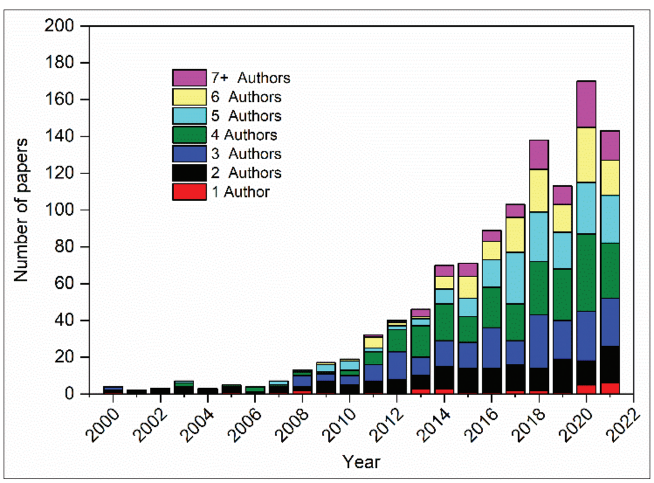


Figure 6: Authorship pattern in the field of biogas production publications from 2000 to 2021



The ten most productive authors in this technology field are listed in Table 3 in descending order according to the total number of publications.

Generalized statistics show that, of the top 10 authors, eight are from Europe and two from China. The influence of the authors has been investigated by considering the total publications (TP), total citations (TC), citation per publication (CPP), h-index, hot articles (HA), hot articles citations (HAC), and productivity index (PI). The highest citation of a publication is 58 by Esposito (Italy), and Angelidaki and Esposito write the highest number of hot articles with a total of 4. These authors had the highest number of citations.

3.6. Institutional Production

The result shows that publications are distributed among 2789 research institutions worldwide. The number of productive institutions is ninety-seven, which accounts for 3.48% of the publications in biogas production. Details of the top research institutions are shown in Table 4 (listed in descending order according to the total number of publications). These research institutions have published 13.27% of the total publications related to biogas production from 2000 to 2021.

For each publication, all affiliated institutions were considered for analysis. Among the top ten research institutions, four are from Italy, two from China, and one research institution each from Denmark, France, Belgium, and the United States.

The research output of these institutions concerning the total publications in the area from 2000 to 2021 is shown in Figure 7.

The ratio of hot articles and hot article citations to total publications is approximately 19.41% and 21.10%, respectively. The Ohio State University is at number ten with 12 publications but ranks number four when all research indicators are taken into account.

3.7. Academic Collaboration

The level of degree of collaboration, quantified in equations (3)-(5), is shown in Figure 8. From 2000 to 2021, increasing trends in collaboration can be observed according to the indicators of degree of collaboration, authoring, institution, and country.

It can be seen that the degree of authorship has increased from 2.8 in 2008 to 4.9 in 2021. The institutional grade has increased

Table 2: Top 10 most productive journals in the field of biogas production from 2000 to 2021

Journal	Total		Relative (%)		Journal Quality		
	Papers	Citations	Papers	Citations	h-index	SJR	SNIP
Bioresource technology	97	4530	8.10	15.69	35	2.48	2.07
Waste management	86	4090	7.18	14.17	33	1.80	2.22
Journal of cleaner production	46	1043	3.84	3.61	18	1.93	2.47
Renewable and sustainable energy reviews	45	4019	3.76	13.92	28	3.52	4.68
Journal of environmental management	32	942	2.67	3.26	17	1.44	1.88
Energies	27	484	2.25	1.68	11	0.59	1.16
Renewable energy	23	727	1.92	2.52	13	1.82	2.38
Water research	21	825	1.75	2.86	13	3.09	2.64
Biomass and bioenergy	20	1475	1.67	5.11	10	1.03	1.38
Environmental technology United Kingdom	19	318	1.59	1.10	10	0.52	0.80

SJR: SCImago Journal Rank indicator, SNIP: Source normalized impact per paper

Table 3: Ranking of the 10 top authors in the field of biogas production from 2000 to 2021

Author	Institute	TP	TC	CPP	HA	HAC	h-index	PI
Angelidaki, I.	Danmarks Tekniske Universitet, Denmark	14	752	54	4	572	84	1.15
Bolzonella, D.	Università degli Studi di Verona, Italy	11	220	20	1	67	41	1.04
Di Maria, F.	Università degli Studi di Perugia, Italy	11	317	29	2	123	25	1.04
Adani, F.	Università degli Studi di Milano, Italy	10	256	26	1	91	53	1.00
Tsapekos, P.	Danmarks Tekniske Universitet, Denmark	8	136	17	0	0	22	0.90
Xu, F.	Xi'an Jiaotong University, China	8	365	46	2	254	20	0.90
Dai, X.	Tongji University, China	7	107	15	0	0	37	0.85
Esposito, G	Università degli Studi di Napoli Federico II, Italy	7	408	58	4	377	46	0.85
Murphy, J.D.	University College Cork, Ireland	7	372	53	3	315	48	0.85
Oechsner, H.	Universität Hohenheim, Germany	7	206	29	1	107	24	0.85

TP: Total publications, TC: Total citations, CPP: Citations per publications, HA: Hot article, HAC: Hot articles citations, PI: Productivity index

Table 4: Ranking of the 10 most productive institutions in the field of biogas production from 2000 to 2021

Journal	Key Indicators			Relative Performance (%)	
	Papers	Citations	h-index	Papers	Citations
Danmarks Tekniske Universitet, Denmark	21	1072	15	35	2.48
Tongji University, China	20	557	11	33	1.80
Ministry of Education China, China	18	294	8	18	1.93
Università degli Studi di Perugia, Italy	18	386	11	28	3.52
Università degli Studi di Milano, Italy	15	411	8	17	1.44
INRAE, France	15	136	6	11	0.59
Università degli Studi di Verona, Italy	14	317	8	13	1.82
Università degli Studi di Napoli Federico II, Italy	13	511	8	13	3.09
Universiteit Gent, Belgium	13	383	8	10	1.03
The Ohio State University, United States	12	1203	9	10	0.52

Figure 7: Relative performance of the main research institutions in the field of biogas production

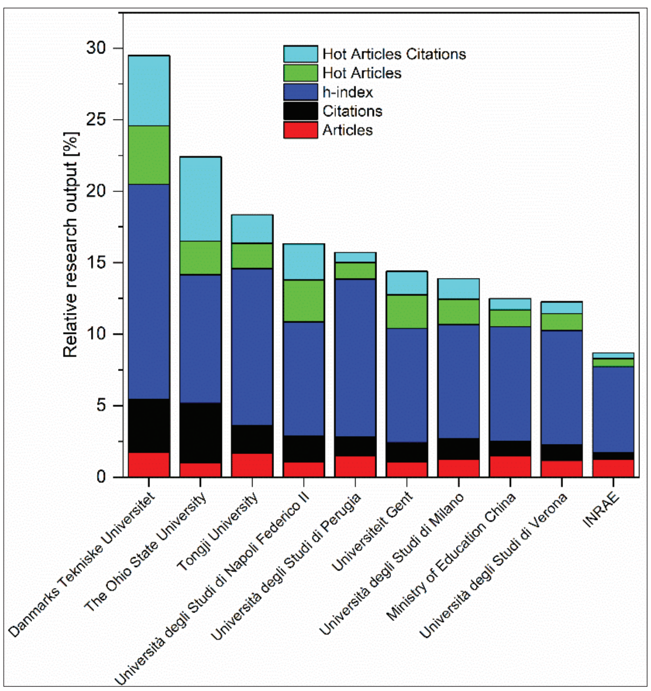
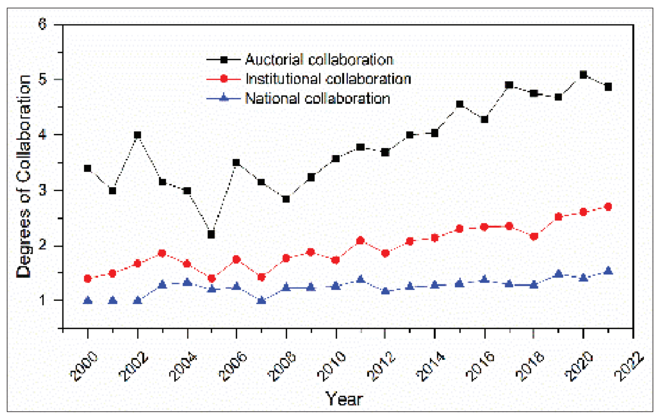


Figure 8: Degrees of collaboration between authors, institutions, and countries from 2000 to 2021



from 1.4 in 2007 to 2.7 in 2021. Finally, the country grade has increased from 1.0 in 2007 to 1.5 in 2021.

The average degree of collaboration (sum of author, institution, and country degrees of collaboration) is shown in Figure 9.

The results suggest that, on average, from 2000 to 2021, an average of 3.8 authors, 2.0 institutions, and 1.3 countries have participated in each publication. The lower collaboration degree values show that publications related to biogas production are concentrated in only a few countries and institutions.

3.8. Articles Citation

The citation pattern was investigated in terms of the hot articles from 2000 to 2021. The timeline of the citation pattern of publications on biogas production is shown in Table 5.

The result suggests that the number of publications and citations is increasing. The highest values of hot articles and h-index are between 2011 and 2018. The highest citation counts are 3538 in the year 2011. Since the number of citable papers is increasing, the number of citations is expected to have an increasing trend from 2018. Non-cited papers have increased from 10 in 2014 to 79 in 2021. Figure 10 represents the annual behavior of citations of publications.

Table 5: Publication statistics of biogas production from 2000 to 2021

Year	Publications			Total	Hot Article		Quality
	Cited	Un-cited	Total	Citation	Papers	Citations	h-index
2021	84	79	163	304	0	0	8
2020	168	27	195	1560	3	169	20
2019	113	13	126	1680	8	544	22
2018	136	10	146	3001	16	1266	31
2017	108	8	116	3344	22	2037	30
2016	88	7	95	2773	15	1560	31
2015	72	5	77	2611	11	1435	29
2014	62	10	72	2593	17	1883	27
2013	47	2	49	2179	13	1596	23
2012	36	6	42	2001	16	1700	21
2011	30	2	32	3538	21	3376	25
2010	17	2	19	1115	8	967	12
2009	17	0	17	1229	9	1133	12
2008	12	1	13	786	4	703	9
2007	6	1	7	461	3	384	6
2006	3	1	4	452	2	448	3
2005	5	0	5	112	1	80	4
2024	2	1	3	85	1	58	2
2003	7	0	7	624	3	570	6
2002	3	0	3	653	2	607	3
2001	2	0	2	101	1	84	2
2000	5	0	5	407	3	402	4

Table 6: Top 10 most cited articles in the field of biogas production from 2000 to 2021

Authors	Country	Year	Total citations	Relative citation (%)	Journal
Rajagopal et al., 2013	Canada	2013	673	2.16	Bioresource Technology
Li et al., 2011	USA	2011	641	2.06	Renewable and Sustainable Energy Reviews
Khalid et al., 2011	UK	2011	576	1.85	Waste Management
Callaghan et al., 2002	UK	2002	445	1.43	Biomass and Bioenergy
Cherubini et al., 2009	Italy	2009	398	1.28	Energy
Guo et al., 2015	USA	2015	397	1.27	Renewable and Sustainable Energy Reviews
Rulkens, 2008	Netherlands	2008	380	1.22	Energy and Fuels
Hagos et al., 2017	China	2017	324	1.04	Renewable and Sustainable Energy Reviews
Carlsson et al., 2012	Sweden	2012	318	1.02	Waste Management
Demirel and Scherer, 2011	Germany	2011	312	1.00	Biomass and Bioenergy

Figure 9: Timeline of average degree of collaboration in the field of biogas production from 2000 to 2021

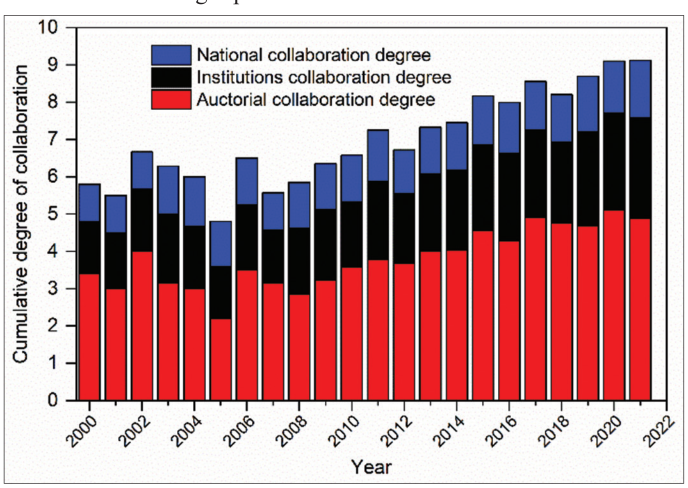
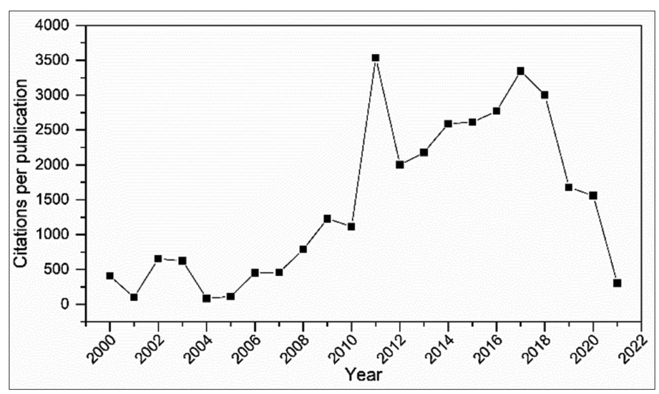


Figure 10: Timeline of citations per publication from 2000 to 2021



The 10 most cited articles are shown in Table 6. These articles represent 14.35% of the total number of citations. Of these articles, two originate from the United States, two from the United Kingdom, and one from Canada, Italy, the Netherlands, China, Sweden, and Germany. The journals in which they were published are: Renewable and Sustainable Energy Reviews (3 articles), Biomass and Bioenergy (2 articles), Waste Management (2 articles), Bioresource Technology (1 article), Energy and Fuels (1 article) and Energy (1 article).

3.9. Keywords the Research

The most used keywords among the publications related to biogas production were also analyzed. The frequency of the keywords is shown in Table 7.

About 8330 keywords were used in total, and "anaerobic digestion" represents 12.91% of the searches with this equation.

The occurrence of the keywords is shown in Figure 11. The most used keyword focuses on applying anaerobic digestion, biogas, organic waste, methane.

Table 7: Frequency of keywords in publications in the field of biogas production from 2000 to 2021

Rank	Keywords	Frequency
1	Anaerobic digestion	1075
2	Biogas	726
3	Organic waste	684
4	Methane	514
5	Bioreactors	471
6	Biofuel	348
7	Anaerobic growth	232
8	Waste management	207
9	Wastewater	193
10	Fertilizers	191
11	Biogas production	181
12	Food waste	166
13	Anaerobic co-digestion	162
14	Waste treatment	155
15	Sludge digestion	134
16	Manure	133
17	Fertilizers	131
18	Substrate	128
19	Chemical oxygen demand	121
20	Wastewater treatment	110

3.10. National Context of Biogas Production in Colombia

Taking into account the search in Scopus, of the 1198 articles published between 2000 and 2021 related to biogas production, only five publications were found in Colombia, representing 0.004% of the total. The results are shown in Table 8.

The publications carried out in the country have been published in the last four years in national and international journals. This shows the interest of the organizations in applying and expanding research related to biogas production and its applications at the residential and industrial levels. Collaboration with organizations in other countries is key to demonstrating this research.

At the Universidad del Atlántico, the assembly of a prototype for the generation of biogas from swine manure is being carried out to

Figure 11: Clustering of the most frequent keywords related to biogas production from 2000 to 202

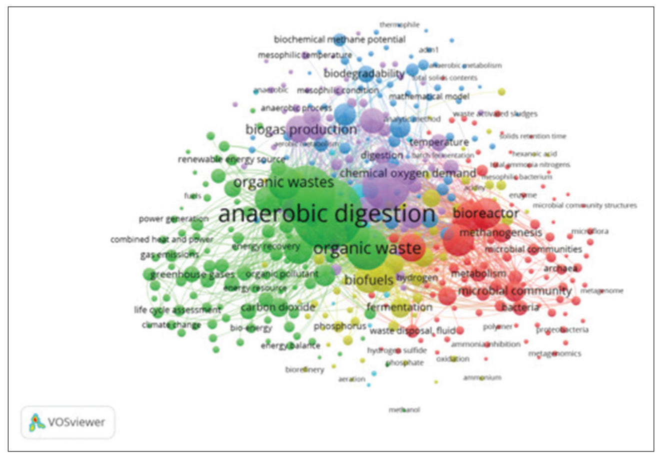


Table 8: Works published by Colombian organizations related to biogas production from 2000 to 2021

Title	Journal	Authors	Institutions	Year	Citations
Low-cost anaerobic digester to promote the circular bioeconomy in the non-centrifugal cane sugar sector: A life cycle assessment	Bioresource Technology	Mendieta, O. (Col) Castro, L. (Col) Escalante, H. (Col) Garfí et al. (Spa)	AGROSAVIA. Universidad Industrial de Santander. Universitat Politécnica de Catalunya-BarcelonaTech.	2021	3
The state-of-the-art of organic waste to energy in Latin America and the Caribbean: Challenges and opportunities	Renewable Energy	Silva, R. (Bra) Sanches, A. (Bra) Ortiz, W. (Ger) Gómez, M. (Col) Coelho, S. (Bra)	University of São Paulo. Instituto 17, São Paulo, Brazil. KTH Royal Institute of Technology, Sweden. Wuppertal Institut - Döppersberg 19, Germany. Universidad de La Sabana.	2020	9
Comparison of biogas production obtained from samples of mitú and sibundoy municipal solid waste	Ingeniería e Investigación	Triana, K. (Col) Lozano, M. (Col)	Universidad Nacional de Colombia.	2019	2
Influence of the use of Co-Substrates on the anaerobic Co-Digestion of municipal solid waste, cocoa industry waste and bottled beverage industry waste	Chemical Engineering Transactions	Rodríguez, A. (Col) Muñoz, A. (Col) Tique, L. (Col) Landino, J. (Col) Santis, A. (Col) Cabeza, I. (Col) Acevedo, P. (Col)	Universidad Cooperativa de Colombia. Universidad Santo Tomás.	2018	2
Mathematical modeling and simulation for biogas production from organic waste	International Journal of Engineering Systems Modelling and Simulation	Delgadillo, L. (Col) Hernández, M. (Col) Machado, M. (Col)	Universidad de Ibagué.	2018	3

Figure 12: Reactor system implemented for the analysis of biogas production at the Universidad del Atlántico

promote the sustainability and productivity of production systems with batch and semi-continuous reactors, as shown in Figure 12.

Implementing this type of technology in our country allows us to take advantage of waste, reduce greenhouse gases and the use of fossil fuels, scale-up production, and generate research and development.

4. CONCLUSIONS

From 2000 to 2021, 1198 articles were published in the field of biogas production by Scopus indexed journals and conference proceedings by 4212 authors from 2789 research institutions from 96 countries. The total number of citations of publications related to biogas production amounted to 31609 citations. The publications are mainly from China, USA, and Europe. The top ten countries and research institutions account for 70% and 13.27% of the total publications in the area of biogas production, respectively. From 2000 to 2021, 3.8 authors, 2.0 institutions, and 1.3 countries have participated in each publication on average, indicating that research in the field of biogas production is concentrated in few countries and institutions. The most productive journal is Bioresource Technology with 97 publications. The most cited article was published in Bioresource Technology and represents 2.16% of the total citations. The most productive author was Irini Angelidaki with 14 articles with 54 citations per publication. The most productive institution was Danmarks Tekniske Universitet Denmark with 21 publications.

According to the keyword frequency analysis, 8330 keywords have been used in 1198 articles, and the keyword "anaerobic digestion" accounts for 12.91% of the total keywords. The research paper on biogas production with the most citations is "A critical review on inhibition of anaerobic digestion process by excess ammonia."

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