

Optimization of anaerobic digestion through automatic control with neural networks: a bibliometric analysis

Carlos Arturo Vides-Herrera¹, Aldo Pardo-Garcia², Juan Jose Cabello-Eras³, Adalberto José Ospino-Castro⁴

^{1,2}Universidad de Pamplona, Pamplona - Colombia, ³Universidad de Córdoba, Montería - Colombia,

⁴Universidad de la Costa, Barranquilla - Colombia

ORCID: ¹[0000-0001-8708-5470](https://orcid.org/0000-0001-8708-5470), ²[0000-0003-2040-9420](https://orcid.org/0000-0003-2040-9420), ³[0000-0003-0949-0862](https://orcid.org/0000-0003-0949-0862), ⁴[0009-0000-1234-4321](https://orcid.org/0009-0000-1234-4321)

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Abstract—The present work was carried out with the objective of presenting the current importance of work related to the optimization of anaerobic digesters using artificial neural networks. A scientometric methodological approach was used for a systematic review of the publications indexed in Scopus until 2023. The H index was used to evaluate the visibility and impact of the journals, authors, countries, and institutions with the highest levels of production and recognition in the field of study. This review also allowed us to analyze the interaction between groups and knowledge networks with the authors and institutions identified in the classification. The results show a significant increase in the number of publications between the years 1973 and 2023, which allow us to characterize on a scale the main dimensions of research, development and innovation related to the study of optimization methods of anaerobic biodigesters for the production of biogas from different waste such as that from the palm oil extraction process. The results show a significant increase in the number of publications between 2016 and 2023, a total of 2847 documents were found, where 95.64% are in English. The country that presents the most publications on the topic is China with a contribution of 19.28%, followed by the United States with 9.8%, India with 7.2% and Spain with 6.2% among others.

Keywords: optimization, anaerobic digestion, RNA, bibliometrics, bibliometric analysis, H index, scopus.

*Corresponding author.

Email: apardo13@unipamplona.edu.co (Aldo Pardo Garcia).

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I. INTRODUCTION

Fossil fuels dominate the world's energy supply. 81% of the total primary energy supply, which includes production, imports, exports, and bunkers, comes from coal, crude oil, and natural gas. Renewable energies such as solar, wind, biomass, geothermal and hydro had a 13.8 share of energy supply in 2018, and despite the high annual growth rate of 2.4% since 2000, production clean energy has remained constant over the past two decades. In 2018 Asia was the continent with the largest supply of energy of fossil, nuclear and renewable origin. North, Central and South America are more dependent on crude oil and its derivatives, which have a 37% share in their energy mix [1]. One of the ways to take advantage of the waste generated in agro-industrial processes is the generation of energy from liquid or solid biomass. This energy can be used, for example, to generate electricity or biogas [2].

One way to contribute to the environment, the planet and therefore to all living beings is to meet and contribute to the sustainable development goals (SDGs) established by the United Nations Framework Convention (UNFCCC) [3]. There are 17 proposed objectives, of which three of them can be specifically contributed to using agro-industrial waste using techniques such as anaerobic digestion to obtain biogas from biomass and thus reduce the disposal of this type of material that, by not being used, becomes a source of environmental pollution, emitting greenhouse gases [4]. SDGs number 6 (Clean water and sanitation), 7 (Affordable and clean energy) and 13 (Climate action) are those that contribute to the treatment and use of agricultural [5] waste.

The modeling and optimization of the anaerobic digestion and co-digestion of different types of waste can be carried out using the surface response methodology and genetic algorithm coupled to artificial neural networks. The response surface methodology (RSM) and the coupled genetic algorithm (GA) model of artificial neural network (ANN) are used to optimize the parameters of the anaerobic [6] digestion process. By means of artificial neural networks, the flow of biogas from an anaerobic codigestion process from agricultural substrates can be predicted quickly and robustly with the help of ant colony optimization algorithm where significant process variables are identified [7].

A technology that is very promising for the use of waste of organic origin is anaerobic digestion (AD), it is a sustainable alternative to treat discarded foods that are growing every day and in turn generate high-value by-products [8] [9]. Anaerobic digestion systems are complex processes that involve biological, biochemical, and physical-chemical phenomena that in turn occur in parallel [4]. Anaerobic digestion is a process of four successive stages that are: hydrolysis, acidogenesis, acetogenesis and methanogenesis [10]. Hydrolysis is the stage where large molecules are converted into smaller molecules that are more accessible to microorganisms [11]. Hydrolysis works with temperatures between 30 - 50 °C and with an optimal PH that is between 5 - 7 [12]. After the hydrolysis stage, acidogenic microorganisms produce volatile fatty acids (VFAs) and other products. VFAs constitute a class of organic acids such as acetates, and larger organic acids such as propionate and butyrate. This process is called acidogenesis. The third stage of AD is acetogenesis which is a process where some of the higher [13] AGVs that have not been made accessible to methanogenic microorganisms are converted to acetate and hydrogen is also produced. Methanogenesis represents the final stage of the anaerobic digestion process, in which methanogenic microorganisms consume intermediate products to produce methane [14].

Small-scale anaerobic digestion (SSAD) is a new system for biogas production based on a technology that is considered promising. SSAD can transform organic matter into biogas (A mixture, composed mainly of methane and carbon dioxide) which makes it a propitious technology for use in power generation applications, agriculture and potentially in the emerging bio-products sector. [15].

The work carried out by [16] consists of using an artificial neural network (ANN) with particle swarm optimization (ANN-PSO) for the prediction and optimization of biogas production from the co-digestion of biogas. POME (Palm Oil Mill Effluent) in a solar biodigester. As a result, the authors show that the ANN-PSO presented a compression of 0.0143 and a correlation coefficient of 0.9923, this shows that the particle swarm method is very effective and flexible for the prediction of biogas production from the anaerobic co-digestion of POME and cattle manure [16]. A basic example of the use of an artificial neural network (ANN) is the one carried out by Erkan Sahinkaya, where the ANN is used to predict the performance of the sulfate reducing bioprocess in a CSTR type reactor, the output of the network corresponds to the effluent parameters, and this was compared with an experimental method obtaining better results [17].

The biogas produced by the degradation of organic matter from anaerobic digestion is mainly composed of methane (CH₄), carbon dioxide (CO₂) and other gases in a small proportion [9]. The biogas production in the AD is influenced by parameters such as the organic load rate (OLR), PH, Temperature, Hydraulic Retention Time (HRT) among others [18]. The organic loading rate is the amount of organic matter added to the digester per unit volume [19]. The PH is a parameter of AD that specifically affects acidogenic and methenogenic bacteria, the adequate PH value to maintain these bacteria is between 5 - 8 [20].

This article presents a bibliometric analysis derived from the systematic review of studies in publications that have a high level of visibility and impact between 2007 and 2022 on the subject investigated, which corresponds to the optimization of biodigestion processes focused directly on the biodigester through different clever techniques; incorporating the analysis of different scientometric indicators and statistical techniques supported by the use of biblioshiny 's RStudio software – Bibliometrix and VOSviewer , to generate new knowledge with systematic and useful information within research, development processes and innovation at a global level.

II. METHODOLOGY

a. Bibliometric analysis

The bibliometric analysis is a way of carrying out a meticulous and exhaustive quantitative review of the scientific literature, which in turn makes it possible to determine research trends in the various research fields.[1] [2]. The use of bibliometric analysis has allowed high levels of implementation of scientific information in the industry [21]. Currently, this technique, which uses mathematical and statistical models, is based on the information provided by different scientific databases based on the interest in a particular topic associated with a specific field in a period of time [22].

b. Impact Factor: H-Index

The impact factor was initially proposed in research science by Garfield [5], in order to know the impact of citations in the different journals on a specific topic [23]. The factor indicator is calculated by dividing the total citations of the articles into the various journals quote Reports (JCR) by the total number of articles published in the different Journals exposed [24]. The H-Index is another indicator that assesses an author's progress in research, both qualitatively and quantitatively, and was proposed by Hirsch in 2005, according to Hirsh. [25] The definition of the h-index is based on the citation of each of the articles that the author published. In this study, the index was used to assess the influence of journals, countries/territories, authors, and institutes [26].

c. Reference network analysis – SNA

Reference network analysis (SNA) is a quantitative indicator that evaluates the citation relationship between authors [27]. This indicator has been used worldwide to know the authors who work in the field [28].

d. Information database

The Institute for Scientific Information (ISI) and Scopus Database Web are widely used for scientific literature searches [29], as a widely accepted database of different scientific fields, Scopus has been considered an essential source of data for bibliometric analysis [30], including more than 1000 document types, Scopus is a tool that provides and standardized records [31][32], in addition, in Science Extended Citation Index (SCIE) and social sciences Subfield Citation Index (SSCI) database includes most influential publications, Some so-called "grey" publications (for example, conference reports and proceedings) are not covered [27]. Therefore, SCI, SSCI, Conference Proceedings Citation Index-Science (CPCI-S) and Conference Proceedings Citation Index-Social Sciences Humanities (CPCI-SSH) are selected as data sources in this study [28][29].

e. The purpose of the study

The study proposes to identify the main research actors related to the optimization of anaerobic digesters using methods of intelligent control and optimization by neural networks. The research results reported through articles registered in the Scopus database were processed with the RStudio software of biblioshiny - Bibliometrix, to obtain the behavior of the bibliometric indicators in the study period, 2015 - 2023. A analysis of the library obtained in Scopus, extracting filtered information using refined search criteria in specialized databases to obtain inputs to characterize the environment in which they are found and the analysis of trends in the subject of study, managing to carry out the treatment of information and compare bibliometric indicators.

f. Population sample

The sample studied is made up of 2274 documents, distributed in articles, documents and review of minutes, this population was obtained from searches with keywords such as Optimization of anaerobic digesters, intelligent optimization method, Artificial Intelligence in process optimization and automatic control.

g. Procedure

The information was obtained from the Scopus database, filtered by keywords such as: optimization of anaerobic digestion, artificial intelligence algorithms in anaerobic digestion, optimization of anaerobic biodigesters, optimization of anaerobic digestion with control using neural networks, this temporally delimited. between the years 1973 to 2024 inclusive, obtaining metadata that was later analyzed with the RStudio software where the data was established in tables and graphs, which were subsequently treated qualitatively and quantitatively to make comparisons and deep analysis of the subject to be studied and investigate.

III. RESULTS

The documents under analysis were obtained from the SCOPUS database, using the keywords "Optimization of anaerobic digestion" and the logical operator AND between each keyword, with a result of 2847 documents, 95.64% of the publications are in English, 2.88% in Chinese, 0.42% in Spanish, 0.28% in French and German, 0.05% in Portuguese, 0.11% in Russian and 0.21% in other languages. The search, although it yields a considerable number of documents, when compared to searches that include more general criteria, is lower than what could be found, for example, ignoring keywords such as "neural network" and "Optimization" which yields a few Found 40,734 documents with the keywords "anaerobic digestion". The logical operator chosen for the search was AND to obtain a more precise search limited to the topic of interest, which in this case is the optimization of anaerobic digestion with neural networks.

a. Annual publication yield

Figure 1. (a) shows the trend in the number of publications that contain some result of studies on the optimization of anaerobic digestion, where there are also investigations that use intelligent control techniques and artificial intelligence (AI) between the years 1973 and 2023, the country with the highest number of publications is China and with the highest H index, this shows a sustained increase in the period analyzed.

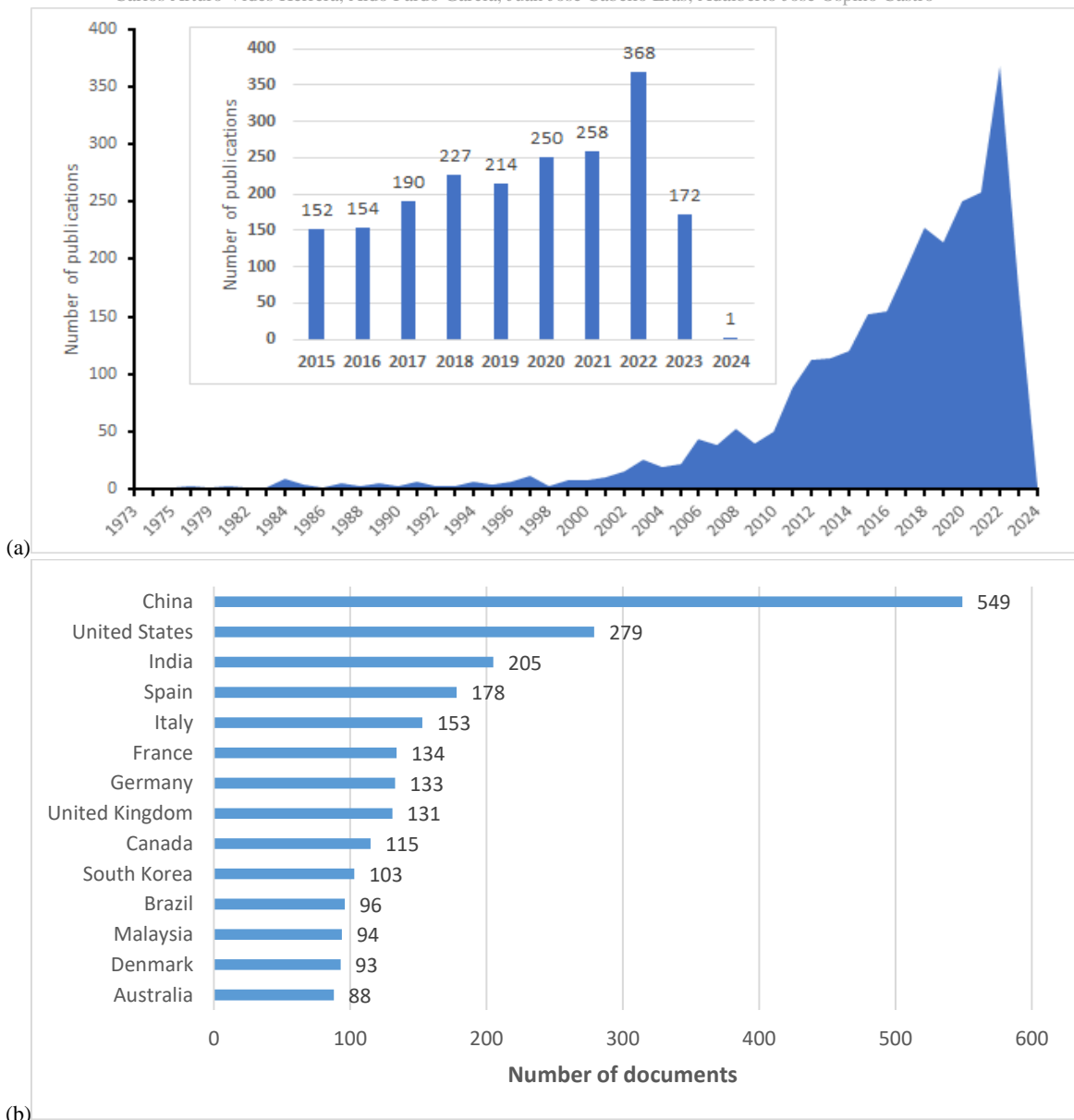
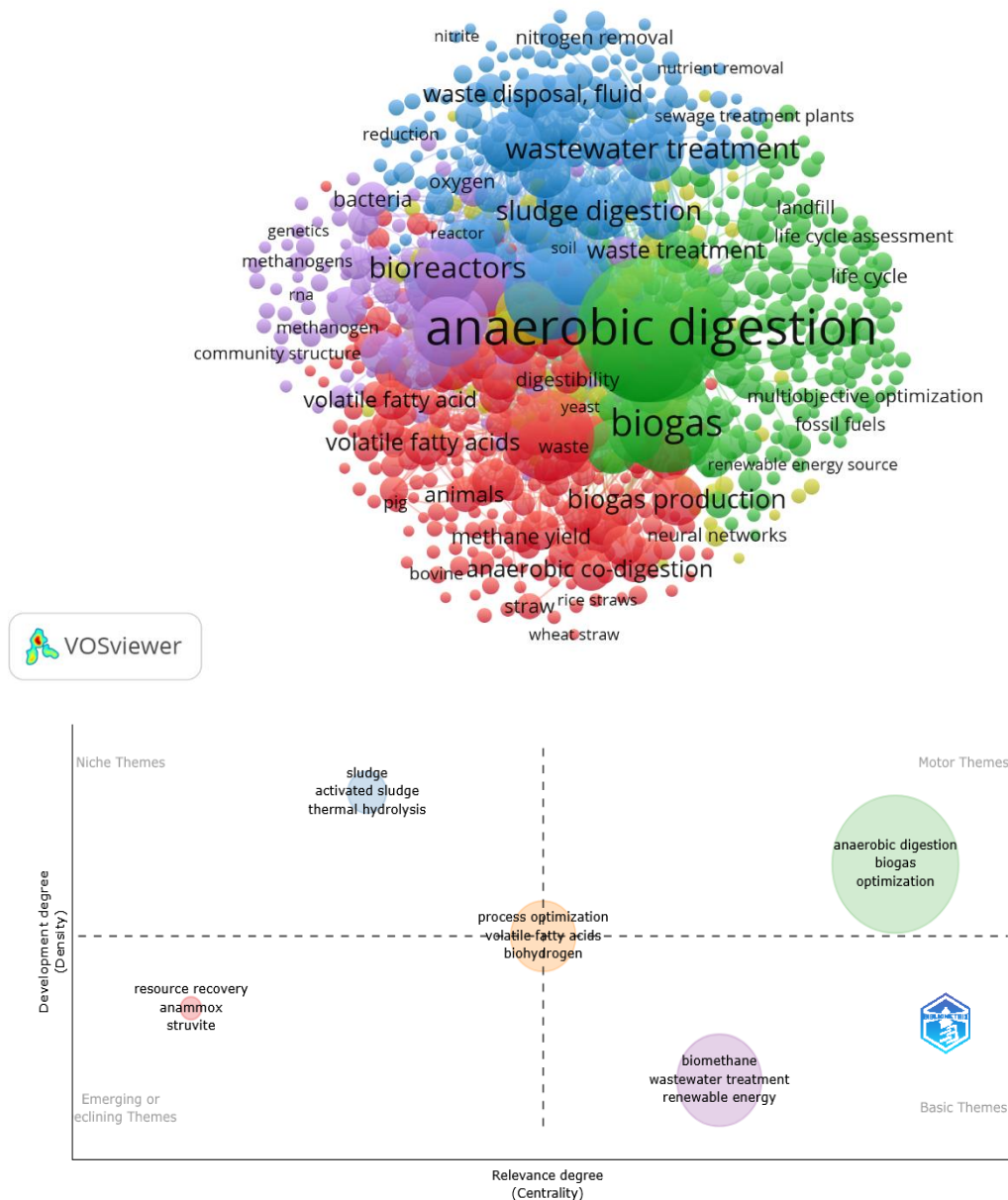


Figure 1: Publications on the subject from 1973 and 2023. a) Trend of publications by year. b) Countries with the largest publications in recent years. Source: Own elaboration.

This analysis allows knowing the research production at a general and specific level, presenting the global distribution of publications related to the subject of study. The 10 countries that contribute the most to the bibliometric indices in the subject of interest are China with 549 articles, United States 279 articles, India with 205 articles, Spain with 178 articles, Italy with 153 articles, France with 134 articles, Germany with 133 articles, United Kingdom with 131 Articles, Canada with 115 Articles, South Korea with 103 Articles and finally Brazil with 96 Articles.

b. Analysis of the main keywords

The analysis of the co-occurrence of keywords is an important aspect in the study of a research topic because it provides an idea of the importance of the object of study and indicates how close it is to the research frontier [33]. First, a study of the co-occurrence of the keywords is carried out considering all the research documents found from the search “optimization”. Anaerobics digestion” and using the VOSviewer [34], with and a minimum number of occurrences of words of 5, the following results are found: 16661 keywords found in the total number of documents; however, the software is not capable of processing this number of keywords, for which the criterion of 5 is used. minimum co-occurrences for a total of 2256, 18 clusters that represent the relationship between the elements, which indicates the groups that are closely related, as expected, the keyword with the highest number of co-occurrences is “Anaerobic Digestion ” with 2467, 2255 links and a total link strength of 57795.



(a)

(b)

Figure 2: Groups of the most frequent authors using the keywords. (to) Terms map based on different groups. (b) Thematic map. Source: Own elaboration.

Figure 2(a) shows the result described above, as can be seen the keywords with the highest number of occurrences and co-occurrences are anaerobic digestion, methane, wastewater treatment, ammonia, manures, substrate, anaerobic co-digestion, water disposal among others, but they are very general for other research topics [35][36][37]. Therefore, a more refined search is carried out including the keywords Control, neural and network to rule out documents that do not have a high relationship to the topic under study. The result of performing a new refined search from the 2847 documents initially found. In figure 3 we can see that now co-occurrence was found between keywords and authors that include Neural Network, Control, Artificial Neural Network, Fuzzy Neural Network, Bioreactor, and Biogas among others. As is to be expected, the ones with the highest volume of occurrence are those that must do specifically with the area or topic under study, some of these are: anaerobic digestion, artificial neural network, neural network, biogas and optimization. Figure 2 (b) shows a thematic map where the author's keywords are grouped according to their relevance and the degree of development of the research fields [38]. The thematic map which was made with Bibliometrix is an intuitive graph to understand the research topics and is divided into four (4) quadrants: i) motor topics, ii) basic topics, iii) emerging or declining topics and iv) topics very specialized/niche[38] [39][40]. For this bibliometric study, the key words " anaerobic digestion", "biogas" and "optimization" as they represent the best developed and most important topics. The keywords "biomethane", "wastewater treatment" and "renewable energy" are as basic topics that are equally important, but are not well developed, which requires more analysis and research[41] [42].

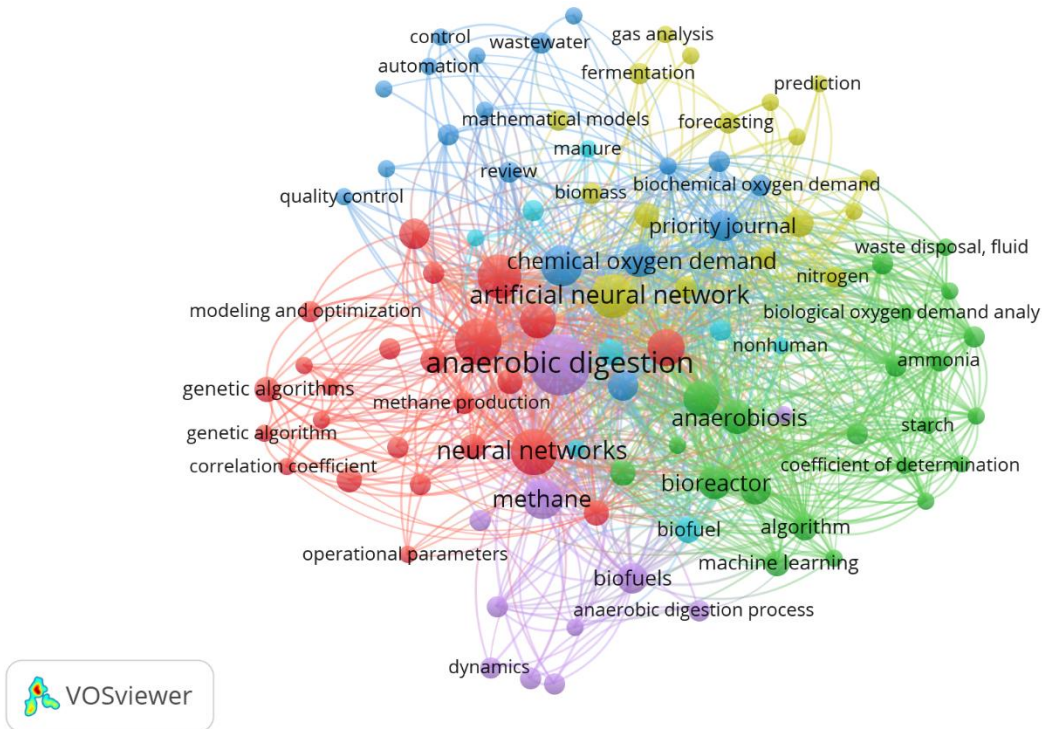


Figure 3: Most frequent authors on anaerobic digestion, artificial neural networks and genetic algorithms. Source: Own elaboration.

Figure 4 shows a clear relationship between anaerobic digestion, optimization and neural networks through the occurrences corresponding to the keywords used by the author.

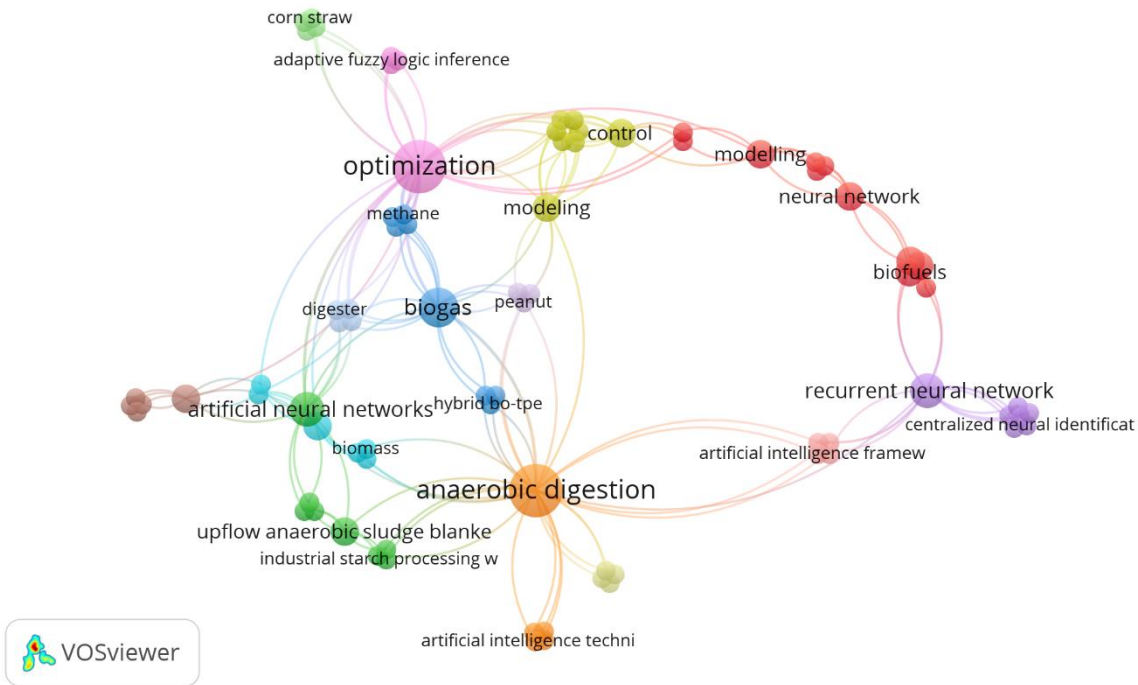


Figure 4: Relations between anaerobic digestion, optimization and neural networks. Source: Own elaboration.

c. Magazines in which it has been published

From the search carried out and subsequently analyzed, 2847 publications were found, of which 1747 were in journals, with a total percentage of the search of 76.8%, with the area of bio-environmental technology producing the most articles or documents, followed by the area of Science and technology of water as can be seen in figure 5 [43].

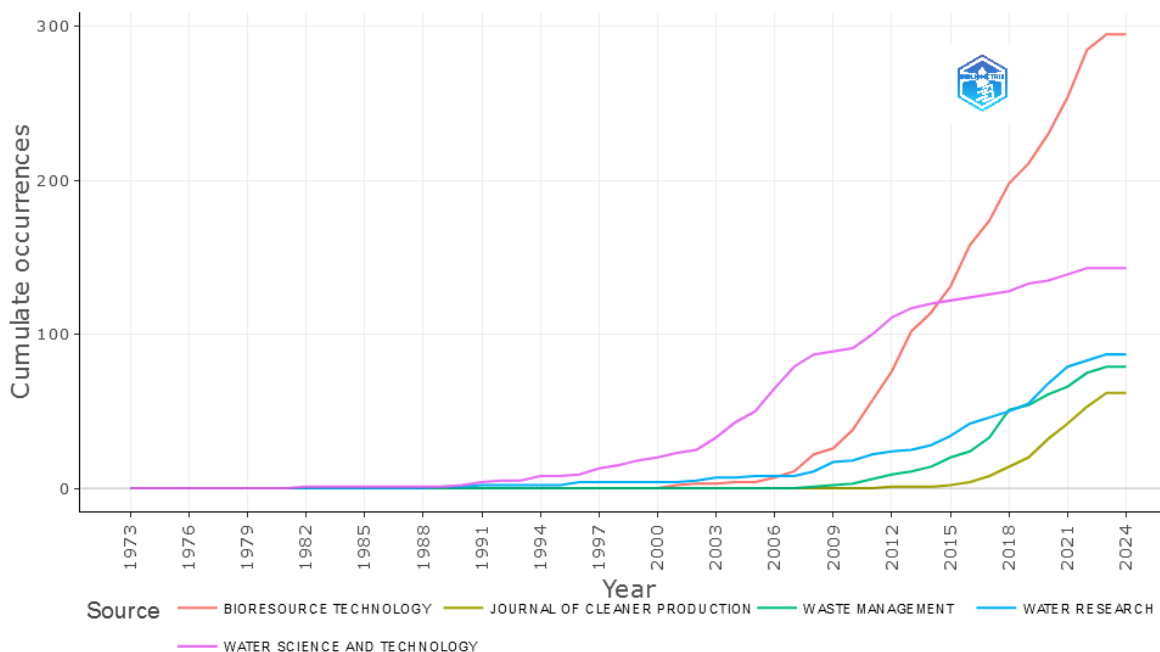


Figure 5: Areas with the highest number of publications.
Source: Own elaboration.

The author with the most global citations is related to the magazine GREEN ENERGY AND TECHNOLOGY, from 2012, followed by BIORESOUR TECHNOL, from 2008, and WANG X, from 2012, among other magazines that can be seen. In figure 6.

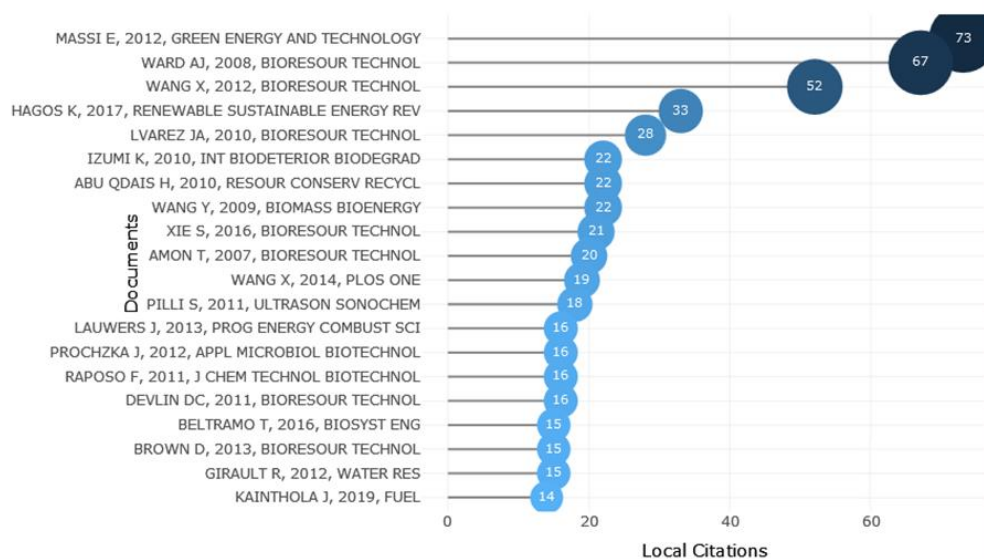


Figure 6: Most cited documents globally.
Source: Own elaboration.

The institutions or universities with the largest number of most relevant publications according to the bibliometric analysis carried out with R-Studio by Bibliometrix [44][45], there is the Technical University of Denmark with several 38 publications, and another institution with a high level of publications is Tsinghua University, as can be seen in figure 7.

Most Relevant Affiliations

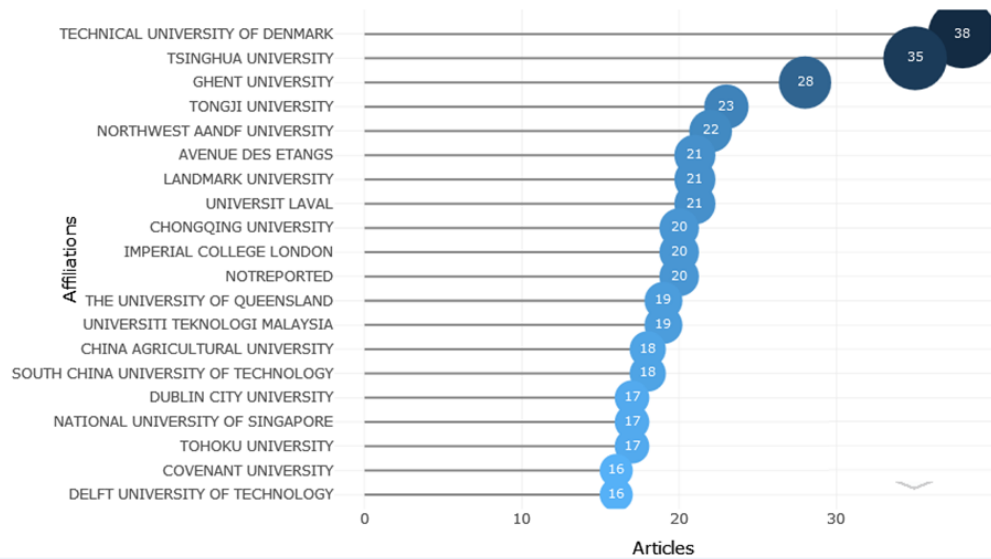


Figure 7: World universities with the largest publications.
Source: Own elaboration.

In Figure 8. We can see the most relevant sources found, Bioresource stands out Technology with 295 articles, Water Science and Technology with 143 articles, Water Research with 87 articles, Waste Management with 79, Journal of cleaner Production with 62 articles, Renewable Energy and Science of The Total Environment with 58 articles each, Journal of Environmental Management with 55 articles, Applied Energy and Environmental Technology (United Kingdom) with 42 articles each.

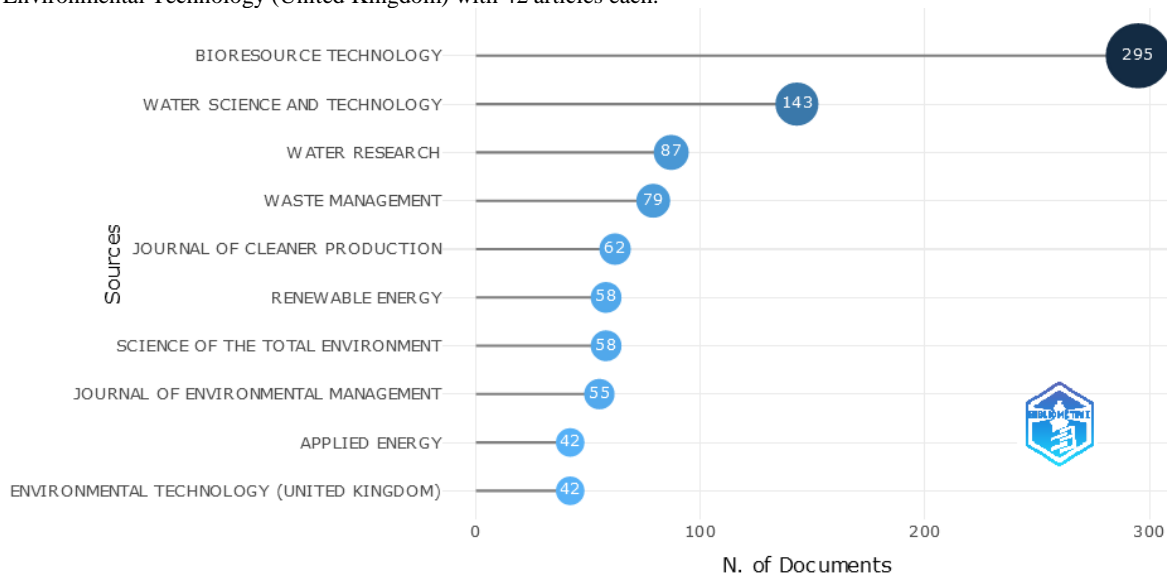


Figure 8: Most relevant source in the period from 2016 to 2023.
Source: Own elaboration.

d. Authors – Articles

The authors with the greatest impact were of Western origin, who have a high percentage of research published in high-impact journals, the author with the highest number of publications is WANG Y with 27 articles, followed by author WANG X with 26 published documents. In the ninth position of the most published authors, we find Angelidaki I, who belongs to the Technological University of Denmark and is the university with the most publications about anaerobic digestion as shown in figure 9.

Most Relevant Authors

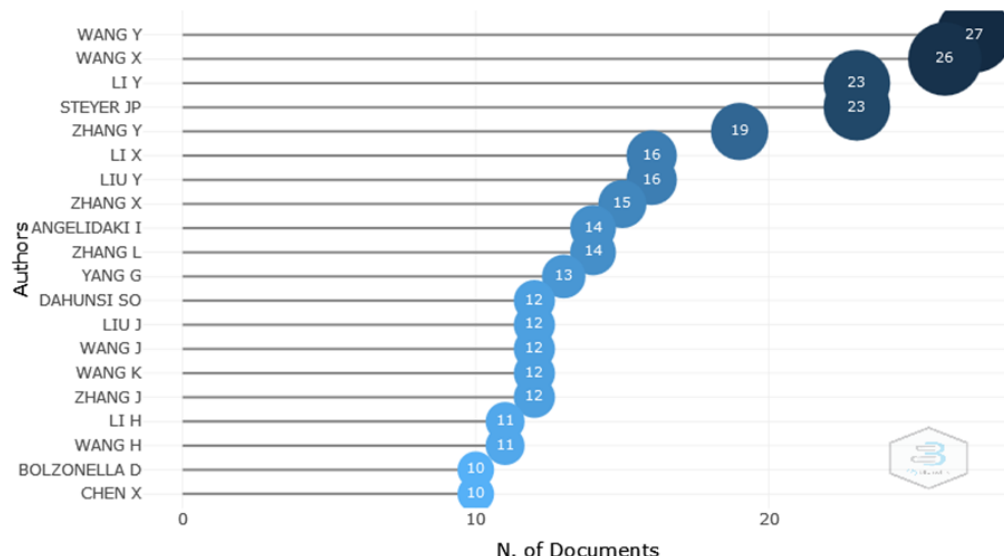


Figure 9: Authors with the most publications.
Source: Own elaboration.

e. Contribution of institutions

Figure 10 shows the ten most productive institutions in research on the optimization of biodigesters between the years 2016 and 2023 [49] [50]. The institution with the highest number of publications is the Technical University of Denmark (TECHNICAL UNIVERSITY OF DENMARK), with 37 articles on the subject, headed by the author Angelidaki, I., who has [51]17 articles on the subject of interest in technology magazines bio-environmental and chemical engineering, it is interesting that this author has 62 papers in the last four years related to anaerobic digestion. The main theme of the publications analyzed in this study has to do with the use of artificial neural networks in various real processes for their implementation and treatment of data from various sources, which come from non-linear processes [52], [53][54].

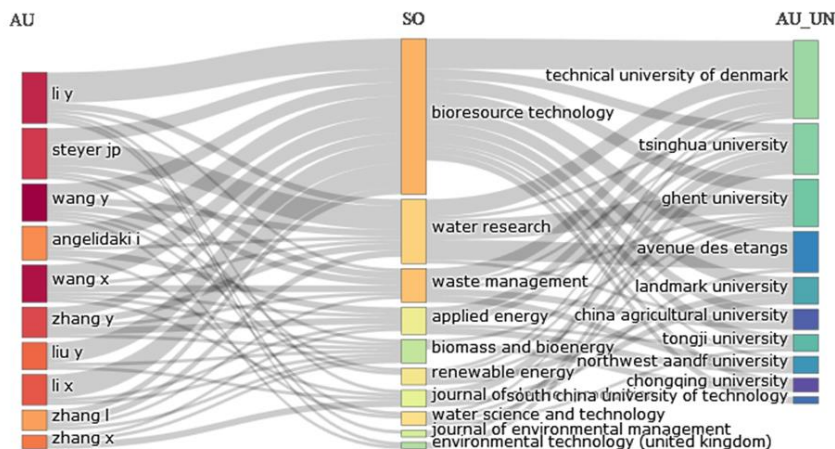


Figure 10: Institutions with the highest number of published documents.
Source: Own elaboration.

f. Most Cited Publications

Regarding local citations, it can be seen in figure 11 that China continues to be the country with the highest number of citations with a score of 5689 citations during the years 2016 to 2023, while Spain maintains second place in research production reflected in articles. high impact and local references.

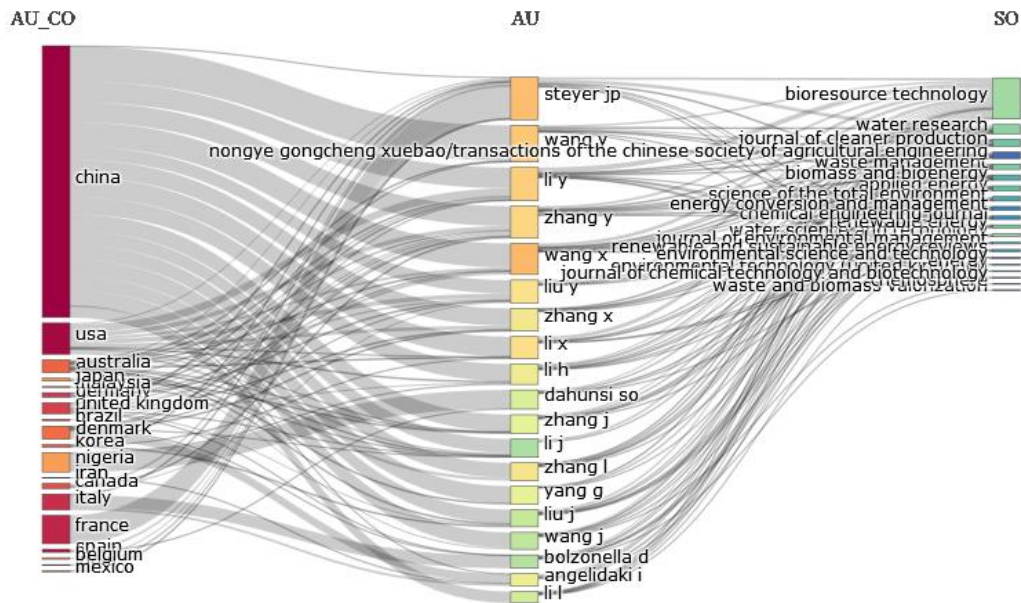


Figure 11: List of Countries, authors and most cited areas.
Source: Own elaboration.

IV. CONCLUSIONS

With the industrial research and development related to the optimization of the anaerobic biodigestion process, it is essential to evaluate the availability of information provided by the different technologies and specialized databases, which provide a mapping of the development situation of the different intelligent methods of optimization that contribute to the improvement of biogas production processes from different types of residual biomass. Therefore, the subject has been studied from the perspective of the systematic review of studies in publications that have a high level of impact during the years 2016 to 2023 about study (Optimization of anaerobic biodigestion processes using control techniques intelligent).

This was possible thanks to the evaluation of the different scientometric indicators, where it was reflected that most of the studies related to the optimization of the anaerobic digestion process are generated in the People's Republic of China, highlighting the author WANG Y with more publications and Zhang Yw as the most cited.

With this information, one would expect that the journals with the greatest impact would be from the East, since it is still the country with the largest training institutions in the field, however, it is found that the university that does the most research on the topic of biodigester optimization is the Technical University of Denmark (TECHNICAL UNIVERSITY OF DENMARK).

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