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# AN IN-DEPTH EXPLORATION OF RECENT ADVANCES AND PROMISING OUTLOOKS IN BIOGAS PRODUCTION

REDENÇÃO – CE
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Dissertação de Mestrado apresentada ao Programa de Pós-Graduação em Energia e Ambiente – PGEA da Universidade da Integração Internacional da Lusofonia Afro-Brasileira - UNILAB, como requisitos à aprovação no componente curricular obrigatório código MAEA0005: Dissertação. Área de concentração: Processos Químicos.

Orientador(a): Dr. José Cleiton Sousa dos Santos.
Coorientador(a): Dra. Rita Karolinny Chaves de Lima.

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*Em homenagem a minha querida mãe Maria Luiza pelo amor incondicional, por cada palavra de fé dita, cada ensinamento e apoio em todos os momentos da minha vida. Dedico todo o meu sucesso! Para toda a glória do Senhor.*

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*“Você nunca sabe quais resultados virão de sua ação. Mas se você não fizer nada, não haverá resultados”.*

*GANDHI, 1927*

**ABSTRACT**

Biogas is a product composed of a mixture of gases that result from a process of biological decomposition of organic material, consisting primarily of methane gas and carbon dioxide, in addition to smaller amounts of other gases. This study aims to provide a comprehensive analysis of biogas production from waste, in general, to ensure sustainability in the biofuel production process. To conclude this goal further, an advanced systematic bibliometric analysis using keywords, co-citations, and bibliographic coupling analysis was performed on 641 peer-reviewed articles from the Web of Science database. This analysis covers the period from 2000 to 2022, thus covering a period of little more than 20 years. The applied method reveals some themes that were identified and addressed in the article: (1) the importance of the topic in academia by country in which they were analyzed; (2) sectors contributing to biofuel production; (3) equipment used in biofuel production; (4) most cited waste sources in the database; (5) application purpose of the biogas; (6) relevance of other energy sources; (7) areas of interest where biofuels are used; and (8) a comparison between the energy production capacity and the number of publications on the topic by country. Furthermore, it also considers potentials, limitations, perspectives, and future trends were highlighted as aspects regarding improving its production process. Therefore, it is concluded that is possible to use organic wastes in the sustainable production of goods with added value to society.

**Keywords:** Biogas**;** Organic Wastes**;** Biogas Production**;** Anaerobic Digestion; Methane Bibliometric Analysis**;** Sustainability; Sustainable.

## FIGURES LIST

## TABLE LIST

## LIST OF ABBREVIATIONS AND ACRONYMS

AC – Average Citations

ANMP – Average Number of Manuscripts Published

C - Country

CAPES – Coordenação de Aperfeiçoamento de Pessoal de Nível Superior

CH – Switzerland

CH3COOH – Acetic Acid

CH4 – Methane

CNG – Compressed Natural Gas

CNPQ – Conselho Nacional de Desenvolvimento Científico e Tecnológico

CO2 – Carbon Dioxide

CSTR – Continuous Stirred Tank Reactor

GDP – Gross Domestic Product

H2 – Hydrogen

H2S – Hydrogen Sulfide

IF – Impact Factor

LNG – Liquefied Natural Gas

MW - Megawatts

NC – Number of Citations

NH3 - Ammonia

NP – Number of Publications

N2 – Nitrogen

N2O – Nitrous Oxide

O2 – Oxygen

pH – Hidrogenionic Potential

PSA – Pressure Swing Adsorption

P(%) – Percentage with the Total Number of Papers

RQ – Research Question

SNG – Synthetic Natural Gas

SOFC – Solid Oxide Fuel Cells

THC – Total Hydrocarbons

UK – United Kingdom

UNILAB – Universidade da Integração Internacional da Lusofonia Afro-Brasileira

US – United States of America

VFA – Volatile Fatty Acids

WOSCC – Web of Science Core Collection

**SUMMARY**

## 1. INTRODUCTION

Energy production processes in human activities have led to numerous environmental problems, including deforestation, biodiversity loss, flora and fauna destruction, and water scarcity (Alexander et al., 2019; Nevzorova and Kutcherov, 2019; Pöschl et al., 2010; Udaeta et al., 2019; Winquist et al., 2019). To mitigate these negative impacts and meets sustainable demands, the search for new energy production alternatives has intensified (Borges et al., 2021; Othman et al., 2017). Biogas is an attractive energy resource that can help meet part of society's energy needs. It has essential characteristics like a low pollution index because of its biological origin (Ertem and Acheampong, 2018), good storage and transportation conditions, and is a reliable, renewable energy source (Cozendey da Silva et al., 2018; Nashmin Elyasi et al., 2021; Shahzad et al., 2013). The pressure uses energy rationally and efficiently and focus on renewable sources has increased because of pollution, global warming, and the declining availability of fossil fuels (Hielscher et al., 2022; Pick et al., 2012). Thereto, fossil fuels are currently the dominant energy source in the transportation and power generation sectors and are responsible for greenhouse gas emissions and global warming (Abdeshahian et al., 2016; Wu et al., 2015a). If fossil fuels remain the sole energy source, the associated environmental problems will likely worsen, especially with the projected increase in global energy demand from these sectors in the coming decades (Arias et al., 2020; Herrmann, 2013; Russo and von Blottnitz, 2017; Yaqoob et al., 2021a). According to ExxonMobil's 2022 report, global demand for transportation, energy, and electricity is expected to increase by 30% and 70%y 2050 (ExxonMobil, 2022), driven primarily by population growth and economic development.

The formation of biogas is a natural microbiological process that occurs whenever organic materials (biomass) decompose in a moist environment without oxygen in the presence of specific microorganisms (Catherine et al., 2016; Moeller and Görsch, 2015; Narsing Rao et al., 2017; Ncube et al., 2021; Valentino et al., 2018; van den Oever et al., 2021). Marsh gas (or swamp gas) is produced naturally as biogas in ruminants' digestive tracts, plants during wet composting, and flooded ice fields in nature (Moeller and Görsch, 2015; Ren et al., 2011). One of its applications in society's daily life is its use as natural gas. On average, natural gas is composed of the following composition of elements: methane ($CH_4$); carbon dioxide ($CO_2$); nitrogen ($N_2$); hydrogen ($H_2$); oxygen ($O_2$); and hydrogen sulfide ($H_2S$). We can summarize the main advantages of this product in the flexibility of using biogas as natural gas, including being used as vehicle fuel in the transport sector; easy transportation as compressed natural gas (CNG) or liquefied natural gas (LNG); and excellent use in the generation of thermal energy, electricity, and biomethane (Farzaneh-Gord and Rahbari, 2018; Garibov et al., 2004; Xu et al., 2022). The conversion of food waste into biogas using anaerobic digestion technology has received increased attention in recent years as it plays an essential role in the valorization of bioenergy and promotes environmental sustainability (Fu and Viraraghavan, 2001; Kumar et al., 2021a; Mbachu et al., 2021; Nashmin Elyasi et al., 2021; V Pérez et al., 2020). Biogas can be produced from various organic wastes like animal droppings (manure), by-products of human activities (sewage sludge, wet market wastes, and municipal solid wastes), and plants (agricultural wastes) by cause of anaerobic digestion. During this process, microorganisms break down the organic matter in four main stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. However, there is in like manner a concurrent process known as sulfetogenesis, which is essential for sulfate reduction (Bartoli et al., 2020; Cavalcante et al., 2021; McDonald et al., 2008a, 2008b; Salama and Abdelsalam, 2020; Sumardiono et al., 2021).

The production of several trace compounds can come from the biogas production process. These trace compounds may vary depending on the types of waste fed into the system and the specific process conditions. Some of the most common trace compounds obtained in the biogas production process include Hydrogen (H2); Acetic Acid (CH3COOH); Volatile Fatty Acids (VFA); Ammonia (NH3); Hydrogen Sulfide (H2S) and traces of greenhouse gases and contaminants (Lecharlier et al., 2022). Hydrogen is often one of the first gases to be produced during the initial phase of anaerobic digestion. However, its concentration tends to decrease as the process progresses and methane becomes the dominant component of biogas. During the decomposition of residues, volatile fatty acids are formed, such as acetic, propionic, and butyric acids. These acids are intermediates in the biological degradation of organic materials and can affect the pH (Hidrogenionic Potential) and the efficiency of the process if they are present in excess. Ammonia is a by-product of the degradation of proteins and amino acids present in organic waste. Although in limited amounts, ammonia can have an impact on the toxicity and pH of the system (Arnold and Kajolinna, 2010). Hydrogen sulfide is formed during the degradation of sulfur compounds present in the waste. It is known for its characteristic rotten-egg odor and can be corrosive in high concentrations. In addition to the main components (methane and carbon dioxide), biogas can also contain traces of other greenhouse gases such as nitrous oxide (N2O), and traces of volatile organic compounds. In addition, contaminants such as traces of heavy metals and atmospheric pollutants may be present, depending on the waste fed to the system. It is necessary to monitor and manage these trace compounds during the biogas production process to ensure production efficiency, the quality of the resulting biomethane and minimize adverse environmental impacts (Arnold and Kajolinna, 2010; Lecharlier et al., 2022; Rasi et al., 2011).

The author suggests that biogas can be utilized for heat and electricity production or as transportation fuel with appropriate treatment, such as purifying it and increasing its heating value to produce high-quality biomethane (Riva et al., 2014). Removing CO2 to produce biomethane is an important process to make the production and use of biomethane more sustainable and environmentally friendly. The process of removing CO2 from biogas to produce biomethane can be complex and involve additional costs. Nevertheless, the production and use of biomethane as fuel have the potential to contribute to the reduction of carbon emissions, the management of organic waste, and the diversification of energy sources. CO2 removal by solid sorbents in a circular approach is a strategy that involves the use of adsorbent materials to capture CO2 from biogas and is part of a continuous and sustainable processing cycle. This process focuses on the reuse and regeneration of adsorbent materials to minimize waste and maximize process efficiency. The process can be summarized in steps, namely: adsorption, regeneration, capture and use of CO2, and recycling of the adsorbent material. This circular approach is advantageous as it reduces the need to constantly purchase new adsorbent materials, which saves resources and lowers operating costs. Furthermore, capturing and storing CO2 contributes to the reduction of greenhouse gas emissions. Nonetheless, it is important to consider technical, economic, and environmental aspects when implementing a circular approach to CO2 removal by solid sorbents. The choice of adsorbent material, regeneration methods, process efficiency, and economic viability are critical factors to be considered for the successful application of this technology. (Dou et al., 2016; Papurello et al., 2022; Rabbat et al., 2022). The use of anaerobic digestion technology to convert renewable feedstocks into clean energy through biogas production has been considered a promising approach (Gao et al., 2013; Karray et al., 2015; Kumar et al., 2021b; Lijó et al., 2017; Longati et al., 2020; Nugraha et al., 2021; slimane et al., 2014). Biogas is a sustainable energy source that consists primarily of methane (60%) and carbon dioxide (35-40%) (Korbag et al., 200AD; Lijó et al., 2017; Mbachu et al., 2021) and is derived from various raw materials, including organic matter from animal waste, which is critical for biogas generation (Holm-Nielsen et al., 2009; Salama and Abdelsalam, 2020). Filtration or cleaning of biogas is an essential process in the production of biomethane from gasification. The substance is not suitable for direct use as biomethane due to the presence of impurities such as carbon dioxide (CO2), sulfur compounds, water vapor, and trace contaminants. Filtering or cleaning involves removing these unwanted impurities to produce a high-quality biomethane that can be injected into the natural gas grid or used as a biofuel. Thus, it is necessary to remove particles, moisture, sulfur compounds, $CO_2$, and other contaminating traces to provide greater quality to the biofuel (Papurello et al., 2019, 2018; Sibiya et al., 2021; Zhu et al., 2020). The purpose of this study is to assess the production of biogas from particulate matter found in waste, the benefits of obtaining this product, and how this process can contribute preservation of the environment. It withal provides a comparative analysis of the number of publications in the field of biogas production and the economic growth of the countries studied. Further, various graphics and images are presented to provide a comprehensive understanding of the players involved in biogas production as a sustainable energy alternative. Moreover, bibliometric analysis was used to enable a better representation of the data presented.

For example, some pre-industrial prototypes and case studies that illustrate different approaches to biomethane production are Jönköping Biomethane Project, Sweden, which used organic waste from restaurants and food industries to produce biogas through anaerobic digestion. The resulting biogas was purified to obtain biomethane and used as fuel for natural gas vehicles. We can also mention the BioSNG Project in the Netherlands, which used the Synthetic Natural Gas (SNG) technology that converts biogas into a gas similar to natural gas through a process called methanation (Papurello et al., 2014). The BioSNG project in the Netherlands developed a prototype to demonstrate the feasibility of this technology, converting organic waste and sewage into biogas and later into SNG. The REWAG Project in Regensburg, Germany used biogas produced from agricultural waste and sewage sludge that was purified to obtain biomethane. The biomethane was then injected into the local natural gas grid, demonstrating the ability to utilize the existing gas infrastructure to deliver renewable energy and lastly, there is also the SmartGreenGas Project in Ireland which has developed a prototype to convert biogas into biomethane using adsorption technology by pressure swing (PSA). The biomethane produced was injected into the natural gas network and used as fuel for natural gas vehicles (Becker et al., 2022; Peppers et al., 2019).

Biogas can also be used in SOFC systems (Solid Oxide Fuel Cells) and its potential application. Solid Oxide Fuel Cells are electrochemical devices that convert the chemical energy of a fuel directly into electricity, without the need for combustion. These cells work at high temperatures, normally above 600°C, which allows them to have high efficiency in energy conversion. Biogas, which is a mixture of methane ($CH_4$) and carbon dioxide ($CO_2$) produced from the anaerobic decomposition of organic materials, can be used as a suitable fuel to power SOFCs (Santarelli et al., 2017). Potential benefits of using biogas in SOFCs include energy efficiency, emission reductions, cogeneration, waste utilization, and distributed generation.

SOFCs have high energy conversion efficiency, which means that a significant amount of the energy contained in biogas can be converted directly into electricity. Unlike conventional biogas flaring, conversion to a SOFC produces electricity without the direct release of CO2 (Lanzini et al., 2017). This can help reduce greenhouse gas emissions. SOFCs can be designed to operate in cogeneration systems (combined production of electricity and heat). The residual heat released during the operation of the cells can be used for thermal applications such as water heating or space heating. Biogas is often produced from organic waste such as agricultural waste, food waste, and sewage (Papurello et al., 2015). The use of these wastes to generate electricity can be a sustainable way of dealing with waste. SOFCs can be used in distributed generation systems, where energy is generated close to the place of consumption. This can be especially useful in areas where the power grid is unstable or where there is no reliable access to electricity. While SOFCs have many advantages, there are also challenges associated with their use, such as the need to operate at high temperatures, the durability of materials, and the complexity of systems integration (Lanzini et al., 2017; Papurello et al., 2015; Santarelli et al., 2017).

The use of bibliometric analysis has become increasingly popular in business research owing to the development and accessibility of software like Gephi, Leximancer, VOSviewer, and scientific databases like Scopus and Web of Science. This methodology has been widely adopted in business research (Donthu et al., 2021; Rodrigues, 2019), largely due to its cross-disciplinary applications and the ease of data visualization through specialized software VOSviewer (van Eck and Waltman, 2010). Other essential software for bibliometric analysis includes Bibexcel, Pajek, Gephi, Scimat, Sci2, and UCINET, all of which have network visualization as a critical aspect (Donthu et al., 2021). There are many free network visualization software options available, so the choice of which use depends on the individual preferences of the researcher. The increased use of bibliometric analysis in business research is not a passing trend but rather a reflection of its usefulness in managing large volumes of scientific data and generating significant research impact (Chen et al., 2021). The bibliometric methodology involves the use of quantitative techniques to analyze bibliometric data (Dutra et al., 2022a). While discussions of bibliometrics date back 1950s, the proliferation of bibliometric data is a relatively recent phenomenon (Almeida et al., 2021; Dutra et al., 2022b), as evidenced by its growth in the fields of business, management, accounting, economics, econometrics, finance, and social sciences (Donthu et al., 2021; Douti et al., 2017; Rodrigues et al., 2023).

Publications using bibliometric data have grown significantly in recent years, with a high average annual number of publications, which has contributed to the advancement of scientific research (Andrade et al., 2019; R. C. Assunção et al., 2021). Therewithal, extensive revisions have improved outdated classical methods, resulting in a large number of articles being positively or negatively corroborated by bibliometric data (van Eck and Waltman, 2010). The article still discusses different types of reactors used to produce biogas, which plays a fundamental role in the conversion process and produce biofuel's beneficial society.

Provide a comprehensive overview of the research in this field and address knowledge gaps, the following research questions (RQs) are considered based on bibliometric analysis:

- RQ1: What are the most cited journals on biogas production?
- RQ2: How are studies on biogas production distributed among different countries and what are the expected future trends in this field?
- RQ3: What are the main research topics and emerging trends in biogas production from waste?
- RQ4: How has the annual number of publications on biogas production grown in countries where biogas is economically significant?

The other subjects related are structured as follows. Section 2 deals with the methodology used in this article as well as its methodological aspects explained in section 2.1, criteria and refinement conditions employed expressed in section 2.2. Subsequently, section 3 points out the results and discussions arising from the data collected, as follows: section 3.1 focuses on relevant information about the keywords used in carrying out the work; section 3.2 emphasizes sectors that contribute significantly to biofuel manufacturing; section 3.3 focuses on other relevant factors present in the biogas production chain; section 3.4 addresses equipment used in biofuel production; and, finally, section 4 addresses research implications, concerning itself with opportunities and prospects. Section 5 refers to the existing limitations of this research. In turn, sections 6 and 7, respectively, deal with the potential of biogas production from waste and the conclusions regarding the article and, soon after, other closing topics just like the presentation of the references used throughout the body of the work. As explained above, this study addressed an updated review and a bibliometric analysis of scientific research on the production of biogas, its derivatives, forms of use, and the advantages of the application. The focus of this review is on the analysis of research progress, updates, and trends in waste recovery, providing utility to products that are usually disposable and that, in short, have no use for consumption. This review contributes to the description of available technologies for this production process, providing the possibility to evaluate different product applications and explore innovative opportunities to use compost by-products in sustainable processes. Therefore, this study effectively proposes future research and is the basis for the transitional production chain of the biofuel processing industry.

## 2. METHODOLOGY

### 2.1. Methodology perspectives

The VOSviewer software was used to visualize the data in network form, as shown in the figures showing correlations from the database. Pie charts and line graphs were inserted using Microsoft Excel effectively present the data extracted from the database and presented in tables in the article. The world map shown in one of the figures was created using ArcMap, software that uses extracted data shows the distribution of the analyzed bibliography by country in a user-friendly manner. PowerPoint software was likewise used to adjust the VOSviewer figures and format information in the Microsoft Excel application.

The software applications were adopted to generate figures, tables, and graphs presented in the research article. The data was collected from the Web of Science database using the specified keywords between the years 2000 and 2022. This data collection is considered sufficiently representative to address the research questions outlined in (Fig. 1), as the Web of Science database is a reliable and robust source of information in the field of science and technology.

### 2.2. Criteria and refinement conditions

Certain parameters were set and entered into the institution's website to gather data from the Web of Science database. (Fig. 1) displays the refinement criteria and conditions utilized.

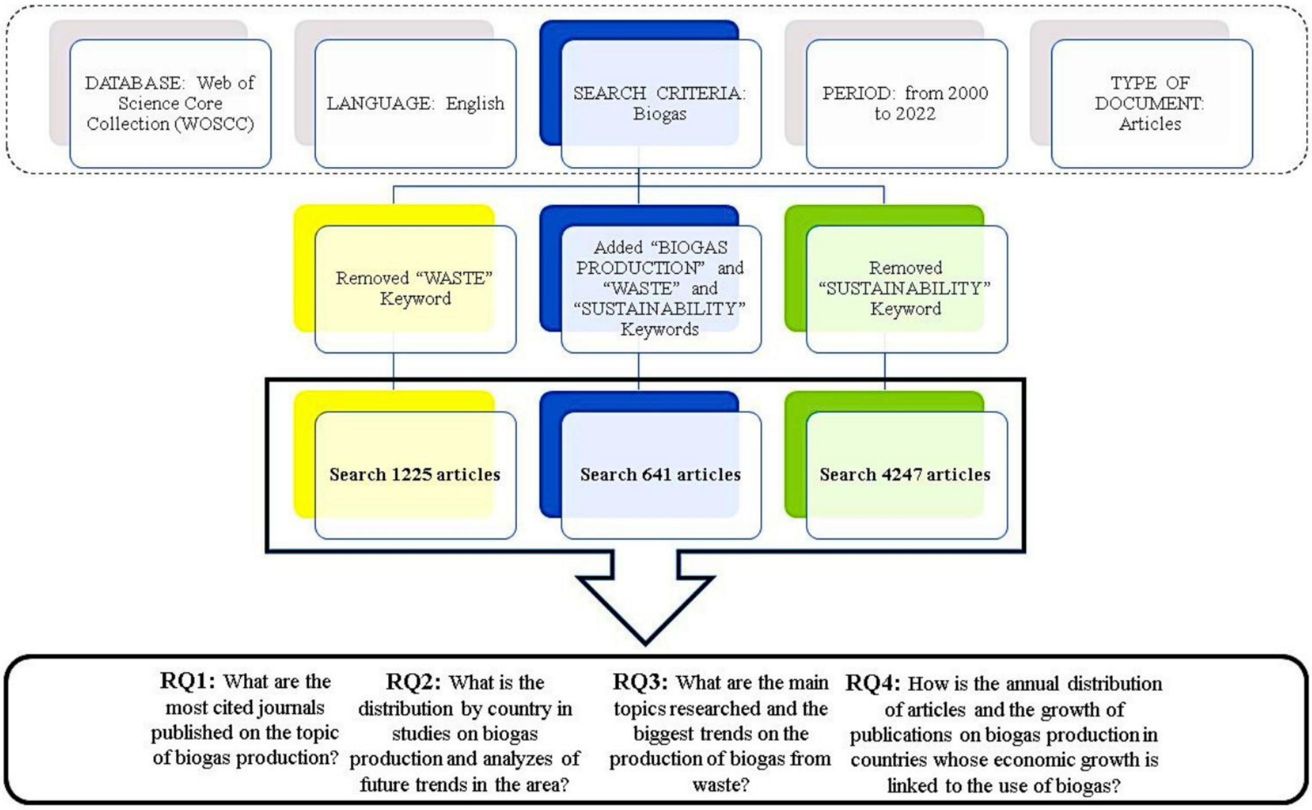



**Fig. 1.** The research framework of search criteria.

They were researched considering the following parameters: Web of Science database, articles published in English, and the period from 2000 to 2022. The collected data were employed to answer the four questions presented in (Fig. 1), considering the results from adding or removing specific keywords. Questions will be answered in discussion topics in the work itself.

## 3. RESULTS AND DISCUSSION

In this section, the results are discussed in greater detail and have the purpose of structuring factual arguments that corroborate with the answer research questions that were listed in the introduction, the so-called RQs (research questions). In topic 3.1 (Biogas production, waste, and sustainability), you will find the answers to RQ1 and RQ2, respectively. Beyond that, Topic 3.2 (Sectors that Contribute to the Achievement of Biofuel) presents information that substantiates RQ3. In turn, topic 3.4 (Biofuel production equipment) expresses data that satisfy RQ4**.**

### 3.1. Biogas production, waste, and sustainability

The paper aims to perform a comprehensive bibliometric analysis of global biogas production and compare the number of publications on this topic with the economic growth resulting from the use of biogas in the countries analyzed (Aziz et al., 2019; Bumbiere et al., 2020; Chuanchai and Ramaraj, 2018; Karlsson et al., 2018; Mattioli et al., 2017; Petravić-Tominac et al., 2020). Thereby, the Web of Science database was used with the search terms “biogas”, “biogas production”, “waste”, and “sustainability” from 2000 to 2022 (Estrada et al., 2012). In (Fig. 2), there is the presentation of the annual number of publications using the keywords chosen for the collection.

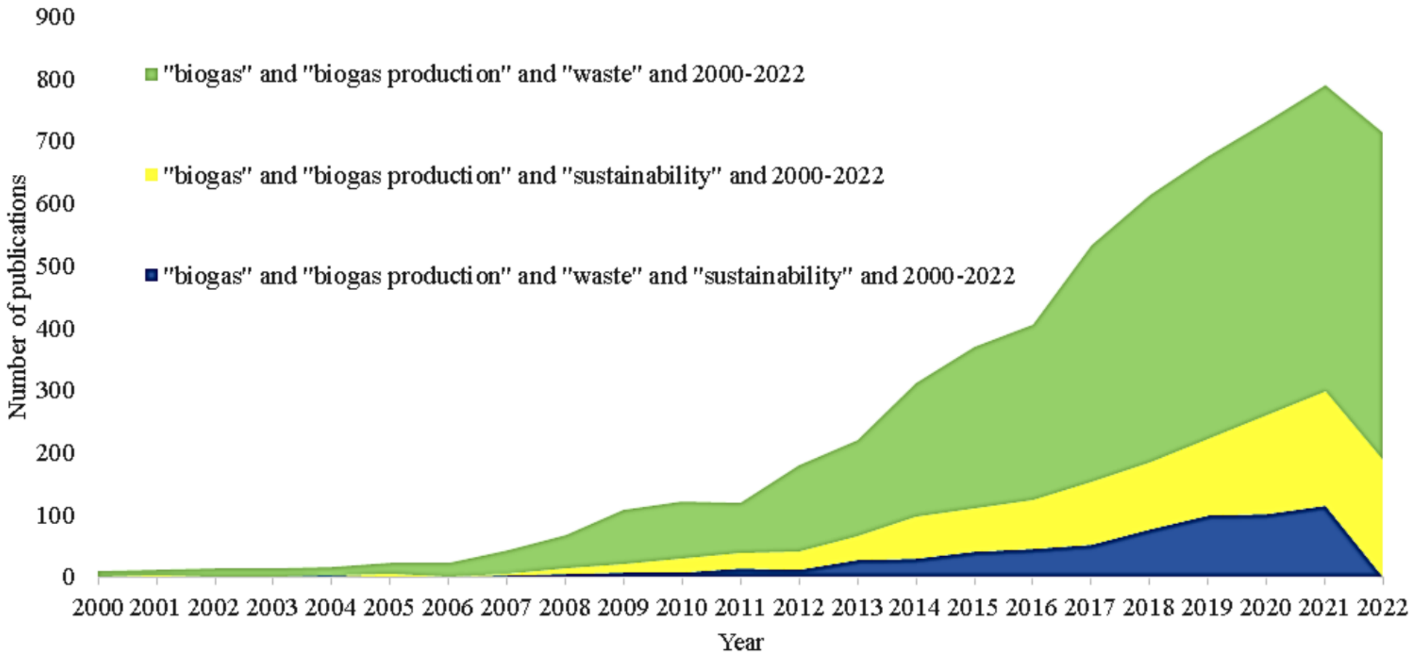



**Fig. 2.** The annual number of publications using the keywords “biogas”, “biogas production”, “waste” and “sustainability” from 2000 to 2022.

(Fig. 2) shows the annual number of publications considering certain keywords, and adding or removing words, which increases the number of conditions and restricts the search even more. It is noted that between 2012 and 2021 there is a considerable increase in the number of publications on this topic, which is in line with the increased importance of the issue of renewable fuels and their preponderance howbeit it comes to environmental preservation (Dayi et al., 2018; Poeschl et al., 2012; Zhang et al., 2020). It is important reveal that, in the section that deals with the discussions and results presented in the work, the chosen analysis, as a period of 10 years between 2012-2021 in the displayed figures, aims to focus on the growth of publications seen in (Fig. 2) following presented. Thus, the year 2022 is discarded for the analysis of this article in terms of the discussions held.

The results from the keywords related to the respective RQ are dealt with in this section:

- RQ1: What are the most cited journals on biogas production?

Going in the same direction, (Table 1) presents the scientific journals that are relevant in a discussion of biogas production, waste, and sustainability, and it also shows the degree of the contribution that the journals bring the scientific environment (Karlsson, 2019; Kohlheb et al., 2021; Spagnolo et al., 2020; Wu et al., 2015b). This information includes the impact factor, number of publications, and citations, which can help determine the importance of a particular journal in the field (Víctor Pérez et al., 2020b; Ruoso et al., 2022). It is too worth highlighting the participating nations, the academic journals involved, and their respective percentage contributions in total publications. The analysis shows that the United States, through the Journal of Cleaner Production and Renewable Sustainable Energy Reviews, has the largest production of publications on the topics studied, accounting for approximately 8% and 7.5% of publications, respectively (Cheng et al., 2019; Prask et al., 2018). Although only the 10 (ten) main scientific journals were presented in (Table 1), it is worth mentioning that the search in the Web of Science database covered more than 260 scientific journals specialized in the subject according to the collection performed. In this way, the other almost 250 journals are also relevant to the theme addressed, despite their quantitative reaching practically 70% of the published articles, only the top 10 were highlighted in several publications to facilitate the visualization of the most relevant ones.

**Table 1** Top ten scientific journals and countries for several publications related to biogas production, waste, and sustainability.

| Rank | Journal | C | IF | NP | ANMP | NC | AC | P (%) | Country | NP | NC | AC | P (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | JOURNAL OF CLEANER PRODUCTION | US | 11.07 | 51 | 2.55 | 1,507 | 29.55 | 7.94% | CHINA | 103 | 2,031 | 19.72 | 16.04% |
| 2 | RENEWABLE SUSTAINABLE ENERGY REVIEWS | US | 16.79 | 48 | 2.4 | 3,75 | 78.13 | 7.47% | INDIA | 62 | 1,535 | 24.76 | 9.65% |
| 3 | SUSTAINABILITY | CH | 3.89 | 28 | 1.4 | 309 | 11.04 | 4.36% | ITALY | 60 | 1,32 | 22 | 9.34% |
| 4 | ENERGIES | CH | 3.25 | 27 | 1.35 | 478 | 17.7 | 4.20% | USA | 55 | 2,599 | 47.25 | 8.56% |
| 5 | BIORESOURCE TECHNOLOGY | UK | 11.88 | 23 | 1.15 | 826 | 35.91 | 3.58% | BRAZIL | 40 | 453 | 11.33 | 6.23% |
| 6 | RENEWABLE ENERGY | UK | 8.63 | 18 | 0.9 | 426 | 23.67 | 2.80% | MALAYSIA | 40 | 1,662 | 41.55 | 6.23% |
| 7 | BIOMASS & BIOENERGY | UK | 5.77 | 15 | 0.75 | 478 | 31.87 | 2.33% | SWEDEN | 35 | 950 | 27.14 | 5.45% |
| 8 | JOURNAL OF ENVIRONMENTAL MANAGEMENT | US | 8.91 | 11 | 0.55 | 238 | 21.64 | 1.71% | ENGLAND | 33 | 998 | 30.24 | 5.14% |
| 9 | WASTE MANAGEMENT | US | 8.81 | 11 | 0.55 | 292 | 26.55 | 1.71% | SPAIN | 30 | 535 | 17.83 | 4.67% |
| 10 | CHEMOSPHERE | UK | 8.94 | 10 | 0.5 | 100 | 10 | 1.55% | POLAND | 28 | 533 | 19.04 | 4.36% |

C = Country; IF: Impact Factor in 2022; NP: Number of Publications (since 2000); ANMP = an Average number of manuscripts published (per year since 2000); NC: Number of Citations; AC = Average Citations = NC/NP; P = percentage with the total number of papers. UK = United Kingdom; US= United States of America; CH = Switzerland.

The information that meets the query made in the RQ is exposed in this section:

• RQ2: How are studies on biogas production distributed among different countries and what are the expected future trends in this field?

An interesting examination of the data on the most prolific countries in terms of publications related to the aforementioned topics is presented in (Table 1). The table provides information such as the number of publications per country, the number of citations, the average number of citations, and the percentage of the total number of articles. The data show that Italy, China, and India are the most prolific in terms of publications on these topics, with Brazil ranking fifth in terms of the number of papers (Guerini Filho et al., 2019, 2018; Ruoso et al., 2022). Given this, it is interesting note that Brazil has an interesting prominent place in the data collected, which expresses the country's ability to provide relevant content in the sector. This contributes significantly to the development of the country. Besides that, since China and India are the two largest populations on Earth, have vast consumer markets, and, consequently, demand a large number of energy inputs in the view to meet their needs, it makes sense that they are the greatest encouragers and scholars about the production of this biofuel (Berglund and Börjesson, 2006; Lorenzi et al., 2017).

(Fig. 3) shows a country-by-country breakdown of the top contributor's publications on biogas production, waste, and sustainability. This figure provides a concise summary of the table discussed earlier.

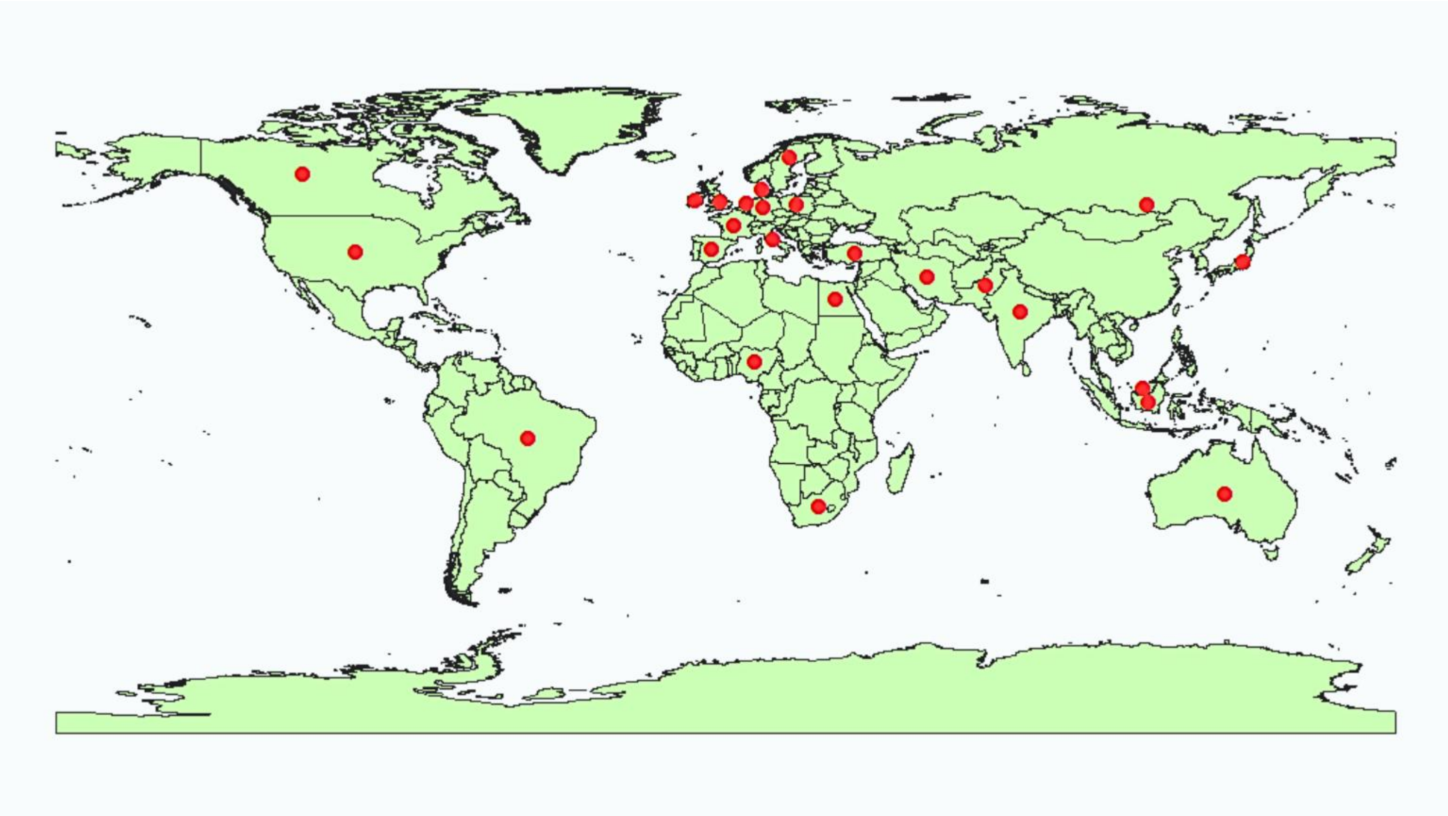


**Fig. 3.** Organization by bibliographic linkage.

The illustration on the map reveals geolocation by countries of those that contribute in a relevant way regarding the publication of articles graphically presented with red circles, considering those presented in (Table 1), among others that are not expressly shown because they are below those listed in the ranking. The countries that are marked with red dots on the theme addressed in the article have, in general, a solid research structure and development of techniques in the production of biogas, as they are countries that, concerning the others, invest heavily in biofuels. Thus, its energy needs are large compared to other nations. Brazil is an important regional player in terms of diversified energy matrices since it is a major consumer and producer of energy in Latin America, so it is expected that Brazil has good worldwide participation in the topics analyzed. In Europe, countries such as Germany, United Kingdom, France, and Italy are among the 10 (ten) largest GDPs (Gross Domestic Product) in the world, being, therefore, consumers of great energy demand and are, recently, making great investments in renewable energy matrices. Therefore, there is a consequent greater interest in the manufacture of this biofuel. China is also not far behind, since it is currently the second largest GDP in the world, behind only the United States of America. The geolocation by countries of those that contribute in a relevant way regarding the publication of articles is graphically presented, considering those presented in (Table 1), among others that are not expressly shown because they are below those listed in the ranking. It is interesting note that Brazil is the only South American country that contributes published articles on the subject matter. Furthermore, it is noticeable that quantitatively the largest number of contributing countries are located on the European Continent. On the other hand, the largest number of publications are located on the Asian Continent due to the participation of China as shown in (Table 1).

(a)

(b)

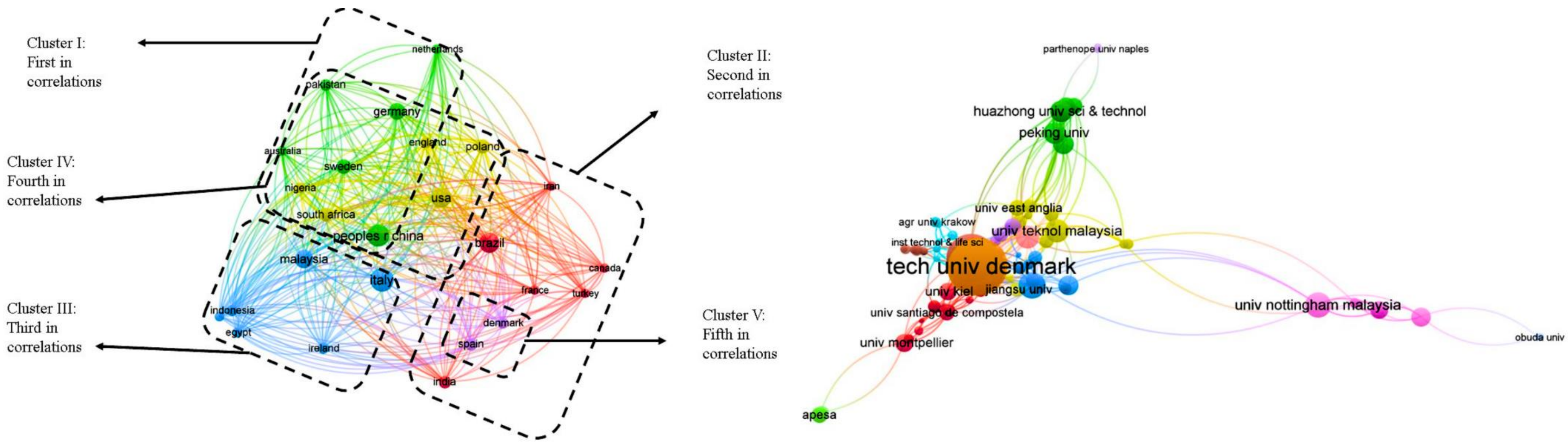



**Fig. 4.** Map of the network visualization. (a) Collaborations between countries based on their joint participation in at least five papers; (b) Bibliographic coupling of institutions, considering at least five citations.

(a) (b)

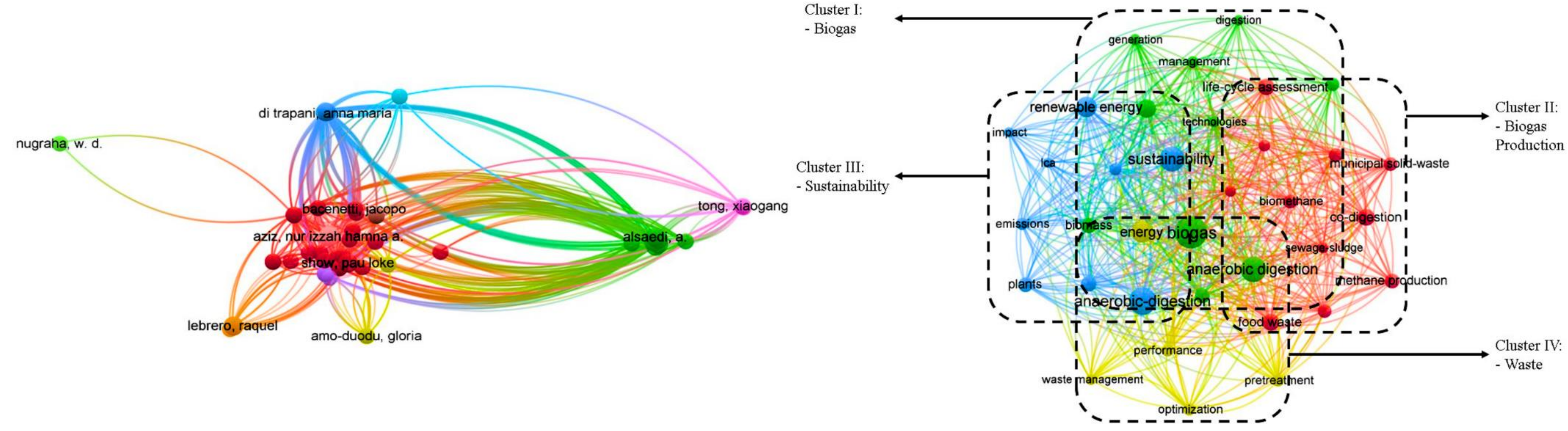



**Fig. 5.** Network visualization map. (a) Bibliographic coupling of authors who have published at least two documents; (b) Keywords in the analyzed papers.

(Fig. 4a) displays a network visualization map that shows the countries that have published at least five articles on the topic. In addition, countries with high levels of collaboration are shown in similar colors, forming clusters. The image shows a clear delineation of the clusters based on their level of relevance, as shown in the visual representation. In the software itself, clusters were established. Note that countries like Netherlands, Germany, and Pakistan are listed in the first cluster; Brazil, Ira, and France are in the second cluster, and so on in the figure. The countries that are represented with the larger ball size are those that have greater relevance in the analysis and, consequently, a greater degree of document production. (Fig. 4b) shows a network visualization map of institutions with a minimum of five citations. (van Eck and Waltman, 2010; "VOSviewer software (version 1.6.18)," n.d.). Following the pattern of the previously established figure in relation clusters, it is noted that the colors group the level of correlation between the institutions that have the highest degrees of relationship, justifying the number of citations between the entities. It should be noted that the colors of the circles correspond their respective clusters. It is also noted that the institution with the highest number of citations, due to the font size of the text, is Tech Univ Denmark - easily seen in the image. The Technical University of Denmark is a Danish higher education institution specializing in undergraduate and graduate courses in the natural, exact, and engineering sciences. This helps to explain the large number of publications on the topics addressed in this work. The other institutions additionally have some relevance in terms of the minimum number of related citations. (Fig 5a) presents the bibliographic grouping based on specific authors found in the data processing.

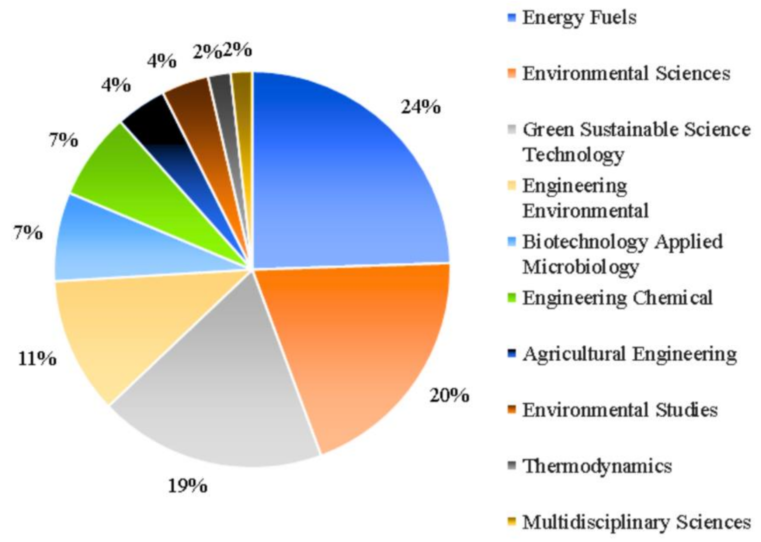
(Fig. 5a) shows a network map based on the bibliographic production of authors who have published at least two documents. The thickness of the lines connecting two authors indicates the degree of co-authorship, while the colors represent groups of authors with a high degree of collaboration. It is expressed that the red-colored cluster highlights the highest concentration of authors and the highest degree of correlation between the authors mentioned in the image. After this, (Fig. 5b) presents a network map showing the keywords used in the analyzed published articles. It's worth noting that each cluster has a demarcation that corresponds topic collected by the software in the Web of Science database. The first cluster deals with the keyword biogas that corresponds in green circles along with the key expressions related term. The second is headed by the word biogas production, which corresponds to red circles linked into main pertinent expressions. The third cluster of topics is led by the keyword sustainability which corresponds blue circles. In turn, the fourth grouping expresses the yellowish circles which cover the topics related to it. Then, in agreement with (Table 1), there is the classification of the most cited journals using residues for the manufacture of biogas.

**Table 2** The most cited papers on waste to biogas.

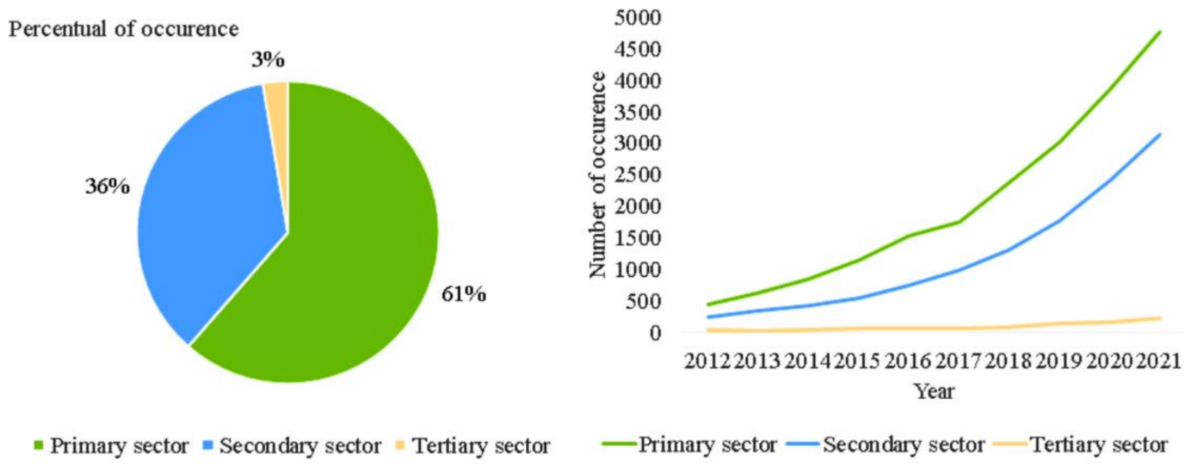
| Ranking | Paper | Citations | References |
|---|---|---|---|
| 1 | Title: Pretreatment of lignocellulosic wastes to improve ethanol and biogas production: A review. | 1623 | Taherzadeh and Karimi, 2008 |
| | Authors: Taherzadeh, MJ; Karimi, K. | | |
| | Journal: International journal of molecular sciences (2008) | | |
| 2 | Title: Review on research achievements of biogas from anaerobic digestion. | 897 | Mao et al., 2015 |
| | Authors: Mao, CL; Feng, YZ; Wang, XJ; Ren, GX. | | |
| | Journal: Renewable & sustainable energy reviews (2015) | | |
| 3 | Title: Pretreatment of lignocellulosic biomass for enhanced biogas production. | 793 | Zheng et al., 2014 |
| | Authors: Zheng, Y; Zhao, J; Xu, FQ; Li, YB. | | |
| | Journal: Progress in energy and combustion science (2014) | | |
| 4 | Title: Reviewing the anaerobic digestion of food waste for biogas production. | 753 | Zhang et al., 2014 |
| | Authors: Zhang, CS; Su, HJ; Baeyens, J; Tan, TW. | | |
| | Journal: Renewable & sustainable energy reviews (2014) | | |
| 5 | Title: Enhancement of biogas production from solid substrates using different techniques - a review. | 561 | Yadvika et al., 2004 |
| | Authors: Yadvika; Santosh; Sreekrishnan, TR; Kohli, S; Rana, V. | | |
| | Journal: Bioresource technology (2004) | | |
| 6 | Title: Evaluation of energy efficiency of various biogas production and utilization pathways. | 538 | Pöschl et al., 2010 |
| | Authors: Poschl, M; Ward, S; Owende, P. | | |
| | Journal: Applied energy (2010) | | |
| 7 | Title: 454 pyrosequencing analyses of bacterial and archaeal richness in 21 full-scale biogas digesters. | 500 | Sundberg et al., 2013 |
| | Authors: Sundberg, C; Al-Soud, WA; Carlson, A. | | |
| | Journal: FEMS Microbiology Ecology (2013) | | |
| 8 | Title: Biogas production from co-digestion of dairy manure and food waste. | 411 | El-Mashad and Zhang, 2010 |
| | Authors: El-Mashad, HM; Zhang, RH. | | |
| | Journal: Bioresource technology (2010) | | |
| 9 | Title: Anaerobic co-digestion process for biogas production: Progress, challenges and perspectives. | 384 | Hagos et al., 2017 |
| | Authors: Hagos, K; Zong, JP; Lu, XH. | | |
| | Journal: Renewable & Sustainable Energy Reviews (2017) | | |
| 10 | Title: Assessment of energy performance in the life-cycle of biogas production | 367 | Berglund and Börjesson, 2006 |
| | Authors: Berglund, M; Borjesson, P. | | |
| | Journal: Biomass & Bioenergy (2006) | | |

(Table 2) presents a key piece of information that is essential for a bibliometric study – the number of citations on a particular topic (dos Santos et al., 2022; Magrí et al., 2017). The table ranks the most cited papers on biogas production from waste (Fernández-Dacosta et al., 2015; Gunes et al., 2019; Hafuka et al., 2011; Otero et al., 2021). It's worth noting that the data analysis period was between 2000 and 2022, which coincides with the analysis period (Liew et al., 2021; Sheng et al., 2011). In consonance with the table, the first place is from a publication carried out in 2008 with 1623 citations and it is a review article using lignocellulosic residues as well as the second place which is a publication from 2015 with 897 citations and deals with anaerobic digestion for obtaining biogas, this is also a review article. It is important mention that review articles on this topic are much discussed in citations and end up retaining a wide range over the years. The third place in many citations addresses a similar subject the first place that considers lignocellulose residues. On the other hand, the fourth and fifth places address different subjects from the previous ones, respectively, a review of anaerobic digestion from food waste and the improvement of biogas production using solid substrates which, in turn, is classified with a review article. The other articles, despite being less cited, have some relevance regarding the number of citations in line with the analysis.

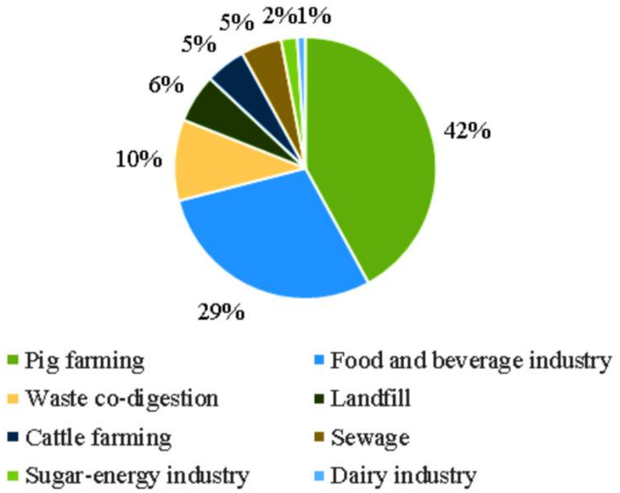
(a)


24%
20%
19%
11%
7%
7%
4%
4%
2%
2%
Energy Fuels
Environmental Sciences
Green Sustainable Science Technology
Engineering Environmental
Biotechnology Applied Microbiology
Engineering Chemical
Agricultural Engineering
Environmental Studies
Thermodynamics
Multidisciplinary Sciences

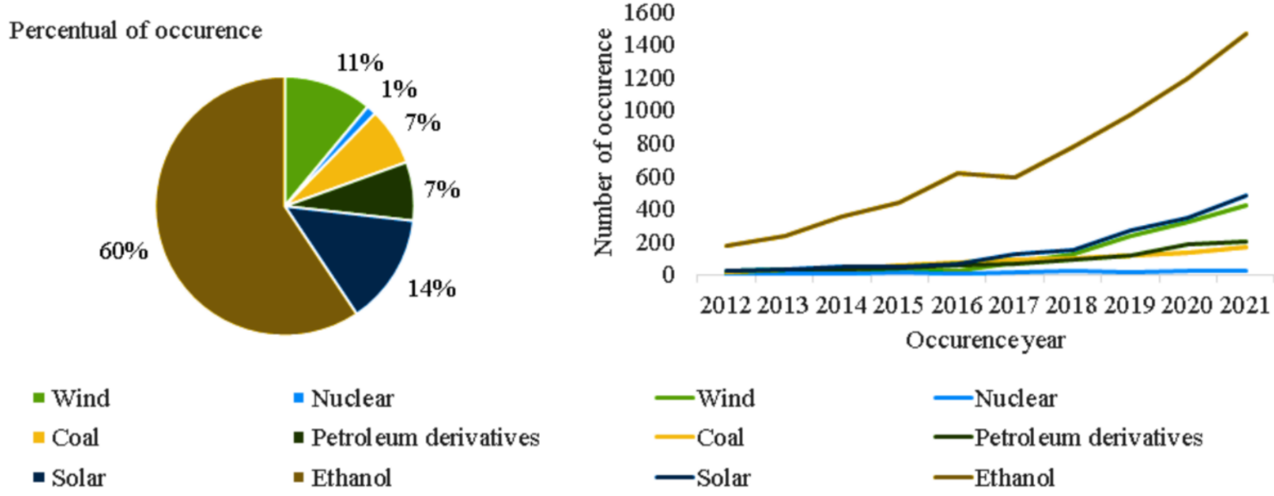
(b)


Percentual of occurence
3%
36%
61%
Primary sector
Secondary sector
Tertiary sector
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Number of occurence
2012 2013 2014 2015 2016 2017 2018 2019 2020 2021
Year
Primary sector
Secondary sector
Tertiary sector

(c)


42%
29%
10%
6%
5%
5%
2%
1%
Pig farming
Food and beverage industry
Waste co-digestion
Landfill
Cattle farming
Sewage
Sugar-energy industry
Dairy industry

(d)


Percentual of occurence
11%
1%
7%
7%
14%
60%
Number of occurence
1600
1400
1200
1000
800
600
400
200
0
2012 2013 2014 2015 2016 2017 2018 2019 2020 2021
Occurence year
Wind
Nuclear
Coal
Petroleum derivatives
Solar
Ethanol
Wind
Nuclear
Coal
Petroleum derivatives
Solar
Ethanol

(e)

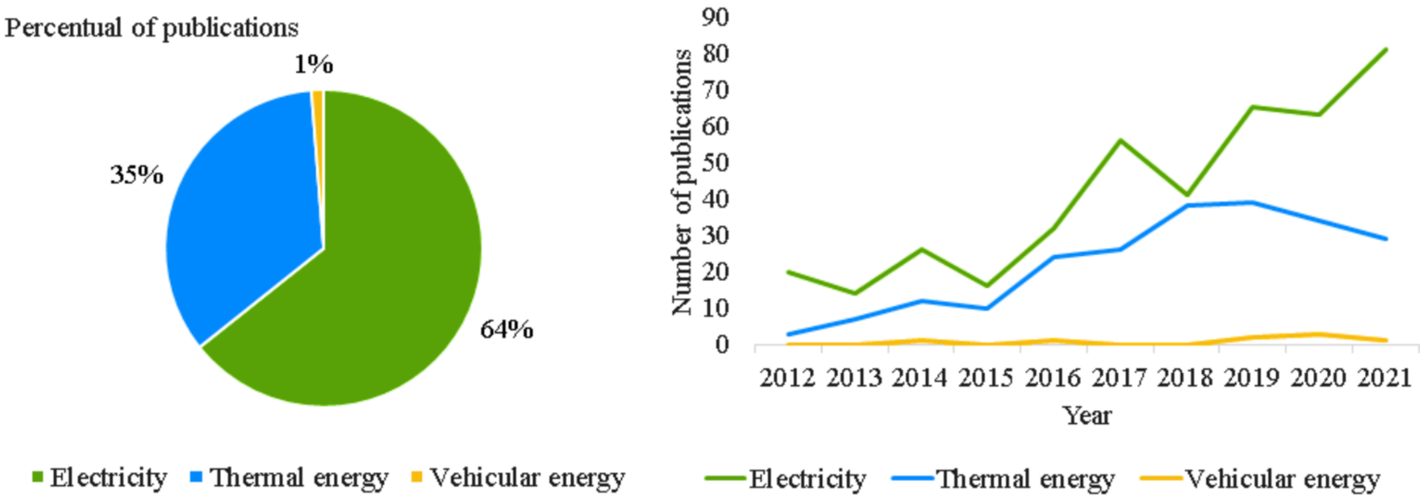



**Fig. 6.** Bibliometric analysis of biogas production research. (a) Distribution of research fields according to the Web of Science database; (b) Most cited waste source in biogas production research over the years; (c) Types of waste most used in biogas production; (d) Number of citations linking biogas and waste production with other energy sources; (e) Number of publications on biogas fuel applications in the most socially relevant areas.

(Fig. 6a) shows the distribution of research fields based on the Web of Science database concerning the addressed topic. The picture shows that more than 60% of the research falls into three categories – Energy Fuels, Environmental Sciences, and Green Sustainable Science Technology. It is appropriate mention that the keywords used are in line with the categories expressed in the database since energies, environment, and sustainability are aimed at meeting these terms. With this, it is clear that this percentage follows the natural trend of recent years since there are growing concerns about these listed categories, in other words, they are themes that have been incessantly debated over the years, nonetheless, they still have a high relevance.

### 3.2. Key sectors at play

The following results, using the specified keywords, corroborate the resolution of the problem established in the following RQ:

• RQ3: What are the main research topics and emerging trends in biogas production from waste?

(Fig. 6b) displays the primary sources of waste cited in research on biogas production over the years (Ai et al., 2020; Bernat et al., 2021; Rashama et al., 2019). Agriculture is the primary source, accounting for 61% of the input used (López et al., 2018; Porto et al., 2021; Sarkar et al., 2015; Siegmeier et al., 2015; Wellinger et al., 2013). The sectors of the economy shown in (Fig. 6b) are segments into which society's economic and productive activities are divided. The division takes place between the sectors. Primary, which concerns agriculture, livestock, and extractives. Secondary, which corresponds to the industry. Tertiary, which aggregates services, formal or informal, provided in the most diverse areas, as well as commercial activities. The industry just contributes significantly with 36% of the waste sources used for fuel production (Bartoli et al., 2020; Liebetrau et al., 2010). The sector with the least expression is the tertiary services sector, which corresponds sole 3% of participation in relation presented quantity. The 10-year period listed in the second graph is enough for us to notice a relative advance in the number of citations over the years, with emphasis on the primary sector, which corresponds to the highest percentage analyzed (Unuofin, 2020). (Fig. 6c) which is the next figure, there are the types of waste that are commonly used for biogas production: pig farming, the food and beverage industry, waste co-digestion, waste from landfills, livestock waste, sewage waste, waste from the sugar-energy industry and waste from the dairy industry (Estrada et al., 2011; Taherzadeh and Karimi, 2008). It is intriguing note that, among the types of waste shown in the figure, only waste from swine farming and the food and beverage industry account for more than 70% of waste used to produce biofuel (Guimarães Freire et al., 2011). Another interesting aspect is that waste from sanitary landfills corresponds only 6% of the contribution as fuel production and this shows that there is a need increase the quota at this specific point (Agustini et al., 2018).

### 3.3. Exploring essential aspects in the biogas production chain

(Fig. 6d) lists other essential energy sources that correlate citations with biofuel production and waste. Based on the information from the graph, the picture illustrates the number of citations linking biogas production for other energy sources. The percentages presented in the database indicate the following sources: ethanol, wind, nuclear, coal, oil derivatives, and solar (Kjerstadius et al., 2015; Ramírez-Arpide et al., 2018). The data show that ethanol is the most common source with a 60% share, followed by solar and wind with 14% and 11% shares, respectively (Aggarwal et al., 2021; Ajieh et al., 2021; Maamri and Amrani, 2014; Melo et al., 2019; Udaeta et al., 2019; Weiland, 2003;

Zhang and Chen, 2017). The other sources have less relevance compared two main sources; nevertheless, they conjointly have relevance with values, videlicet: 7% for coal, 7% for petroleum derivatives, and only 1% for nuclear sources. We highlight the fact that the number of occurrences joint in ethanol sources grew enormously in relation other five cited sources. This is due to several programs carried out in several countries that had the purpose of promoting ethanol fuels as an alternative, mainly, fuels: gasoline and diesel oil (Babič et al., 2012; Lee et al., 2021),(Campello et al., 2021; Ingrao et al., 2019). It is noteworthy that specific sources have increased in importance in related research sources from 2012 to 2021. The due high number of citations present in the most prominent source, which is ethanol, it is possible state that in the last 10 or 15 years there has been a significant increase in actions related this type of fuel, such as government maintenance and support from the private sector so that this element was widely disseminated as an energy alternative (Zhang et al., 2014). Another notable aspect is the number of publications on biogas applications in the various social areas of interest, as shown in (Fig. 6e). The image displays the number of publications on the application areas of fuel production, particularly in areas of higher relevance for society, such as thermal energy, vehicle energy, and electricity (Ayodele et al., 2018; Budžaki et al., 2017; Nindhia et al., 2021; Víctor Pérez et al., 2020a; Pose-Boirazian et al., 2021; Salvador et al., 2019; Zeng and Kaltschmitt, 2016). Electricity has the largest share (64%), followed by thermal energy (35%) and vehicle energy, with only 1% in the analyzed period (Alexander et al., 2019; Nevzorova and Kutcherov, 2019; Zhang et al., 2022). The data indicate that electricity is the most crucial product for society, given its overall utility. Furthermore, there is a stagnation in terms of publications regarding vehicle energy (Mao et al., 2015). Another data extracted is the progression in the number of publications involving these topics, with emphasis on electricity and thermal energy, which had more significant growth in the analyzed period.

### 3.4. Advanced machinery for biogas production

The following are instances of reactors that are utilized for biogas production (Fu et al., 2018; Uddin and Wright, 2022):

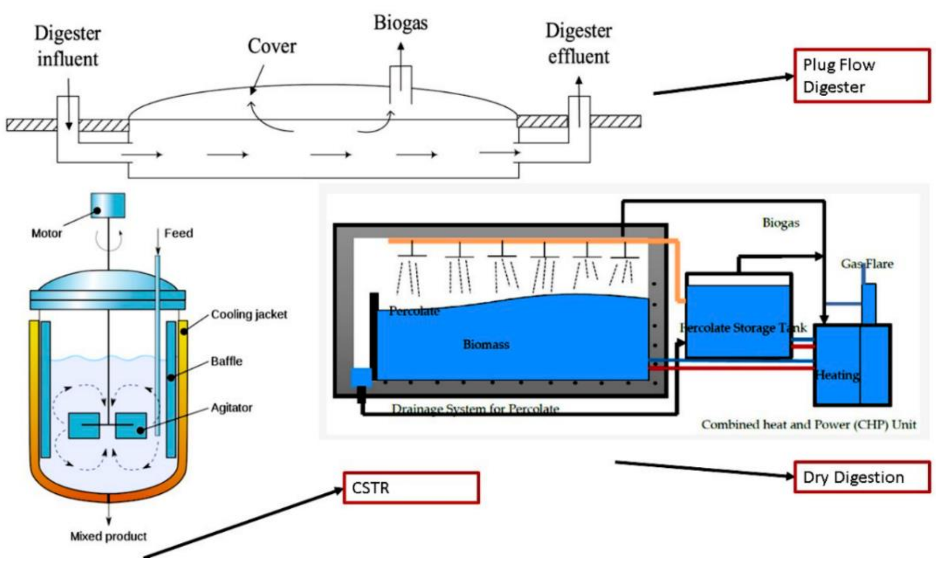
Plug flow digester;

Continuous stirred tank reactor (CSTR);

Dry digestion.

(Fig. 7a) displays descriptive illustrations depicting the functioning of the aforementioned equipment, correspondingly.

(a)




(b)

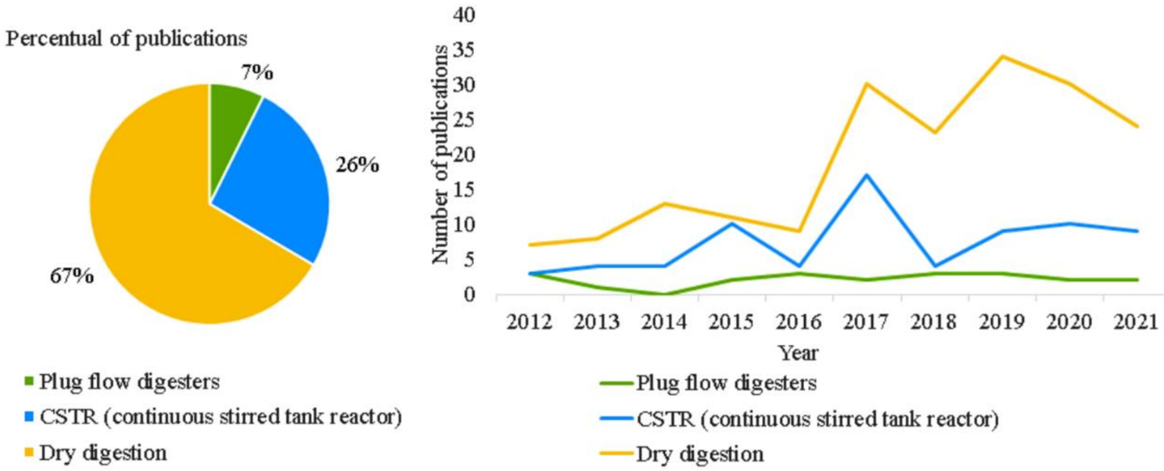



**Fig. 7.** Reactors that can be used in the production process. (a) Illustration of digester; (b) Number of publications on biogas production from digesters used to produce fuel gas.

The reactors mentioned above have specific processes that can be used for fuel production, each with its characteristics, as shown in the illustration in (Fig. 7a) (Agung Pambudi et al., 2017; Tufaner and Demirci, 2020). Else, the number of publications on the production of the target fuel was analyzed, considering each type of reactor mentioned in the previous figure (Poppe et al., 2015; Wiles and Watts, 2012). (Fig. 7b) displays the previously mentioned information relating to the types of reactors used in carrying out the process, as well as showing the progress, over the 10 years analyzed, in the number of publications that list the equipment covered. The reactor type known as dry digestion stood out as the most published among the various reactor types analyzed, accounting for 67% of the publications on the topic during the specified period (Abdelsalam et al., 2021; Fu et al., 2018). Meanwhile, CSTR accounted for 26% and plug flow for 7% of the publications (Cao et al., 2017; Chen et al., 2009; Hudakorn et al., 2019; Lindeque and Woodley, 2019; Satar and Husain, 2009; Toftgaard Pedersen et al., 2017). The dry digestion method is the most advantageous as it is the simplest and least expensive in terms of machinery (Aljuraifani et al., 2018; Ferreira et al., 2018). This is the best option since it involves easier processing, not to mention that the cost of the equipment is a lot dramatically lower, as will be presented in a table later in the article.

(Table 3) exposes the methods, types of digesters, and the average acquisition cost of these types of equipment for the manufacture of biofuel (Lansing et al., 2010; Sundberg et al., 2013).

**Table 3** Literature information on methods, types of digesters, and average costs of biogas production.

| Biogas production method | Type of digesters | Application | The average cost of equipment | Reference |
|---|---|---|---|---|
| Anaerobic fermentation process | Plug flow digester | Commercial | US$ 20,000.00/und | Lansing et al., 2010 |
| Anaerobic fermentation process | CSTR (continuous stirred tank reactor) | Commercial and Academic | US$ 25,000.00/und | Wiles and Watts, 2012 |
| Anaerobic fermentation process | Dry digestion | Commercial and Academic | US$ 7,266.00/und | Abdelsalam et al., 2021; Fu et al., 2018; Samer et al., 2022 |

(Table 3) displays different details in methods used, types of digesters, and the average expenses incurred in generating biogas using these devices (Lebrero et al., 2016). Besides, it should be mentioned that the biofuel production method may have either commercial or academic applications (Iordan et al., 2016; Wellinger et al., 2013). Another fundamental piece of information pertains to the anaerobic fermentation process utilized in these types of equipment for generating the energy source (Castilho et al., 2009; Choi et al., 2010; Choi and Lee, 1999; Rodríguez Couto and Sanromán, 2005; Yu et al., 2006). Among the advantages that we can mention of this type of reactor are the relatively low-pressure temperature, variation of raw material, production of fertilizers, and obtaining clean gas. Regarding the disadvantages, we can mention: the need for temperature control, harmful by-products, - like sulfates - accumulation of organic wastes, and the high cost of installing the machinery.

### 3.5 Exploring biogas production via anaerobic digestion

The production of biogas through anaerobic digestion is a technology that offers several advantages and disadvantages, as well as being subject to trends and developments in the field of renewable energy. Among the benefits, we can mention: renewable energy, waste reduction, energy, heat generation, generation of by-products, and odor reduction. Anaerobic digestion treats organic waste, preventing its decomposition in landfills, where it releases methane, a potent greenhouse gas. It can generate electricity, and heat can meet the energy needs of homes and industries and even be integrated into the electric grid. The digestion process produces digestate, a nutrient-rich material that can be used as an agricultural fertilizer and reduces the odor associated with treating organic waste.
On the other hand, among its disadvantages, we can mention: initial investment, process control, gas emissions, and energy efficiency. The construction and installation of an anaerobic digestion plant can involve considerable costs, especially for more advanced systems. The anaerobic digestion process is sensitive to variations in operating conditions such as temperature, pH, and waste concentration, and maintaining these ideal conditions can be challenging. Furthermore, although biogas is a cleaner energy source than fossil fuels, burning biogas can still emit polluting gases and carbon dioxide. Another possible disadvantage is that the efficiency of biogas production can vary depending on the quality and quantity of waste used.

The main trends in this technology are the ability to integrate energy sources, as biogas can be combined with other renewable energy sources, such as solar and wind energy, to provide a more stable and reliable energy source. Decentralized applications, in addition to extensive waste treatment facilities, there is a trend towards smaller-scale anaerobic digestion systems such as household and community units. Greater environmental awareness of society, as there is a growing interest in more sustainable energy sources, including biogas, and, consequently, providing more significant government incentives, as many governments are offering financial and regulatory incentives to promote the production of biogas and other forms of renewable energy. Overall, the production of biogas through anaerobic digestion has the potential to be an essential source of renewable energy, helping to solve waste problems and contributing to the transition to a more sustainable future in terms of energy and environment.

The results presented below, in this section, obtained through the analysis of collected data act to answer the following RQ:

- RQ4: How has the annual number of publications on biogas production grown in countries where biogas is economically significant?

(Fig. 8) performs a comparison between the leading countries in biogas production capacity and the leaders in publications of related articles.

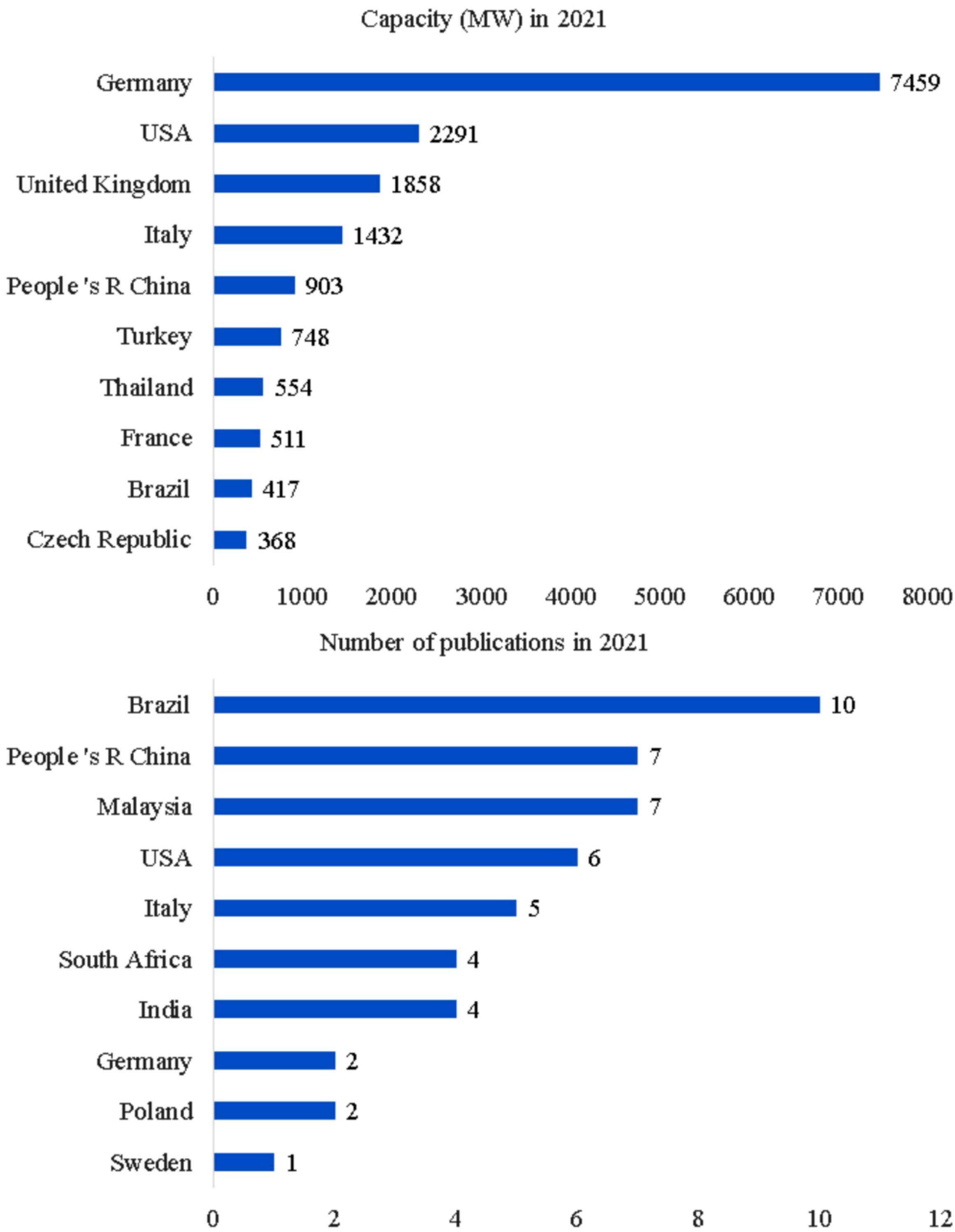



**Fig. 8.** Comparison between leading countries in publications and countries in energy production capacity from biogas in 2021.

(Fig. 8) compares the leading countries in publications on biogas and those with the highest energy production capacity from biogas (Ahmed et al., 2015; Arthur et al., 2020; Bedoić et al., 2021; Boldrin et al., 2016; Moeller and Zehnsdorf, 2016; Rodríguez et al., 2018; Volschan Junior et al., 2021). Based on the data, the top 10 countries in terms of both publications and energy production capacity are presented (Aziz and Hanafiah, 2020; Hertel et al., 2015). In particular, Germany, the United States, and the United Kingdom are the leading countries in biogas energy production, followed by Italy, China, Turkey, Thailand, France, Brazil, and the Czech Republic (Bakkaloglu et al., 2021; Bumbiere et al., 2021; Liu et al., 2017; Rostkowski et al., 2012; Sarker et al., 2019; Tagne et al., 2021; Willis et al., 2012). Conversely, Brazil, China, and Malaysia were the countries with the highest number of published articles on this topic during the period analyzed, followed by the United States, Italy, South Africa, India, Germany, Poland, and Sweden (Amo-Duodu et al., 2021; Ankur et al., 2020; Brémond et al., 2021; Ferella et al., 2019; Foong et al., 2021; Montenegro Camacho et al., 2017; van Stappen et al., 2016; Wang et al., 2017; Zhang et al., 2015). It is worth noting that Brazil appears and has a significant presence in the database in terms of the number of publications on the subject, and therefore has some relevance in terms of energy production capacity from this biofuel (Harun et al., 2011; Sgroi et al., 2015b, 2015a; Wang et al., 2019).

Whilst actions promoting this type of fuel in the country are in evidence, it is noted, given the data expressed in the previous figure, that Brazil is still short of its real production capacity for this biofuel, since there is a notorious mismatch between the two variables shown in the image. It is possible to state this considering a certain level of relationship between these aspects, although they are, in fact, different points albeit analyzed together. Hence, because of the revealed data, it is clear that there is not necessarily a direct relationship between the country's biofuel production capacity and the number of its publications in the related year, while it is not an appropriate position that there is no relationship between these aspects.

## 4. OPPORTUNITIES AND PROSPECTS

Faced with the need to obtain the benefits of this product and the understanding of the process to contribute preservation of the environment, the importance of reducing waste sources must be emphasized as a priority (Nilsen, 2020). Besides, in the food supply chain and waste generated by consumers or other biomass waste produced in the industrial, agricultural, or horticultural sectors can enter this chain as inputs. In any case, properly using one of these strategies should be designed and adopted by informing and training waste generators about treatment methods. Knowing how to reduce waste, understand the benefits, and identify opportunities to convert it into energy should be considered. In the same direction, priority should be, videlicet: (1) establishing guidelines and rules for the agricultural, industrial, and service sectors to encourage them to foster the culture of adapting waste for the biofuel production process; (2) Expanding social awareness about the adverse effects of indiscriminate waste generation, inclusive informing them of how food waste converting energy can be harmful; and (3) encourage the use of biofertilizers and biofuels just like encourage research and financial support from society as a whole, as there may be greater participation of biofuels as an energy source.

Besides, many applications of biofuels derived from biomass and organic residues must be considered, as well as their relevant role in the decarbonization of transport systems, which has been widely discussed in several research works (Chiaramonti et al., 2021). Accordingly, the current scenario and its various social, economic, and environmental aspects in humanity provide opportunities for a gradual and beneficial transition until the use of greener energies, such as biofuels and electricity, in the transport sector. Using biofuels in this sector can be a favorable solution, though it can significantly reduce non-renewable fuels and concomitantly end in positive environmental results (Nunes et al., 2020). Notwithstanding, biofuels are used in several sectors, as presented in the article. More analysis, research, and funding are needed to commercialize equipment and vehicles powered by alternative fuels like those already mentioned to encourage biofuels in the transport sector (Farias et al., 2020). The environmental, economic, and social impacts of using organic wastes for this purpose align with the three pillars of sustainability and support sustainable development in rural areas. Despite that, a systemic approach must be carried out by collecting the interconnections between the variables and the complexities of the treated system to assess what is sustainable and provides an effective transition of energies (Shams Esfandabadi et al., 2020; Stern et al., 2015). Such systematicity can align data (Shastri et al., 2011), machine learning (Wang et al., 2022), and artificial neural networks (Gopal et al., 2021) with the view to support decision-making regarding process and product improvement in an optimal way (Sridhar et al., 2021). Assuming a multidisciplinary behavior is extremely important, as developing adequate and inclusive strategies in these situations.

## 5. RESEARCH LIMITATIONS

The research work was guided by certain limitations that will probably offer future paths to further development by the researchers involved. Firstly, the grouping of data was carried out in two ways using bibliometric methods: bibliographic analysis of coupling and co-citations. There is likewise the possibility of using other grouping methods, for instance, data mining, which is also positive for the theme. Secondly, albeit there is an attempt to cover all topics about the essential elements of biofuel production from organic wastes, it is worth remembering that the data were collected exclusively from the Web of Science database, thus making it valid and even recommending the use of other databases for the element or expand the study, such as Scopus or Scielo - excellent references in this area of research. All this is important, as future research could be performed. The use of techniques such as gray literature review and snowballing should be proposed with the purpose of enriching the work.

## 6. POTENTIAL BIOGAS PRODUCTION FROM ORGANIC WASTES

Despite this, applying the anaerobic digestion method has a series of restrictions ranging from low biogas yields due to the inhibitions caused by the substrate compounds to the high acquisition costs with specific equipment in the constitution of the biodigester (de Morais Andrade et al., 2022; Souza Neto et al., 2023). Considering these disadvantages, several scientists and researchers have analyzed various ways to improve this process to increase biogas production (Hagos et al., 2017). Metallic particles such as cobalt, iron, nickel, or iron oxide can also be used as nanoparticles to reduce the production of hydrogen sulfate without affecting the methane concentrations manufactured in the process (Pramod Jadhav et al., 2022). Given this, this technique increases the yields of biogas and methane concomitantly with the improvement of the efficiency of the anaerobic digestion method (author's citation) (Samer et al., 2022). These nanoparticles are composed mainly of metals and metallic oxides and play an auxiliary role in anaerobic digestion, providing biodegradation of organic material (Rani et al., 2017).

Turning organic waste into a valuable energy source is a remarkable skill and has attracted much attention (Borges et al., 2021). When waste is degraded into biogas of renewable energy and rich in methane (CH4), the method with biodigesters with dry digestion - using anaerobic digestion - stood out for treating waste and developing renewable energy (Pieja et al., 2017). Harmful elements are reduced to a maximum, odors are practically eliminated, and the quality of the environment is preserved since waste is properly treated and energy is substantially conserved (Keerthana Devi et al., 2022).

### 6.1. Enhancing biogas production

Presented in the molecular formula CH4, methane is also known as swamp gas. It is a colorless gas with no smell (Pieja et al., 2017). It has low solubility in water. When in contact with air, it can become highly explosive. This gas is known for its energetic properties and for being produced by the digestion of cows. However, there are several other sources (Pérez et al., 2019). This gas is one of the compounds responsible for the study effect, being more potent in this regard than carbon dioxide since methane's heating effect is 84 (eighty-four) times greater than carbon dioxides. Methane is in the total hydrocarbons (THC) group and is a simple hydrocarbon. Methane does not enter the pollutants that operate as air quality indicators; however, it is part of the group of short-lived climate pollutants (Yang et al., 2022). The compound, when inhaled, can cause suffocation, loss of consciousness, cardiac arrest, and damage to the central nervous system. Several disadvantages are associated with using non-renewable resources to maintain a sustainable environment, including high prices and limited availability (Aboyade, 2004).

Using technologies such as nanoparticles in biogas processing reduces the number of pathogens and the amount of energy required for the process making it more efficient and effective in its achievement (Abdelwahab and Fodah, 2022; P Jadhav et al., 2022). Annually, more waste is produced worldwide due to the increasing level of agricultural and industrial production and higher domestic consumption (Kolbl et al., 2016). It is estimated that between one and a half billion and three billion tons of waste are produced yearly due to this process (Gbangbo et al., 2023). Raw materials such as organic manure, food waste, sludge, straw, faces, leaves, chicken remains, household waste, and other industrial waste can be input into the product purchase (Bernat et al., 2021; Shahzad et al., 2017). Countries with significant development and a considerable population have a strong capacity to convert waste into energy products, including biogas production by anaerobic digestion (Kumar et al., 2021b).

### 6.2. The future perspectives of renewable energy on biogas production

Biogas is undoubtedly a fuel with great potential, as it is called the fuel of the future for sectors that depend on oil (Bumbiere et al., 2021). It is clean, safe, more renewable, and environmentally friendly than other options (Korbag et al., 200AD). In addition, the high restriction on the commercialization of petroleum derivatives and the increased demand increased prices for these compounds, which led academics to consider other possibilities of using biogas as a viable alternative (Willis et al., 2012). The biogas production process continues to be difficult, despite its clean and safe use. Inputs from biomass can be easily obtained since there is an infinity of possible sources, including wood, agricultural residues, plants, organic residues, and other types of residues of animal and vegetable origin (El-Dalatony et al., 2022; Rajendiran et al., 2022). However, successfully replacing oil from petroleum is not an easy task since many obstacles and difficulties must be overcome to guarantee its development potential (Russo and von Blottnitz, 2017). Operating costs are prohibitive in pre-treatment procedures, such as those used to prepare lignocellulosic biomass. In addition, organic biomass has been used in biogas production due to its high oil content, which does not emit carbon dioxide with a high degree of growth (Florencio et al., 2017; Zheng et al., 2014).

There may be a replacement of fossil fuels in bioenergy production (Mattioli et al., 2017). Biomass from microbes is an expensive and complex undertaking, and the extraction of usable lipids requires a high amount of energy in the process (Agustini et al., 2018; Toledo-Cervantes et al., 2018). In this sense, using nanotechnologies for manufacturing large-scale biogas presents a series of challenges to overcome because the constitution of biogas based on nanocatalysts is still "in its infancy" in this context (Wang et al., 2022). In addition, some research, which aims to optimize the production of biofuels by increasing the efficiency and effectiveness of the process, is still ongoing to make better use of resources (Valenti et al., 2017). In the past, producing large-scale biogas has been customarily carried out using waste derived from animals and some types of edible crops, for instance, corn, sugar cane, and others. Producing biogas from non-edible sources is considerably less usual and applied in small amounts (Weiland, 2010). Renewable energy sectors with advances in nanotechnology promise significant innovations in the generation of electricity, biomass, and technologies related to the use of hydrogen, being considered more promising in the various sectors that deal with the theme of renewable energies and operate as precursors of the following discoveries in the field (Wong et al., 2019) of academic research and practical-laboratory research.

There are some examples that we can point out as relevant, namely: nanocrystalline films and surface micro-texturing in photovoltaic and electrochemical cells, as well as nanoscale catalysts and membranes or thermochemical generation of hydrogen for applications in fuel cells (Hai et al., 2023; Ishaq and Ishaq, 2022). In this way, such applications that are still under development have the potential to considerably expand production and processing efficiency while decreasing the indirect costs of the process (Abdeshahian et al., 2016). Producing biofuel using nanoparticles can lead to a considerable improvement in yield due to these compounds' unique characteristics adding high reactivity, high surface-to-volume ratio, and high specificity, in addition to other characteristics (Zaidi et al., 2023).

To increase the number of biofuels by a wide variety of substrates using nanoparticles in metallic compounds, successfully used in the technique (Guimarães Freire et al., 2011). However, several technical barriers must be overcome for the technique to be used successfully: the high acquisition cost of metallic compounds and a smaller amount of toxic compounds whose aggressive residue content is less relevant, making the compound purer and of higher quality (Fernandes et al., 2017). With this, nanotechnology can accelerate biogas production, leading to a rise in the volumes of biogas produced from non-edible sources (Amo-Duodu et al., 2023). Since biogas cannot be used alone and must be associated with other fuels to be used, it will continue to be challenging to exchange energy from oil for biogas (El-Dalatony et al., 2022). There is a possibility in the future that the use of biogas as an alternative energy source that is environmentally friendly will increase tremendously.

## 6.3. Challenges and limitations in biogas production and utilization

Technologies currently being used in biogas production are not very effective since there is nothing new in technology that has effectively developed process agility while reducing costs (Kalia and Singh, 2020). These characteristics rule out the possibility of producing efficiently on large scales for the entire population's needs. The current business complexes that effectively carry out this production manage to provide some energy, but very few investors from the private market or even the Government are willing to encourage this industry (Mupambwa et al., 2019). As mentioned above, many landowners in rural areas have installed small, low-power organic biomass production systems (Yaqoob et al., 2021b). After being purified and compacted, biogas still has contaminants in its composition. Even if it is used only to move vehicles, engine corrosion can occur and damage those who use it (Singh et al., 2022). Following this same direction, in these situations, biogas only economically compensates to be produced in regions with abundant inputs, such as in rural regions. Consequently, biogas plants in metropolitan regions are not viable ("Worldwide trends in the scientific production on rural d," n.d.).

On an industrial scale, the productive economy of biogas is less favorable than the production of other fuels. This explains the lack of interest in its incentive. Few private investors or even the Government are willing to promote this industry, considering its great difficulty in improving the cost-benefit ratio (Odejobi et al., 2022). Its production process is susceptible to meteorological conditions and, mainly, temperature, and factors that restrict its expansion are also considered since there is an ideal temperature range that helps bacteria to carry out their function in the biodigestion process (de Sousa et al., 2022). If the temperature is far below the ideal value, the biodigesters need more heat from the external environment, making the process difficult (Freitas et al., 2022). Reinforcing the restrictive aspects, it is essential to emphasize that the high processing costs, the difficulty in scaling research, both those focused on the academic environment and those focused on the laboratory environment, the lack of incentive in the development of prototypes and industrial production of biogas, starting from the prejudice due to erroneous information that there are risks in the processing, leading to public perception of environmental, health and safety risks in the use of new technologies are also factors that make the commercialization and development of the biogas market immensely difficult (Kossmann et al., 1999).

## 6.4. Future aspects

Biogas could be used at 100% concentration to power vehicles, provide energy and serve as a propellant in the industry with its heating capacity. However, there is still no adequate technology to burn compressed biogas (Gopal et al., 2021). Ignition timing, flow rate, and hardware changes must be explored to make this possible. In addition, green hydrogen can be mixed with pure compressed biogas to increase the calorific value of the biofuel and, consequently, the engine power (Vidal-Barrero et al., 2022). It is worth noting that this technology is still in its infancy and needs to be studied in greater detail as to its feasibility (Mould et al., 2022). Biorefineries have been playing an essential role in the biotransformation of methane, as biological oxidation has been used as an economical method in the purification of hydrogen sulfide (Reinelt et al., 2022). Following the trend, technologies focusing on membrane separation have advanced and surpassed those such as scrubbing and adsorption (Rasheed et al., 2022). Due to this, there is lower energy consumption cost.

Organic polymers can be used in membrane separation because they have a low production cost and excellent resistance in the process (Werkneh, 2022). Projects with bioreactors, such as bubble column reactors, can be an alternative when mechanical agitation is not required. As for its extraction, biogas can be exploited if there is adequate management of microbial resources and monitoring by advanced control in biodigesters (Sempere et al., 2022). The advancement of technologies used for the efficient conversion of organic wastes composed of biomass and method and its acceptable use as a natural substitute for natural gas or car fuel is the objective of this trend research (Vardar et al., 2022). On the other hand, the production of hydrogen using tools from a biogas composition system and fuel cells are applications that also deserve significant attention. However, they require more significant incentives from those responsible for policies - considering that they involve more significant financial risks for their adoption - to provide sustainable changes in current technologies (Zhao et al., 2022).

## 7. CONCLUSIONS

The need to understand the benefits of obtaining biogas as a product and how the production process can contribute to the preservation of the environment since there is a need to deepen the knowledge of the actors involved in the manufacture of this biofuel as an energy alternative and having considering that this article can contribute with relevant information on this topic. Therefore, this study evaluates the relationship between biogas production and economic growth in Brazil in the context of renewable energies. It was concluded that the bibliometric analysis method responsible for data collection helps considerably in treating data from the database. The number of publications is the most significant parameter in this work. There was a correlation between the number of publications and the energetic, productive capacity in the analyzed profiles. The results confirmed that there is not necessarily a proportional relationship between the number of articles and the productive capacity in the analyzed countries. However, it cannot be said that there is no relationship, as several countries are in similar positions between these parameters. Among the biodigesters mentioned, the dry digestion method proved to be the most viable, and this performance is in line with the growth in the number of publications in the last ten years.

Given the various figures and tables presented in which, there was an increase in the number of citations in works as well as the number of publications - which can be explained due to the greater social attention that has been paid to discourses on sustainability, sustainable technologies, global warming, among others -, it is inferred that organic wastes, sustainable environment, and biofuel production are aspects that are increasingly addressed and discussed in recent years, as there is a growing production of waste and waste of organic origin capable of feeding this production chain. Therefore, to reduce the environmental impacts caused by the incorrect destination of these by-products. Such residues can be used as raw material for producing products with greater added value, such as biogas.

## COMPETING INTEREST STATEMENT

The authors confirm that no known financial or personal relationships could have influenced the work reported in this paper.

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## APPENDIX A

Antonio F.S. Rodrigues, Ananias F. da Silva, Francisco L.B. da Silva, Kaiany M. dos Santos, Marcelo P. de Oliveira, Millena M.R. Nobre, Batista D. Catumba, Misael B. Sales, Allison R.M. Silva, Ana Kátia S. Braz, Antonio L.G. Cavalcante, Jeferson Y.N.H. Alexandre, Paulo G.S. Junior, Roberta B.R. Valério, Viviane de Castro Bizerra, José C.S. dos Santos.

**Article: A scientometric analysis of research progress and trends in the design of laccase biocatalysts for the decolorization of synthetic dyes.**

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Abstract: This article conducted an advanced and comprehensive scientometric analysis of worldwide trends in decolorizing synthetic dyes by laccase. Articles were collected, analyzed, and classified according to the different substrates, enzymes, supports, immobilization procedures, and reactors involved. These studies were carried out in 200 institutions across 58 countries, with only 10 concentrating 88% of the total publications. China, India, and Turkey were identified as the main contributors to this research theme. Additionally, 26% of the institutions surveyed published only one article in the analyzed period. The results of the presented analysis encompassed data generated from 1999 to 2021, spanning more than two decades of specialized research. A ranking of article publications in scientific journals involving laccase, immobilization, enzymes, and dyes is listed. Also listed are the ranking of the 10 most prolific countries in the area of immobilized enzymes and the 10 most cited articles on the immobilization of enzymes with dyes. This analysis includes information related to the methods of support and costs of manufacture involving enzyme and immobilization routes. Finally, a discussion is presented exploring the fact that innovative technologies have been developed to render enzyme production more sustainable and economically viable.

Keywords: Laccase; Immobilization; Enzymes; Bibliometric analysis; Dyes