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Research Article

Energy Recovery from Biogas in Domestic Waste Water Treatment Plant in the Last 5 Decades: A Bibliometric Analysis

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ABSTRACT
Biogas, a by-product of effluent treatment, is increasingly no longer seen as a passive, taking on the role of an asset. This work carried out a bibliometric study of the world production of biogas from domestic wastewater, focusing on the evolution of knowledge over the decades. For this purpose, a search for scientific articles was carried out in the Scopus database and, from the documents obtained, a review of literature was developed to access information and reveal quantification patterns. The analysis of the graphs and networks generated proved efficient in the exploratory study of the scientific and technological evolution of biogas from domestic sewage, making it possible to observe a highlight for the recovery of dissolved methane, as well as for the gains in reducing emissions of GHG from biogas reuse, in addition to the focus on nutrient and energy recovery, which underscores the importance of anaerobic processes for obtaining energy and nutrient conservation, as well as their potential contribution to achieving the goals related to the Sustainable Development Goals.

Keywords: Biomethane, Bioenergy, Sewage, Wastewater, Bibliometric, Vosviewer.

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INTRODUCTION

Due to rapid population growth, the demand for energy and the rate of wastewater generation has been growing disorderly.[1,2] In the last four decades, carbon fossil fuels primarily met the world's energy consumption (84.7%).[3] Wastewater treatment plants are systems responsible for consuming a considerable portion of the energy used in most cities in developed countries.[4-6] An alternative that can help to minimize these two problems is the use of wastewater for the production of new products, which can be used later, such as renewable energy, fertilizers, and clean water.[2,7]

Energy recovery from wastewater treatment contributes to achieving the Sustainable Development Goals (SDGs) linked to the 2030 Agenda signed by the United Nations (UN). Among the 17 SDGs, at least four may have more direct positive effects due to the adoption of wastewater treatment systems with sustainable solutions: as SDG 6 (water and sanitation), because of a more sustainable management of wastewater treatment and your sub-products; SDG 7 (affordable and clean energy), because of the reduction in the use of fossil fuels; SDG 13 (climate action), due to the move for a reduction in GHG emissions; and SDG 11 (sustainable cities and communities), due to the possibility of providing energy for these regions and creating a circular economy strategy.[8]

The use of urban wastewater as an energy source has a long history, primarily through anaerobic conversion.[6,9] With the emergence of upflow anaerobic sludge blanket (UASB) technology in the 1980s,[10] several countries, mainly those in Latin America and India, began to adopt this anaerobic sewage treatment technology in their Sewage Treatment Stations (WWTPs).[9] This adoption enabled the evolution of the understanding that WWTPs can play an essential and central role from an energy point of view, contributing to enable circular cities.[7] This can be done by using the chemical energy of the biogas produced by anaerobic processes[11] which, after purification and conversion, can be transformed into thermal and electrical energy[12,13] and in biomethane.[14-17]

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Review articles on sewage treatment found in the literature usually address several topics in different scenarios and levels of complexity. Among these, the most significant portion focuses on research related to nutrient and energy recovery, driven mainly by the increase in energy cost and nutrient value, in which the importance of anaerobic digestion for these recovery processes is highlighted.[2,6,18,19] The work of Chrispim, Scholz, and Nolasco,[7] Soares *et al.*,[20] and Muñoz and Guieysse[21] discuss the technological advances related to the recovery of biogas in the treatment of effluents, highlighting the use of techniques to improve the production of biogas, with co-digestion systems with microalgae for energy recovery. Battista *et al.*[22] reviewed state-of-the-art for the co-digestion of food waste and sewage sludge, producing biofuels and recovering nutrients, with the "circular economy" approach. Chernicharo *et al.*[9] reviewed programs aimed at recovering dissolved CH4, which is of concern as it is emitted into the atmosphere when effluents are discharged. These losses not only represent potential energy loss but also contribute to the emission of greenhouse gases. Other review works address gaseous emissions and GHGs related to the anaerobic digestion processes of treatment plants, such as Zhang *et al.*,[23] and Eijo-Río *et al.*,[24] presenting its global implications for sustainable development. Azizi *et al.*,[25] reviewed the literature on the interference of (nano)microplastics in anaerobic digestion, highlighting the potential environmental risks of using biosolids contaminated with (nano) microplastics. Bragança *et al.*[26] assess the literature on biogas impurities with a summary of methodologies for removing undesirable compounds. Salomon and Silva[27] determined the potential for generating electricity from biogas from various sources, such as municipal solid waste, domestic sewage, vinasse, and animal manure. The reviews by Shin and Bae[28] and Crone *et al.*[2] presented the results on AnMBR treatment systems within the context of environmentally friendly breeding and DWW treatment systems with energy recovery. Arespacochaga *et al.*[29] review the effects of siloxanes on the energy recovery of sewage biogas. Nnaji and Chong *et al.*[30] review advances developed in approaching high-rate anaerobic digester technologies, with emphasis on UASB reactors.

There are challenges to implementing energy recovery from wastewater, such as expanding knowledge on the part of the stakeholders involved in these systems about the technologies considered and the positive effects generated by these strategies.[31] In addition, biogas generation in sewage treatment and its related data for energy recovery are topics little explored in the available literature.[32] Therefore, it is crucial to encourage studies on the energy recovery of biogas and how technologies can be well integrated into existing treatment systems and new facilities.[7]

The deepening of this theme is essential to promote technological development. For that, an accurate understanding of state of the art is crucial. Among the means of understanding scientific and technological evolution, prospective studies are based on elaborating indicators from bibliometric metrics. The bibliometrics review approach can be understood as the analytical methods used to analyze an academic publication's production. Through statistical techniques quantitatively, this approach also includes the potential to identify and trace research trends regarding production.[33] In addition, bibliometrics is used to identify patterns over time and provide insight into the dynamics of the area or field of study.[34]

The indicators used in bibliometric analyzes can be based on the production of scientific articles and patents, based on their citation dynamics and their links (co-authorship, co-citations, among others).[35-37]

Due to the importance of considering the development of studies with approaches on biogas obtained from organic waste and its role in subsidizing future technological developments, discussions, and public policies,[27] we justify the objectives of the present study. This work aims to carry out a bibliometric review of the literature on the reuse of energy from sewage biogas in domestic ETE in the last 5 decades.

The questions answered in this manuscript were: Which countries contributed to research on energy recovery of biogas obtained from domestic WWTP? What are the publication trends on biogas energy recovery obtained from domestic WWTP over the decades? Is the triple helix (company, university, government) involved enough? What is the participation of institutional networks (governmental, private)? What kinds of funds are involved in research? What are the primary sources of investment? What are the significant publications on biogas obtained from domestic WWTP? What are the influential journals in the field on biogas obtained from domestic WWTP?

METHODOLOGY

Figure 1 shows the integrated analysis carried out to achieve the objectives of the present study. The analysis includes: (i) the literature search strategy on the production of biogas from domestic wastewater, (ii) the bibliometric review of the identified documents, with verification of trends over the last 46 years, and a micro-analysis based on a 10% cut of the most cited articles.

Phase 1- Research Strategy

This study is based on a bibliometric review. Bibliometrics is a commonly used method for establishing state of the art in a given area of research, being conducted from quantitative and statistical analyzes that aim to understand patterns in selected publications. In this way, it is possible to analyze the relationships between the researches to obtain conclusions about the knowledge about the area studied.[38] In general, studies of this type analyze aspects such as information about the authors, number of citations, titles, keywords, and abstract data.[39-43]

Table 1: Description of the relationship between work questions, analyses, and data sources in this study.

Questions	Analysis	Data Source
What are the leading countries contributing to research on energy recovery of biogas obtained from domestic WWTP?	General statistics / Co-authorship spatial network.	All Articles
What are the publication trends on biogas energy recovery obtained from domestic WWTP over the different decades?	General statistics / Word co-occurrence network.	All Articles
What is the contribution relationship between the university/research center/ government/company for research on biogas energy recovery obtained from domestic WWTP?	General statistics / general features.	All Articles
What are the main types of funds involved in research?	General statistics / general features.	All Articles
What are the influential publications in the field on energy recovery of biogas obtained from domestic WWTPs?	General characteristics and citation tables.	10% of the most cited articles
What are the influential journals in the field on energy recovery of biogas obtained from domestic WWTP?	General statistics / general characteristics and citation tables.	10% of the most cited articles

For the selection of publications that participated in this work, elements of the systematic review were used, which follows a structured process following pre-specified eligibility criteria, to ensure that the results obtained are reliable and significant for end users.[44,45] The systematic review consists of certain phases for the selection of publications, these being:[46] definition of scientific questions; definition of databases and keywords, as well as strategies used for the search; establishment of filtering criteria for studies; conducting the search in the databases; filtering studies according to established criteria; analysis of studies.

Thus, the present work was carried out following a research strategy that used evidence on data sources, selection, and analysis criteria, carried out according to the following two phases (Figure 1), as detailed below.

In the first step, the problem is delimited to define the scope of the research. Thus, it is necessary to clearly define the proposed

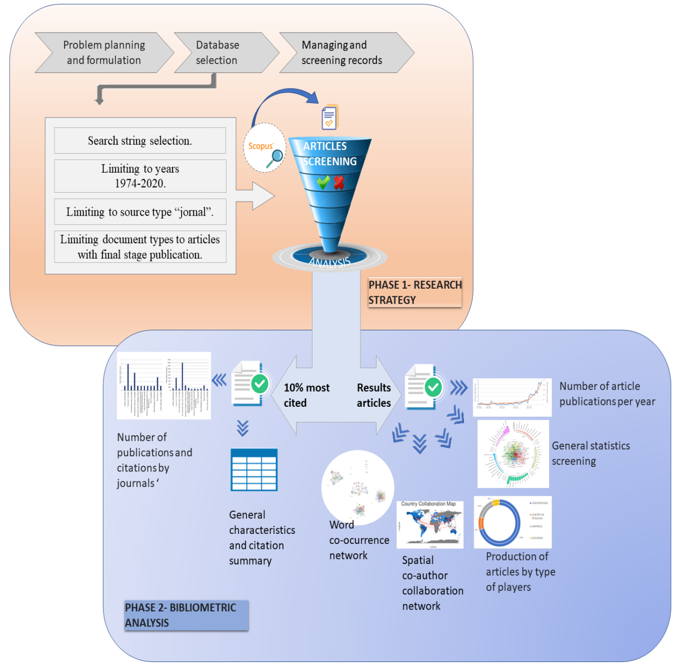

Figure 1: Flowchart of materials and methods used to develop this study.

research questions, the exclusion criteria for the final selection of essential documents, and the definition of the expected results.[47]

Each method has intrinsic issues (Table 1) that address the relationship between work issues with the associated proposed analysis and the data source used.

Bibliographic records were obtained from the SCOPUS database, which Elsevier owns. SCOPUS is a digital bibliographic platform internationally recognized among researchers for having high-quality standards, the most extensive database focused on science and technology, and a wide variety of peer-reviewed technical literature documents.

Scopus was accessed through the Portal of Periodicals of the Brazilian Coordination for the Improvement of Higher Education Personnel (CAPES) in August 2021.

From the definition of the database used, we proceed to the definition of the search strings. The unique search terms to compose this research was identified through a preliminary search in the SCOPUS database, using the words "biogas and sewage*". The most used terms in titles, abstracts, or keywords were observed in the documents obtained.

Then, manual tests were performed, including the identified terms, in order to collect the terms that retrieved the largest number of articles with the least negligible bias, resulting in the most suitable set of keywords for the search. With that, finally, the chosen search terms were interconnected in a single search, joined by means of boolean connectors of the AND and OR type, thus establishing: ((domestic or urban) and ("wastewater treatment plant*" or "wastewater treatment plant*" or sewage* or sewage*

Table 2: Criteria for selecting and excluding documents used in the bibliometric review.

Criteria for inclusion:	Exclusion criteria:
1. Biogas obtained from domestic ETEs in urban regions. 2. Works that addressed Energy recovery.	1. Works that did not address the use of domestic wastewater as a substrate. 2. Works focused on biogas obtained from rural ETEs. 3. Documents whose central theme was decentralized treatments.

Table 3: Description of the steps, search strings, and the number of documents obtained in the process of filtering the documents used in the bibliometric review.

Description	Search strings	Number of articles obtained
Identification	TITLE-ABS-KEY-AUTH (((domestic OR urban) AND ("EFFLUENT TREATMENT STATION*" OR "EFFLUENT TREATMENT PLANT*" OR sewage* OR sewer* OR effluent* OR wasterwater* OR "WASTER* WATER*")) AND (biogas OR "BIO GAS" OR biomethan* OR methane))	946
Eligibility	TITLE-ABS-KEY (((domestic OR urban) AND ("EFFLUENT TREATMENT STATION*" OR "EFFLUENT TREATMENT PLANT*" OR sewage* OR sewer* OR effluent* OR wasterwater* OR "WASTER* WATER*")) AND (biogas OR "BIO GAS" OR biomethan* OR methane)) AND (EXCLUDE (PUBYEAR, 2021)) AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (SRCTYPE, "j"))	649
Screening	Reading all titles and/or abstracts of articles returned in the search, identifying and excluding possible articles that do not fit the objective.	217

or effluent* or waste waterwastewater* or "wastewater*")) and (biogas or "biogas" or biomethane* or methane)).

For this study, therefore, only documents in the final stage of publication, of the article type, published in journals from 1970 to 2020 were considered. Therefore, documents published in the year 2021 were excluded.

The results generated in the SCOPUS database obtained through the single search, presented above, correspond to the global universe of the research.

For the eligibility of the results, a screening of the documents obtained was performed. for eligibility of results. This step consisted of reading the titles, abstracts and/or full texts to exclude articles that did not address questions about energy recovery from biogas from domestic effluents.

The string used in this research retrieved documents on biogas production, including various approaches such as energy recovery. Therefore, in order not to distort the results of the research, it was decided, based on the central theme (biogas production), to identify the documents that presented discussions on energy recovery, through manual sorting. Thus, works that did not meet this requirement were excluded (Table 2).

Among the words that composed the string of this research, terms related to “energy” were not used, as there are a variety of types of potential energies, as well as several synonyms/expressions that can exemplify and represent the concept of energy recovery, as well as associated types of energy.

As a result of the selection process, a sum of articles was obtained (Table 3).

Phase 2- Bibliometric Analysis

As defined earlier, bibliometrics uses statistics and visualization methods to explore the structures and patterns of a study setting. The bibliometric analysis was developed using all scientific articles from the definition method described in Table .

From the search performed, a file with “.csv” format was generated in the SCOPUS database and fed into the VOSVIEWER® platform for building network maps. VOSVIEWER® is a free software that uses its algorithm for analyzing the similarity of terms and whose main steps are the identification of terms and filtering of the most relevant ones, mapping and grouping of terms, as well as grouping and visualization through maps of a network.[37] This platform allows generating different panoramas of scientific visualization, among which the following maps were chosen: network by co-authorship by country, network by co-authorship by authors, and semantic network.

Bibliometric maps, also called network maps, are endowed with two fundamental attributes: distance and dimension. The distance refers to the length of the continuous line joining the nodes, indicating the degree of proximity between two or more items; the dimension is characterized by the item's size, which proportionally expresses its importance, given by the number of occurrences. The distances and dimensions of the represented items produce different groupings on the map. Also called clusters, these concentrations express similarity levels, usually represented by spheres.

The second stage of this phase comprised the analysis of scientific development over the decades. For this, the exact single search presented was used, including in the year filter only the years that comprise the decades of interest, generating separate "CSV" files for each decade studied. The search results generated in the SCOPUS database corresponded to the universe of the 1970s, 1980s, 1990s, 2000s, and 2010s of the research. They were analyzed using bibliometric data from the VOSVIEWER® platform to construct network maps for each decade.

In addition to the pattern analysis performed by the bibliometric review method, a micro-level analysis was conducted by selecting part of the articles for a qualitative investigation. This process aims to answer the group of questions this paper seeks to answer (Table), which cannot be answered only by investigating the metadata obtained in the bibliometric analysis.

Thus, of the articles obtained after the final screening, it was established that a portion corresponding to 10% would be used for this qualitative analysis. First, the entire group of publications was ranked according to the number of citations. Then the tenth most cited part was defined as the group of articles destined for micro-analysis. The number of citations used for ranking is constant in the database used in this study.

RESULTS AND DISCUSSION

The search in the SCOPUS database returned 649 scientific articles (see Table of supplementary materials S1 for details), in which, after filtering, 432 articles were excluded, obtaining a volume of 217 articles, which comprise the global universe of the research, the which includes scientific articles published between 1974 and 2020 (Figure 2).

Understanding the number of publications per decade (Figure 2) can be done in three phases with different analyses: the first, centered on the first three decades, shows that the production of scientific articles showed a smooth and relatively homogeneous growth, with an average equal to 0.7 articles per year. The second phase, referring to the following ten years, reveals that growth showed a strong upward trend, with an average equal to 2.7 articles per year. The third phase, referring to the 5th decade, in which a more vertiginous growth is observed at the beginning of this decade, followed by an intense growth mainly in the year 2020, which accumulates 28 publications, with the annual average in this decade being equal to 17 articles.

The first block comprising the first three decades (the 1970s, 1980s, and 1990s), represents a period of little published research. However, the decade 1990s show an increase in work due to the need to mitigate climate change, generating actions to combat the adverse effects of anthropic activities. The possible explanation for this is that it was forced by world agreements such as the United Nations Framework Convention on Climate Change, the United Nations Framework Convention on Climate Change (UNFCCC)[48] and the Kyoto Protocol.[49]

As a reflection of the UNFCCC-92 convention, Agenda-21 was created, which does not have a specific space on energy, which, among other approaches, addresses the issue of changing consumption patterns focused on several points, especially energy, transport, and waste. It also presents the approach to sustainable development, encouraging the use of new and renewable energy sources. In addition, chapter 21 highlights the management of solid waste and effluents and the need to increase funding for pilot research programs to test different options for the reuse and recycling of waste. Among these, small artisanal recycling industries, organic fertilizer production, irrigation with treated wastewater, and energy recovery from waste stand out.[50]

The Kyoto protocol represents the first international legal agreement on greenhouse gas emissions. This protocol establishes one of the ways to reduce emissions by using new and renewable forms of energy, technologies for sequestering carbon dioxide, and environmentally sound technologies that are advanced and innovative. Another point is the limitation and/or reduction of methane emissions through its recovery and use in waste treatment, as well in the production, transport and distribution of energy.[49]

Subsequently, several other agreements were launched, such as the Millennium Development Goals (MDGs) in 2000[51] and 2015 the publication of the Sustainable Development Goals (SDGs),[8] in which in goal 7 of each document has goals on sustainable energy.

Figure 3 shows the top ten countries, funds, journals, affiliations and authors that published the most significant number of articles on energy recovery from biogas obtained from sewage, as well as the network of co-occurrence of keywords with a minimum of 1 occurrence per term.

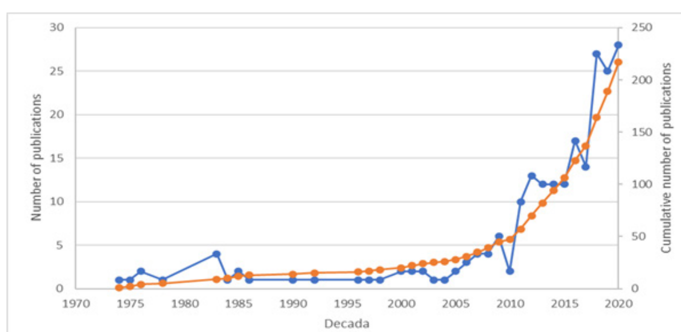

Figure 2: Number of publications and a cumulative number of publications for the period between 1974-2020 in the Scopus database, based on articles researched in the area of energy recovery of biogas obtained in the treatment of domestic wastewater.

Among these affiliations, the ten that published the most are all universities, of which 70% are public universities and another 30% are private. The university with the highest number of publications was the Technical University of Denmark (six articles). This private Danish university has a vital innovation infrastructure, with several incentive projects, such as a research center and programs focused on entrepreneurship as a bridge between industry and academia, a technology park, an incubator, and projects on renewable energy and circular cities. Next is Newcastle University (five articles), a private university based in the United Kingdom. Next is the University of São Paulo (five articles), a Brazilian public university, the Harbin Institute of Technology (five articles), a Chinese public university, The University of Queensland (five articles), a private university based in Australia, Xi 'a University of Architecture and Technology (five articles), public university in China, Cranfield University (four articles), located in the United Kingdom, of public nature, the Federal University of Minas Gerais (four articles), Brazilian public university, the Universiteit Gent, (four articles), a public university based in Belgium and the Universitat de València (three articles), based in Spain, of public character.

The 242 terms in the network shown in Figure 3 were grouped into 4 clusters. The ten words with the highest number of occurrences were: "wastewater" (143 occurrences), "wastewater treatment" (140), "biogas" (126), "methane" (110), "anaerobic digestion" (94), "bioreactor" (93), "waste disposal" (71), "sludge" (70), "cod" (58), "wwtp" (58) (Figure 3). The high occurrence of these terms indicates a greater focus of research due to their general relationship with energy recovery from biogas. Still, it should be noted the great occurrence of the term "sludge", which demonstrates, in addition to the energy issue, a concern with the management of solid waste and, therefore, the use of sludge as a raw material for anaerobic digestion.

The largest cluster found contains 74 words, represented by the red color. In this cluster, the most frequent terms have conceptual approaches related to energy products and physical facilities of WWTPs. The highlighting terms were: "wastewater" (143), "wastewater treatment" (140); "biogas" (143 (sum of "biogas" (126), "biogas production" (17)), and "energy" (170 sums of "energy" (41), "energy balance" (15), "energy conversion" (6), "energy demand" (5), "energy efficiency" (10), "energy resource" (15), "renewable energy" (10), "electricity" (12), "electrical production" (12)) This cluster also concentrates other quite frequent terms that are related to emissions and environmental issues, such as "greenhouse effect" (24), "CO_2" (22); "emission" (19), "sustainability" (15), "carbon footprint" (7). There is a correlation between minimizing environmental impacts through reducing GHG emissions and energy recovery from the biogas that would be lost. Studies such as Smith A.L *et al*.,[52] Sanchis-Perucho P.,[53] and Robles Á. *et al*.[54] show reduce the impacts of global warming associated with emissions of dissolved methane in effluents using methodologies based on the treatment of domestic wastewater with AnMBR, which achieved higher net energy productions and reducing greenhouse gas emissions.

Another study that addresses the reduction of GHG emissions was the work of Chan Gutierrez E. *et al*.[55] The results indicate that it verified the economic viability of a biomethane plant for a Mexican city using two scenarios. The one in which food waste and sewage sludge co-digestion was used resulted in a positive economic performance based on the Net Present Value (NPV). The author also states that by replacing diesel with biomethane from food waste, it is possible to reduce 17.91 $MtCO_2$ and 6.06% of the GHG emissions target for 2050.

The most prominent terms associated with biological treatment were: cleaning and digestion process were gathered in the green cluster (65 terms), highlighting "anaerobiosis" (55), "biofuel" (39), "anaerobic growth" (35), "bacteria" (27), "biomass" (31), "nitrogen" (24), "methanogenesis" (22) and various species of bacteria related to desulfurization and denitrification processes.

The blue cluster (61 terms) presented a more centralized position, grouping terms predominantly associated with technologies (equipment and reactors) and process parameters. The technologies listed in this cluster with the highest number of occurrences are "bioreactor" (93), "membrane" (33), "anmbr" (19), others less explored "transmembrane" (9), "anaerobic fluidized bed" (5), "deflector anaerobic reactor" (5). The cluster associated with the process parameters highlighted terms such as: "cod" (58), "process parameter" (38), "temperature" (37), "bod" (31), "hrt" (22), others least explored "low temperature"

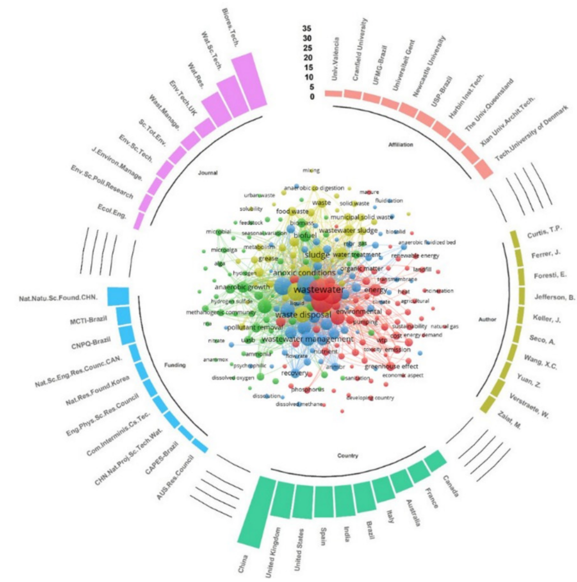

Figure 3: Word co-occurrence network built with the 217 selected articles, built from the words presented in the titles, abstracts, keywords, and general information of the ten primary resources of the 5 decades of documents published between 1974–2020, using the criterion minimum of 5 occurrences per term.

(10), "dissolved methane" (9), "psychrophilic" (7), "flow" (7), "fluidization" (6). Anaerobic Membrane Bioreactor (AnMBR) systems are being proposed as a promising technology for the treatment of domestic effluents as they can generate high quality effluents during operation at reasonable hydraulic retention times and low temperatures. However, although in processes with AnMBRs there are energy savings that do not require aeration mechanisms, substantial energy is required in processes that avoid the encrustation of residues in the membrane.[52]

The analysis of the spatial distance of the clusters reveals that the blue cluster forms an interface between the three other clusters, reinforcing that technological development is the primary basis for advancing energy recovery processes from biogas.

The yellow cluster (41 terms) comprises questions related to the processes of "anaerobic digestion" (94), "anaerobic co-digestion" (24), associated with the terms "food waste" (24), "food" (17), "waste disposal" (71), "waste treatment" (41), "waste" (28), "municipal solid waste" (18), "solid waste" (12), "municipal waste" (5). Co-digestion tends to concentrate research since it favors the balance of nutrient loads, reflecting more significant degradation of organic matter and recovering more methane. Furthermore, it is an essential aspect of combined waste management. Compared to monodigestion, co-digestion of multiple substrates offers significant advantages, including a more balanced supply of nutrients, a diluting effect of toxic and inhibitory compounds, and an overall increase in biogas production as a result of the increased supply of organic compounds.[56] Of the documents that focus on co-digestion processes, most focus on processes that use food waste with sewage sludge.[57-62]

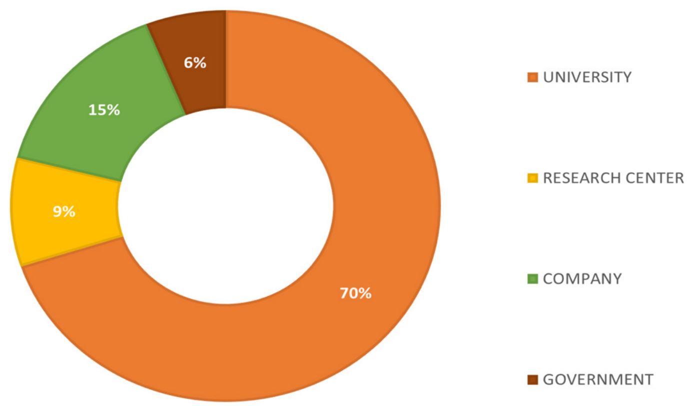

Figure 4: Proportion of contribution between universities, research centers, governmental organizations, and companies for research on energy recovery of biogas obtained in the treatment of domestic wastewater.

Table 4: Position in the citation ranking, titles, year of publication, jornal, keywords (if applicable) and number of citations of the 22 most cited publications (among those selected for this study).

Rank	Title	Year of publication	Journal	Keywords (if applicable)	Number of citations
1	Domestic wastewater treatment as a net energy producer-can this be achieved?	2011	Environmental Science and Technology		1106
2	Anaerobic fluidized bed membrane bioreactor for wastewater treatment.	2011	Environmental Science and Technology		340
3	Biohydrogen gas production from food processing and domestic wastewaters.	2005	International Journal of Hydrogen Energy	Food processing wastewater; Hydrogen production.	326
4	A two-stage microbial fuel cell and anaerobic fluidized bed membrane bioreactor (MFC-AFMBR) system for effective domestic wastewater treatment.	2014	Environmental Science and Technology		198
5	Pilot-scale temperate-climate treatment of domestic wastewater with a staged anaerobic fluidized membrane bioreactor (SAF-MBR).	2014	Bioresource Technology	Anaerobic; Domestic wastewater; Energy; Fluidized-bed; Membrane bioreactor.	175

Rank	Title	Year of publication	Journal	Keywords (if applicable)	Number of citations
6	Enhanced bio methanation of kitchen waste by different pre-treatments.	2011	Bioresource Technology	Anaerobic process; Food waste; Hydrolysis; Liquefaction; Volatile fatty acids.	165
7	ZeroWasteWater: Short-cycling of wastewater resources for sustainable cities of the future.	2011	International Journal of Sustainable Development and World Ecology.	algal roof; end-of-pipe; microalgae; OLAND; recovery; recycling; reuse; sustainability.	156
8	Navigating wastewater energy recovery strategies: A life cycle comparison of anaerobic membrane bioreactor and conventional treatment systems with anaerobic digestion.	2014	Environmental Science and Technology		155
9	Optimization and microbial community analysis of anaerobic co-digestion of food waste and sewage sludge-based on microwave pretreatment.	2016	Bioresource Technology	Anaerobic co-digestion; Archaeal community; Bacterial community; Food waste; Sewage sludge.	143
10	Side-stream sludge treatment using free nitrous acid selectively eliminates nitrite oxidizing bacteria and achieves the nitrite pathway.	2014	Water Research	Denitritation; Free nitrous acid; Nitritation; Nitrite pathway; Sludge treatment.	139
11	Anaerobic treatment of municipal wastewater with a staged anaerobic fluidized membrane bioreactor (SAF-MBR) system.	2012	Bioresource Technology	Anaerobic; Biosolids; Fluidized-bed; Membrane bioreactor; Municipal wastewater.	139
12	The optimisation of food waste addition as a co-substrate in anaerobic digestion of sewage sludge.	2003	Waste Management and Research	Anaerobic; Co-digestion; Food waste; Mesophilic and thermophilic conditions; Methane production rate (MPR); Optimal mixing ratio; Sewage sludge; Wmr 694-8.	121
13	Full-scale anaerobic co-digestion of organic waste and municipal sludge.	2008	Biomass and Bioenergy	Anaerobic digestion; Biogas production; Organic waste; Sludge digestion.	113
14	Treatment of biogas produced in anaerobic reactors for domestic wastewater: Odor control and energy/resource recovery.	2006	Reviews in Environmental Science and Biotechnology.	Anaerobic sewage treatment; Biogas; Biogas utilization; Denitrification; Hydrogen sulfide; Kyoto protocol; Methane; Odor control.	111

Rank	Title	Year of publication	Journal	Keywords (if applicable)	Number of citations
15	Long-term reduction potential of non-CO_2 greenhouse gases.	2007	Environmental Science and Policy	Abatement potential; Mitigation scenarios; Non-CO_2; Technology development.	109
16	Quantification of dissolved methane in UASB reactors treating domestic wastewater under different operating conditions.	2011	Water Science and Technology	Biogas; Dissolved methane; Domestic wastewater; UASB reactor.	107
17	Effect of thermal pretreatment on the biogas production and microbial communities balance during anaerobic digestion of urban and industrial waste-activated sludge.	2016	Bioresource Technology	Anaerobic digestion; Fluorescent *in situ* hybridization; Industrial sludge; Microbial balance; Thermal pre-treatment; Urban sludge.	98
18	Full-scale production of VFAs from sewage sludge by anaerobic alkaline fermentation to improve biological nutrients removal in domestic wastewater.	2018	Bioresource Technology	Alkaline fermentation for VFAs production; Full-scale; Nutrients removal; Sewage sludge; Thermal-alkaline hydrolysis.	96
19	Anaerobic treatment of municipal wastewater at ambient temperature: Analysis of archaeal community structure and recovery of dissolved methane.	2012	Water Research	Archaeal community structure; Degassing membrane; Dissolved methane; Municipal wastewater; Psychrophilic condition; Upflow anaerobic sludge blanket process.	94
20	Co-digestion of food waste in a municipal wastewater treatment plant: Comparison of batch tests and full-scale experiences.	2016	Waste Management	Co-digestion; Energy autarky; Food waste; Sewage sludge; Synergistic effect.	93
21	Microbial population dynamics in urban organic waste anaerobic co-digestion with mixed sludge during a change in feedstock composition and different hydraulic retention times.	2017	Water Research	16S rRNA; Anaerobic digestion; Methanogenesis; Microbial diversity; Urban organic waste.	92
22	Production of biogas from municipal solid waste with domestic sewage.	2007	Journal of Hazardous Materials	Anaerobic digestion; Biogas; Organic feeding rate; Organic waste.	89

As for the affiliations that published the 217 articles, which make up the object of this study, one hundred and sixty different affiliations were identified, of which 70% are universities, 15% companies, 9% research centers, and 6% government entities (Figure 4).

The publications analyzed in this work involved funding from 139 different entities. Figure 3 presents the ten funding funds that most funded research. The National Natural Science Foundation of China is a Chinese government fund that subsidized eleven of the articles considered, the most significant cooperation from the

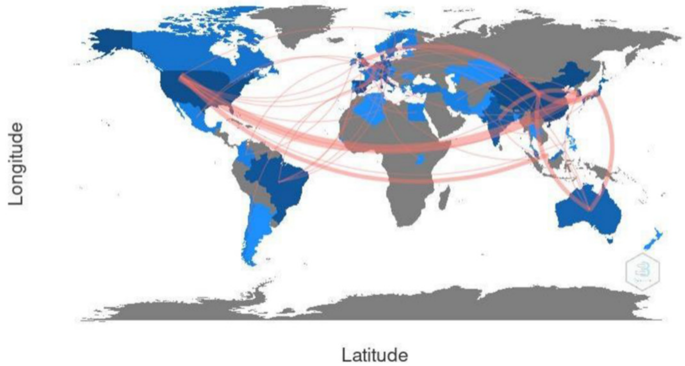

Figure 5: Planetary-scale view of co-authored collaboration for countries credited with at least one publication on energy recovery of biogas obtained from domestic wastewater treatment between 1974 and 2020. The thickness of the red lines represents the strength of the collaborations between countries.

same fund identified in this work. China also funded another four surveys from the China National Critical Project for Science and Technology on Water Pollution Prevention and Control fund. It is interesting to highlight that among the ten that most financed research, three Brazilian public entities support research, which occupies, in this ranking: the second place, represented by the National Council for Scientific and Technological Development (CNPq) (7 articles); the third place, represented by the Ministry of Science, Technology Innovation (MCTI) (7 articles); and tenth, represented by the Coordination for the Improvement of Higher Education Personnel (CAPES) (3 articles).

Figure 5 reveals the flow of the global geographic distribution of the collaboration of countries that stand out in the publication of articles on energy recovery from biogas obtained from sewage. The map lists fifty-eight different connections established between thirty-three countries. China had the most connections, thirteen in total, made up of nine countries, with three established collaborations with Japan. In sequence, the United Kingdom, with ten collaborations signed between eight different countries, and both Germany and Japan, established eight collaborations. China and Japan have significant representation in technological innovation in this sector, being responsible for several companies that produce inputs for the chemical treatment of sewage and water, as well as equipment and reactors for primary and secondary treatment. Germany is a pioneer in the use of techniques for the reuse of sewage biogas.

Figure 6 shows the evolution of keywords over five decades, among which the expressive increase in the number of terms is notable. In the 1970s, for example, only 14 terms were used once or three times by authors in abstracts, keywords, or titles. Therefore, the network was characterized by a low richness and low frequency of terms, among which the terms “wastewater” and “methane” stand out. This network also has a term that has no connection with the others, “industrial gas.” The following decade (the 1990s) resulted in the construction of a semantic network with 67 words that occurred a maximum of six times, among which the terms “wastewater treatment”, “biogas”, “methane”, “wastewater”, “anaerobic digestion” and “economic aspect”. The network map of the 1990s allows the visualization of 72 words that occurred a maximum of five times, including topics related to equipment and reactors, environmental management, nutrient recovery, and energy-related terms. The year 2000 represents a milestone in the expansion of research. The network of this decade has 288 terms, addressing varied issues such as environmental management, recovery of natural resources, alternative energy, emissions, and microalgae. In the 2010s, the network has 1000 words with a maximum number of repetitions of 114 times.

MICRO ANALYSIS

As 217 articles were defined that fit the established criteria, the 10% most cited - established as a cut for the microanalysis - resulted in 22 articles. The titles of these articles and their respective positions in the ranking of citations are shown in Table 4.

The most cited article on the list, whose number of citations is quite expressive and on a slightly larger scale than the subsequent ones, is focused on the sustainability of sewage treatment systems, discussing the possibility of the process producing more energy than consumed. In addition to this, articles number 7 and number 15 also have their biggest target on sustainability. Article 7 explores the idea of establishing short cycles for the cities of the future based on cradle-to-cradle implications, as in the definitions of circular economy (although the work does not necessarily use this term). In this sense, energy recovery (electrical and thermal) from the biogas produced in the anaerobic treatment of sewage is included. Article 15 explores the potential for reducing non-CO_2 GHG emissions, including options for such mitigation in sewage treatment. Among these, there is the recovery of methane present in biogas.

Co-digestion with food residues is cited by several articles (more precisely 3, 6, 9, 12, 13, 20, 22) as one of the ways to improve the anaerobic digestion process, from the better destruction of the organic matter. In this way, there is a more remarkable recovery of methane gas, which is also positive for energy production/ recovery. Co-digestion is commonly considered one of the alternatives for processing sewage sludge combined with other municipal waste. A single processing step for both is considered (which is positive from an economic point of view).

There is also a significant amount of work (positions 9, 17, 19, 21) whose focus is the study of the microbial population responsible for the anaerobic digestion of sewage. Optimizing parameters related to these components is essential to improve the digestive process, generating more methane and contributing to energy recovery. Still, there is great emphasis on anaerobic digestion processes from Biological Membrane Reactors (MBR). Articles 2, 4, 5, 8, and 11 are focused on this theme, and it is crucial to

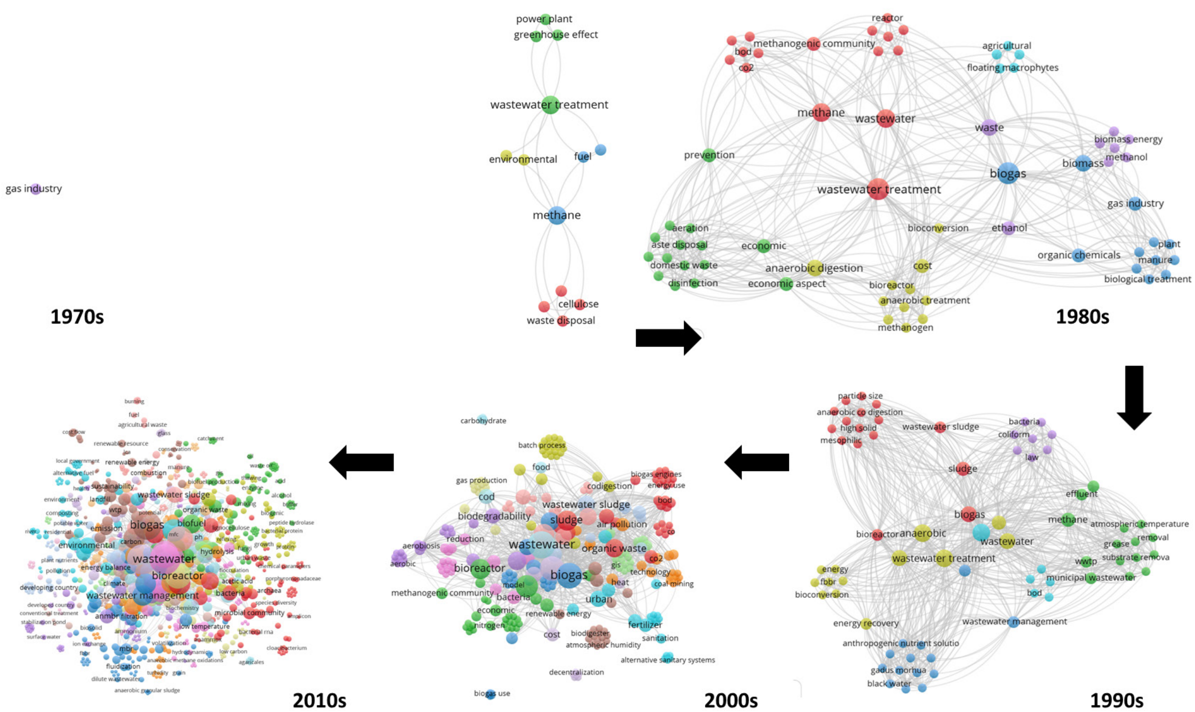

Figure 6: Keyword networks (cited in titles, abstracts, and by the authors) built every ten years representing the evolution of established connections and the richness of terms (with a minimum of one occurrence per term) in the energy recovery of biogas from domestic wastewater.

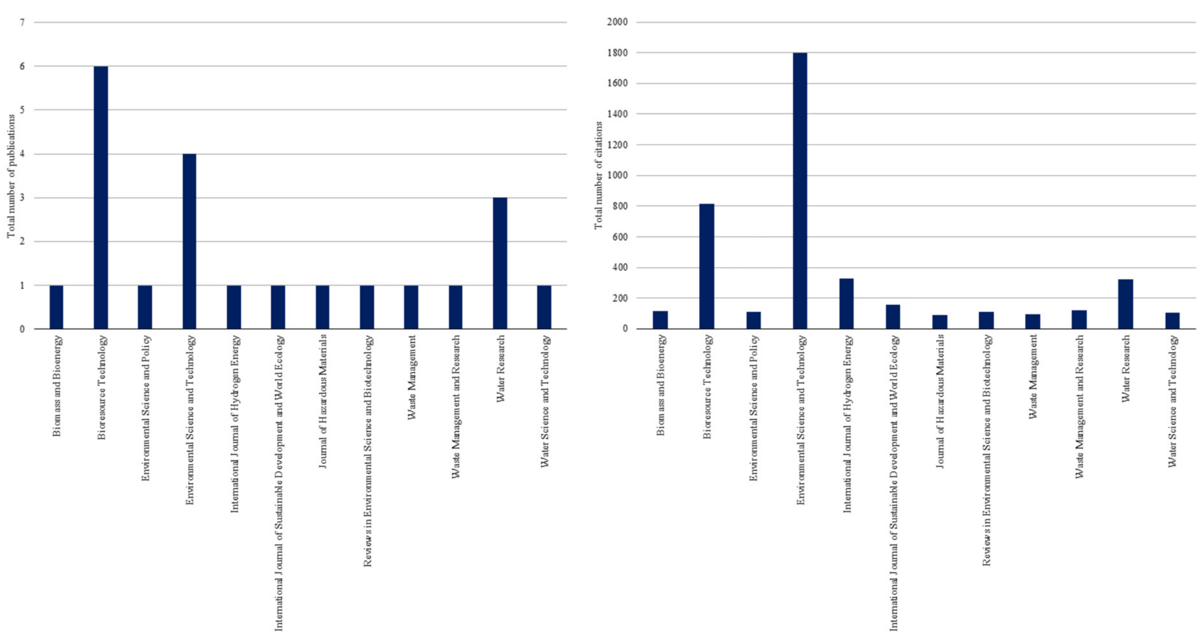

Figure 7: Total number of publications and citations of journals that are among the 22 most cited publications (among those selected for this study).

Figure 8: Flow of focus on energy recovery in research on energy recovery of biogas from domestic sewage treatment in WWTP's.

precisely observe the years of publication of the works – 2011, 2014, 2014, 2014, and 2012, respectively. MBR is a relatively new technology (as recent are the most cited publications in this field) and still little explored on an accurate scale due to its efficiency in digestion and biogas production.

Figure 7 presents two graphs that show the journals in which the 22 articles of the microanalysis were published, the first total number of publications, and the second, the total number of citations.

It is observed that the journal Bioresource Technology has the most significant number of publications among the most cited, being the second largest in the total number of citations. Similarly, Environmental Science and Technology has the highest number of citations, the second in the number of articles among the 22 most cited. It should be emphasized that both magazines are focused on technologies, one of the main pillars for developing and promoting energy recovery processes from biogas.

The journals responsible for publishing 10% of the most cited articles are related to topics such as biomass and bioenergy, bioresources, environmental sciences and policies, sustainable development, ecology, hazardous materials, management waste management, research, and water science.

However, a few words were observed with a greater focus on energy recovery and/or sustainability in the systems studied. For the most part, energy recovery is treated as a secondary focus, targeted mainly as a positive point generated from improving process efficiency. It shows that the search for this energy recovery follows a flow similar to what is represented in Figure 8.

Considering the alarming climate change scenario, the trend in the coming years should change. For example, the more recent climate agreements signed worldwide, with emphasis on the Global Methane Pledge, signed in 2021 by 103 countries to reduce CH4 emissions by up to 30% by 2030.[63] Another example is the Glasgow Climate Pact, a document produced at the 2021 United Nations Conference on Climate Change (COP26), which states that the use of fossil fuels should be gradually reduced, also considering a 45% reduction in carbon dioxide emissions by 2050.[64]

As for carbon dioxide, it should be taken into account that, although present in smaller amounts in biogas, this is still a significant part of the product generated by anaerobic digestion. In addition, much of the biogas produced in sewage treatment systems is flared, transforming the methane into CO_2, which is then released into the atmosphere, contributing to increased gas emissions.

CONCLUSION

Based on a bibliometric review, this work aimed to analyze the scientific literature on the energy recovery of biogas from sewage in domestic WWTP in the last 5 decades. From the practical aspects, some points stand out.

Although MBR presents itself as a relatively new technology and is still little explored on an accurate scale, it stands out in terms of scientific research, having potential for use due to the efficiency in the digestion process, as well as in the production of biogas. There is also a significant trend in research related to the recovery of biogas from the co-digestion of sewage with other residues, with an emphasis on domestic solid residues, livestock, and garden pruning. Another highlight is the development of research aimed at recovering dissolved methane, which is worrying since the gas is emitted into the atmosphere when the effluents are discharged. These losses do not only represent energy loss but also contribute to GHG emissions.

Nutrient and energy recovery is mainly driven by increasing energy cost and nutrient value, highlighting the importance of anaerobic processes for energy recovery and nutrient conservation for future recovery.

Although many studies have been found, the main focus is on improving the efficiency of processes, with energy recovery being mostly treated as a secondary focus. However, it is observed that there is an upward trend of research on this topic, given the alarming climate change scenario and the latest climate agreements signed worldwide, which give great focus to the reduction of GHG emissions.

Supplemental Materials

Table S1 — The table containing the survey results was carried out in the Scopus database between the years 1969–2020 without performing the screening. The table is structured with the following fields: Citation information (Author(s), Author(s) ID(s), Document Title, Year, EID, Source Title, Volume, Issue, Pages, Citation Count, Source and Document Type, Publication Stage, DOI, Access Type), Bibliographic Information (Affiliations, Serial Identifiers (e.g. ISSN), PubMed ID, Publisher, Publisher(s), Original Document Language, Mailing Address, Abbreviated Source Title), Summary and Keywords (Summary, Keywords, Index Keywords), Funding Details (Number, Acronym, Sponsor, Funding Text), Table S2 - Resource Information Statistics with based on the TOP 10 of authors, countries, funding, journals, and affiliation of documents published between 1974-2020, on energy recovery of biogas generated from domestic wastewater treatment., Table S3- Proportion of contribution between universities, research centers, bodies gov authorities, and companies for research on energy recovery of biogas generated from domestic wastewater treatment, Table S4 - Spatial interaction between collaboration and co-authorship for documents published between 1974-2020 on energy recovery of biogas generated from domestic wastewater treatment.

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Data Availability

The authors confirm that data supporting the findings of this study are available in the article and its accompanying materials.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHORS' CONTRIBUTIONS

This study was taken care of by the entire team of authors, who agree with the content of the manuscript. The authors' contributions were: design by P.M.B.V.P., S.O.A., R.N.V.; methodology by P.M.B.V.P., S.O.A, R.N.V. and W.J.S.F.R.; running software by P.M.B.V.P and R.N.V.; writing—preparation of original draft by P.M.B.V.P. and S.O.A.; writing - proofreading and editing by P.M.B.V.P., S.O.A, R.N.V., T.F.M. and W.J.S.F.R.; supervised by R.N.V., T.F.M. and W.J.S.F.R.; financing acquisition by T.F.M. and W.J.S.F.R. All authors read and agreed with the published version of the manuscript. The manuscript represents original research and is part of the PMBVP doctoral project.

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