UNIVERSIDADE ESTADUAL DE LONDRINA

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BIOGÁS E MÉTODO DE TOMADA DE DECISÃO MULTICRITÉRIO:
EXPLORANDO TENDÊNCIAS, ANÁLISES CIENTOMÉTRICAS E APLICAÇÃO DE UM NOVO MODELO

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Dissertação apresentada ao Programa de Pós-Graduação em Administração da Universidade Estadual de Londrina – UEL, como requisito parcial para a obtenção do título de Mestre.

Orientador: Prof. Dr. Saulo Fabiano Amâncio Vieira.

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RESUMO

LUENGO, Cláudia Abe Gargel. **Biogás e método de tomada de decisão multicritério:** explorando tendências, análises cientométricas e aplicação de um novo modelo. 2025. 78 páginas. Dissertação (Mestrado em Administração) – Centro de Ciências Sociais Aplicadas, Administração, Universidade Estadual de Londrina, Londrina, 2025.

Esta dissertação está organizada em dois estudos, o primeiro estudo busca avaliar o tema do biogás e a tomada de decisão através da análise bibliométrica. Examina a produção científica internacional sobre "biogás e tomada de decisão". Foram analisadas publicações das bases de dados *Web of Science* e *Scopus*, para evidenciar tendências, influências teóricas e metodológicas. A metodologia empregada foi a cienciometria, abordagem quantitativa que analisa o desenvolvimento científico e tecnológico, apoiando a tomada de decisão científica com base em dados extraídos de publicações acadêmicas. A análise foi realizada em duas etapas: inicialmente, os artigos foram avaliados separadamente por meio do *software* VOSviewer (196 artigos); posteriormente, as amostras foram unificadas e analisadas no *software* Bibliometrix (145 artigos). Os artigos mais citados abordaram métodos multicritério de tomada de decisão como AHP, BWM, TOPSIS e VIKOR. A análise contribui para orientar futuras pesquisas e avançar no campo científico.O segundo estudo, traz a aplicação de um modelo multicritério para a escolha da melhor rota de conversão de biogás e biocombustíveis, utilizou-se a metodologia AHP para a ponderação de pesos e o método TOPSIS para a escolha da alternativa mais próxima do ponto ideal. Este trabalho tem como objetivo, a aplicação de um modelo multicritério para auxiliar os tomadores de decisão públicos na escolha das três rotas de conversão: pirólise, biodigestor modelo lagoa coberta e biodigestor modelo CSTR, com a avaliação dos critérios ambientais, sociais, econômicos e técnicose cada critério é composto por 5 subcritérios que devem ser comparados relativamente um ao outro por um especialista e também ser votados por tomadores de decisão,após foi aplicado os métodos AHP (*Analytic Hierarchy Process*) e TOPSIS (*Technique for Order of Preference by Similarity to Ideal Solution*), os quais foram utilizados para selecionar a alternativa mais próxima da alternativa "positiva ideal". Entre o ranking de critérios percebe-se que os critérios ambientais e sociais tiveram maiores notas comparados ao técnico e econômico.

Palavras-Chave: Biocombustíveis, Multi-criteria Decision Analysis (MCDA), AHP, TOPSIS, Tendências de Pesquisa.

ABSTRACT

LUENGO, Cláudia Abe Gargel. **Biogas and multi-criteria decision-making method:** exploring trends, scientometric analyzes and application of a new model. 2025. 78 pages. Dissertation (Master's in Administration) – Center for Applied Social Sciences, Administration, State University of Londrina, Londrina, 2025.

This dissertation is organized into two studies, the first study seeks to broadly understand the topic of biogas and decision making through bibliometric analysis. Examines international scientific production on "biogas and decision making". Publications from the Web of Science and Scopus databases were analyzed to highlight trends, theoretical and methodological influences. In addition, collaboration networks and important journals in the area were identified. The methodology used was scientometrics, a quantitative approach that analyzes scientific and technological development, supporting scientific decision-making based on data extracted from academic publications. The analysis was carried out in two stages: initially, the articles were evaluated separately using the VOSviewer software (196 articles); subsequently, the samples were unified and analyzed using the Bibliometrix software (145 articles). The most cited articles addressed multi-criteria decision-making methods such as AHP, BWM, TOPSIS and VIKOR. The analysis contributes to guiding future research and advancing the scientific field. The second study involves the application of a multi-criteria model to choose the best biogas and biofuels conversion route, using the AHP methodology for weighting and the TOPSIS method for choosing the alternative closest to the ideal point. This work aims to apply a multi-criteria model to assist public decision makers in choosing the three conversion routes: pyrolysis, covered lagoon model biodigester and CSTR model biodigester, with the evaluation of environmental, social, economic and technical criteria. and each criterion is made up of 5 sub-criteria that must be compared relative to each other by an expert and also voted on by decision makers, after applying the AHP (Analytic Hierarchy Process) and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution). which was used to select the closest possible alternative to the "ideal positive" alternative. Among the ranking of criteria, it is clear that the environmental and social criteria had higher scores compared to the technical and economic ones.

Keywords: Biofuels, Multi-criteria Decision Analysis (MCDA), AHP, TOPSIS, Research Trends.

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LISTA DE ABREVIATURAS E SIGLAS

AHP	Analytic Hierarchy Process
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
BWM	Best-Worst Method
VIKOR	Višekriterijumska Optimizacija I Kompromisno Rješenje (Otimização Multicritério e Solução de Compromisso)
CSTR	Continuously Stirred Tank Reactor
IPCC's	Painel Intergovernamental sobre Mudanças Climáticas
PPM	Partes por milhão
GHG	Green house gas
GEE	Gases de efeito estufa
WOS	Web of Science
CR	Cited references
RSU	Resíduos sólidos urbanos
P&D	Pesquisa e Desenvolvimento
UASB	Up flow Anaerobic Sludge Blanket
BLC	Biodigestor Lagoa Coberta
PVC	Policloreto de vinil
PEAD	Polietileno de Alta Densidade
MCDM	Multiple-criteria decision-making
PIP	Ponto Ideal Positivo
PIN	Ponto Ideal Negativo
CA	Coeficiente de Aproximação
ENV	Environmental
SOC	Social

ECO	Econômico
TEC	Técnico

SUMÁRIO

ORGANIZAÇÃO DO TRABALHO:

A dissertação está organizada em dois estudos buscando uma abordagem ampla sobre o tema, com o objetivo de produzir contribuições teóricas e práticas para o desenvolvimento do campo de estudo. Com os estudos pretendeu-se analisar a produção existente, apresentar as tendências e análises cientométricas para o campo, a aplicação de um novo modelo multicritério para a escolha de rotas de conversão para a produção e gestão de biocombustíveis em um município de médio porte do Estado do Paraná. Os métodos utilizados de tomada de decisão multicritérioforam AHP e TOPSIS que através dos critérios ambientais, sociais, econômicos e técnicos e os subcritérios, podem servircomo guia para os gestores municipais para futuras implantações para biogás e biocombustíveis.

Estudo 1: Biogas and Multicriteria Decision-Making: Exploring Trends and Scientometric Analyses
Submissão a definir.

Estudo 2: Application of a Multicriteria Decision Model for the Selection of Conversion Pathways for Biofuel Production and Management in a Medium-Sized Municipality in the State of Paraná.
Submissão Energies
ISSN: 1996-1073Impact Factor 3.0

Luengo, C. A. G., Amâncio-Vieira, S. F., Fidelis, R., & Contani, E. A. d. R. (2025). Application of a Multicriteria Decision Model for the Selection of Conversion Pathways for Biofuel Production and Management in a Medium-Sized Municipality in the State of Paraná. *Energies*, *18*(9), 2367. https://doi.org/10.3390/en18092367.

O primeiro artigo enfoca o mapeamento da produção científica, os principais *journals* que publicam a respeito do tema, os autores mais citados, a rede de colaboração entre os autores, colaboração entre os países, lacunas de pesquisa e *trend topics*.

O segundo estudo conta com a aplicação de um modelo multicritério utilizando os métodos AHP e TOPSIS com a avaliação de quatro critérios sendo eles: ambiental, social, econômico e técnico, e para cada critério estão vinculados cinco subcritérios, em que um especialista através da comparação par a par estipulou os pesos para cada subcritério, após a mensuração dos pesos, foi realizada entrevistas com os gestores municipais, pesquisadores e gerentes de projetos interessados e estudiosos da viabilidade de plantas de biogás e biocombustíveis para a avaliação da rota de conversão (pirólise, biodigestor tipo lagoa coberta e biodigestor CSTR) mais próxima da alternativa positiva ideal e o ranking dos critérios com as melhores avaliações.

BIOGAS AND MULTICRITERIA DECISION-MAKING: EXPLORING TRENDS AND SCIENTOMETRIC ANALYSES.

ABSTRACT

With economic growth and the challenges of reducing environmental impacts, several countries have adopted sustainable alternatives to advance the transition to renewable energy sources. Given the advantages of biogas and initiatives to mitigate greenhouse gas emissions, this study examines the international scientific production on “biogas and decision making”. Publications from the Web of Science and Scopus were analyzed, to highlight trends, theoretical and methodological influences. Besides, collaboration networks and key journals in the field were identified. The methodology employed was scientometrics, a quantitative approach that analyzes scientific and technological development, supporting scientific decision-making based on data extracted from academic publications. The analysis was conducted in two stages: initially, the articles were separately assessed using VOSviewer software (196 articles); subsequently, the samples were unified and analyzed using Bibliometrix software (145 articles). The most cited articles addressed multicriteria decision-making methods such as AHP, BWM, TOPSIS, and VIKOR. Finally, two thematic maps present key drivers, their relevance, and development within the field. This mapping provides an overview of the evolution of biogas and decision-making studies, highlighting relevant topics, emerging areas, and knowledge gaps. The analysis contributes to guiding future research and advancing the scientificfield.

Keywords: Biogas; Multicriteria Decision-Making Method; Scientometrics; Research Trends;

1. INTRODUCTION

Challenges of reducing environmental impacts aimed at the economic growth have been taking several countries to adopt sustainable alternatives and advance in the transition to renewable energy sources (Duarte, 2024). In 2015, amid growing concerns about global warming, negotiations began to establish an agreement that would promote joint solutions among countries (Trindade et al., 2019). The Paris Agreement, adopted in 2015 during the 21st Conference of the Parties (COP21), established measures to reduce carbon dioxide emissions from 2020 onwards, aiming to keep the global average temperature increase below 2ºC and limit it to 1.5ºC above pre-industrial levels (Brasil, 2024).

In this context, governments worldwide are committed to strengthening their response to the climate threat and enhancing their capacity to manage its impacts. Since then, studies like the "IPCC's AR6 Climate Change 2021: The Physical Science Basis" report highlight an average human-induced global temperature increase of 1.07ºC (IPCC, 2024). Besides, the Observatório do Clima (2023) emphasized that greenhouse gas (GHG) concentrations exceeded 400 ppm in 2015, a level that, according to the World Meteorological Organization (WMO), will remain above this threshold for generations. As key GHGs, Carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) are linked to significant impacts on global warming and biodiversity (Gautam; Agrawal, 2021). At this point, biogas emerges as a promising alternative. It mitigates carbon emissions, generates renewable energy with a neutral carbon balance, and helps reduce the greenhouse effect (Piñas, 2016). The energy crisis, rising fossil fuel prices, and environmental concerns have reignited interest in biogas technology, which offers a reliable and affordable renewable energy source (Rao et al., 2014).

Unlike solar and wind energy, biogas can be generated continuously and stored at a low cost, either as raw material or compressed gas. Its "negative carbon footprint" stands out by reducing emissions and reusing organic waste that would otherwise pollute soil and air (Milanez et al., 2018).Sanitation, carbon emissions, energy, and public management are examples of issues addressed by Biogas. On the other hand, it also promotes the reducing dependence on hydropower, fossil fuels, and natural gas. It enables the integration of local productive arrangements with sustainable development goals and efficient administration, contributing to carbon credits and environmental improvements (Yamaji et al., 2024).

The production of biogas requires selecting appropriate technologies and strategies that incorporate principles of sustainability, resilience, and circularity. Multicriteria decision-making is essential for selecting alternatives based on technical and strategic criteria, providing support for public policies related to energy and environmental sectors (Fetanat; Tayebi; Moteraghi, 2023).The decision-making process includes steps such as problem identification, method selection, and alternative analysis, often associated with complex and multidimensional issues. Technical and subjective criteria can be evaluated to assist in defining solutions that meet the diverse interests of stakeholders (Alves, 2018).

Amid efforts to mitigate GHG emissions and the advantages of biogas, this study examines the international scientific production on the topic of "biogas and decision making." Using the Web of Science and Scopus databases, publications were analyzed to identify trends, theoretical and methodological influences, key collaboration networks, and the most relevant journals in the field.

2. SCIENTOMETRIC RESEARCH ANALYSIS

Scientometrics is a quantitative and statistical approach that identifies the processes of scientific and technological development, supporting scientific decision-making through information derived from academic publications. The term "scientometrics" was coined in 1969 and gained widespread acceptance and expansion with the establishment of the journal *Scientometrics* in 1978. The term is often referred to as synonymous with informetrics, bibliometrics, bibliometric analysis, scientific mapping, or knowledge structure in the literature; however, these fields are also recognized as distinct areas (Liu & He, 2023). Scientometrics originated in information science and library science but is now applied in a variety of other disciplines to identify research scenarios, such as structural growth, interrelationships, and productivity, as well as to map historical footprints, emerging critical points, or academic fields. It is a useful tool to familiarize researchers with their research topic (Liu; He, 2023).

Bibliometrics has the potential to introduce a systematic, transparent, and reproducible review process based on statistical measurements of science. This approach provides objective and reliable analyses, allowing for the structured organization of large volumes of information to identify trends over time, researched themes, shifts in disciplinary boundaries, productivity levels, and an overall view of existing research (Donthu et al., 2021).Bibliometrics is an important method for evaluating scientific research, studying the distribution structure, quantitative relationships, and variation laws of literature. It is a mature method for literature analysis and information mining (Xie; Zhang; Wu, 2020).

Metric studies have evolved from bibliometrics, scientometrics, webometrics, and, more broadly, informetrics. These studies involve a wide range of bibliometric indicators, grouped into: production indicators, citation indicators, and linkage indicators (Oliveira; Gracio, 2011).The production indicator is based on counting the number of publications by a researcher, reflecting their productivity and impact within the scientific community they are associated with. Citation analysis, considered by many authors as the most relevant area of bibliometrics, involves indicators that assess the total number of citations and the average citations per published work, highlighting scientific impact, influence, and visibility (Oliveira; Gracio, 2011). On the other hand, bibliometric linkage indicators are generated from the co-occurrence of authorship, citations, and keywords, and are widely used in constructing knowledge structure maps and relationship networks (Reis; Spinola; Amaral, 2017).

3. METHODOLOGICAL PROCEDURES

This study aimed to identify research related to the topic of biogas and decision-making, focusing on scientific productions on the subject. In this context, the target population consisted of international journals related to the biogas field of knowledge. For the selection of articles, international journals were analyzed through the Web of Science and Scopus databases observing their inclusion of peer-reviewed publications and their extensive use in the academic and scientific community.

The Web of Science is a multidisciplinary database that indexes only the most cited journals in specific fields, with coverage from 1945 to the present (Brasil, 2024). Scopus, on the other hand, is a multidisciplinary scientific database encompassing all relevant literature. It includes 26,591 active peer-reviewed journals, 84 million records post-1969 with references, and various indexed publishers (Elsevier, 2024).The database searches were conducted in 2024, as detailed in Table 1.

Table 1: Research Search In the Web of Science ans Scopus Databases.

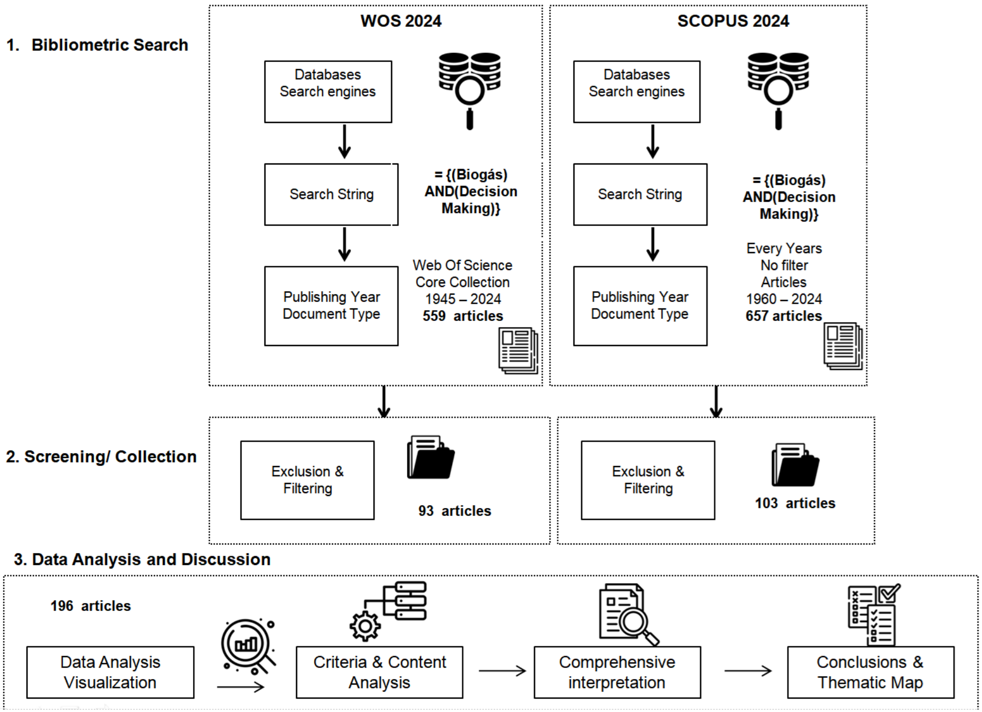
	WoS 2024	Scopus 2024
Search Date	August 2, 2024	August 9, 2024
Search Fields	All Fields	Article tittle, Abstract, Keywords
Timeframe	No timeframe	No timeframe
Search Term	biogas and decision making	biogas and decision making
Filters Applied	No filters	No filters
Total Articles Found	559 articles	657 articles
Reading and Selection	**93 articles**	**103 articles**
Total selected	**196 articles**	

Source: Authors, 2025.

In August 2024, a search was performed on the Web of Science – Core Collection using the term "biogas and decision making" in All Fields. This search yielded 559 articles, without applying timeframes or filters. After reading the abstracts, 93 articles addressing the proposed topic were selected. In the Scopus database, the search was also conducted in August 2024 using the term "biogas and decision making," focusing on Article Title, Abstract, and Keywords fields. Similar to the Web of Science, no timeframes or filters were applied. This search yielded 657 articles, of which 103 were selected after reviewing the abstracts. In total, 1,216 articles containing the keywords "biogas and decision making" were identified.

Following the reading and verification of the relevance of articles related to biogas and multicriteria decision-making, 196 articles were selected (Figure 1).

Figure 1: Methodological Procedures



Source: Authors, 2025.

Synthesis of Journal Analysis Procedures

After selecting articles from the Web of Science and Scopus databases, this work analyzed the following:

Bibliometric Citation Indicators:

- Number of citations;

LinkageIndicators:

- Co-authorship analysis;
- Relationship networks and keywords;

Bibliometric Production Indicators:

- Author productivity (Lotka's Law);
- Journal productivity (Bradford's Law);

In addition to these indicators, trending topics, thematic maps, and scientific collaboration between countries were analyzed. For these analyses, the bibliometric software VOSviewer and Bibliometrix (the Biblioshiny interface) were used. The analysis process began with the review of 1,216 articles, of which 1,020 were excluded for not addressing biogas in relation to multicriteria decision-making, leaving 196 articles selected for analysis.

The samples from the Web of Science (WOS) and Scopus databases were initially analyzed separately using VOSviewer software, focusing on co-authorship networks (authors), co-authorship networks (strongest connections), keywords, co-citation, and most cited references. The individual analysis was performed to preserve all possible outputs from VOSviewer, considering that unifying the samples would compromise the results and limit the analyses.

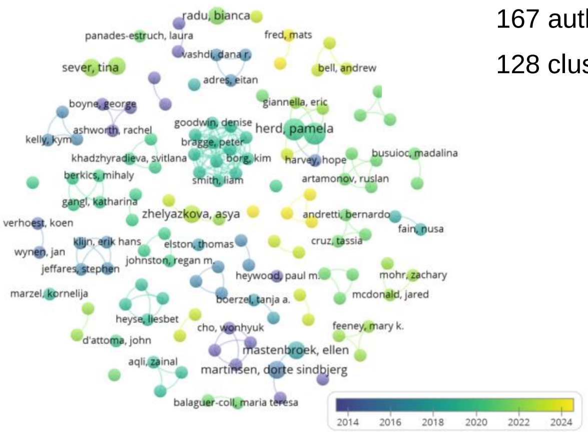
Subsequently, the samples were unified using Bibliometrix software, where most of the data was preserved. After excluding 51 duplicate articles, a total of 145 articles were analyzed collectively, considering: globally most cited documents, a keyword TreeMap (Keywords Plus), Bradford's Law, Lotka's Law, trending topics (Keywords Plus), thematic maps (titles), keyword co-occurrence networks (thematic map - titles), thematic maps (Keywords Plus), keyword co-occurrence networks (thematic map - Keywords Plus), thematic evolution maps (titles), and collaboration maps between countries.

4. RESULTS: ANALYSES AND DISCUSSIONS

For the analysis of results using VOSviewer software, the networks of the two samples (Web of Science 2024 and Scopus 2024) will be presented individually. Observing the co-authorship network of article authors, it was found that, in 2024, the Web of Science sample presented a co-authorship network consisting of 128 clusters and 167 authors. Meanwhile, the co-authorship network of the Scopus database comprised a total of 346 authors and 331 clusters. Comparing the samples, it is evident that the number of authors and clusters is higher in the Scopus database compared to the Web of Science. There was an observed increase of 158.59% in the number of clusters and 107.18% in the number of authors in Scopus compared to the Web of Science sample.

Figure 2: Co-authorship Network – Authors.

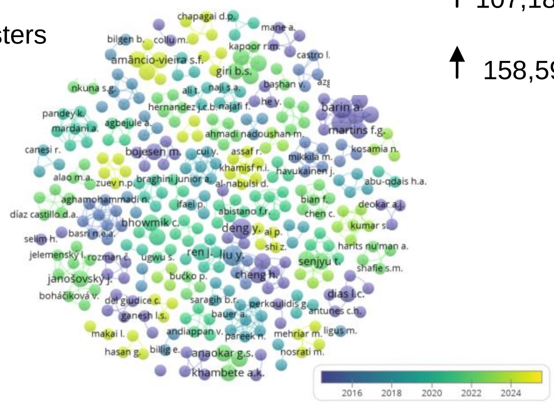
Web of Science



167 authors

128 clusters

Scopus



↑ 107,18% authors

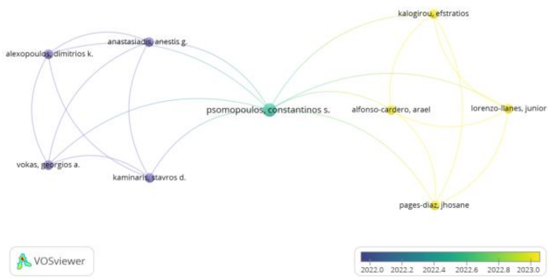
↑ 158,59% clusters

Source: Authors, 2025.

Regarding the most significant connections between the samples, it was observed that although there was an increase in the number of clusters, the number of authors involved in the connections decreased. In the software, authors with at least one authored document were selected. In the Web of Science sample, nine clusters were formed, each with a single author. In the Scopus sample, nineteen clusters were formed, with eighteen having a single author and one cluster consisting of two authors.

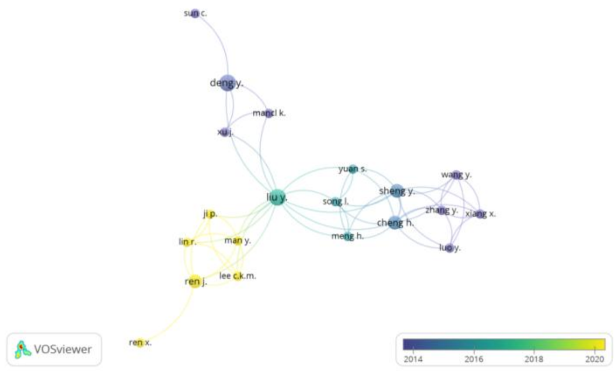
Figure 3: Co-authorship - Authors with Strongest Connections

Web of Science



9 *clusters* (All with 1 author)

Scopus



19 *clusters*

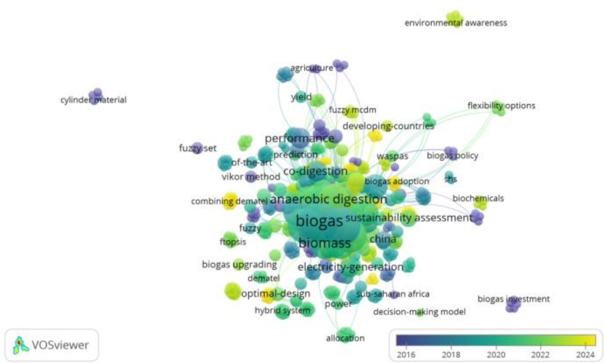
(Only 1 cluster with 2 authors)

Source: Authors, 2025.

In the analysis of the keywords used in the samples, "biogas" and "decision-making" emerged as the most frequent, appearing in both the Web of Science and Scopus databases. Although the difference in the number of articles selected between the WoS 2024 and Scopus 2024 databases is only ten articles, the number of keywords in the Scopus database represents an increase of 98.21% compared to the Web of Science database.

Figure 4: Keywords

Web of Science

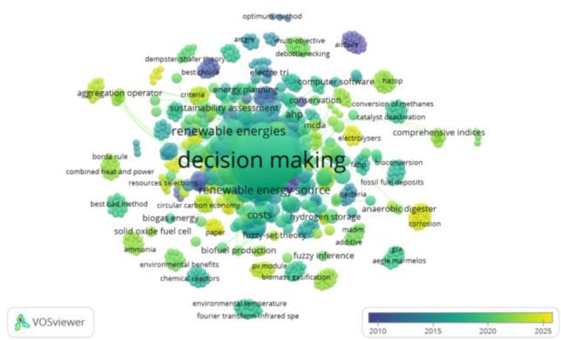


616 *key words*

Biogas – 21 articles

Decision Making – 20 articles

Scopus



1221 *key words*

Decision making – 78 articles

Biogas – 68 articles

Source: Authors, 2025.

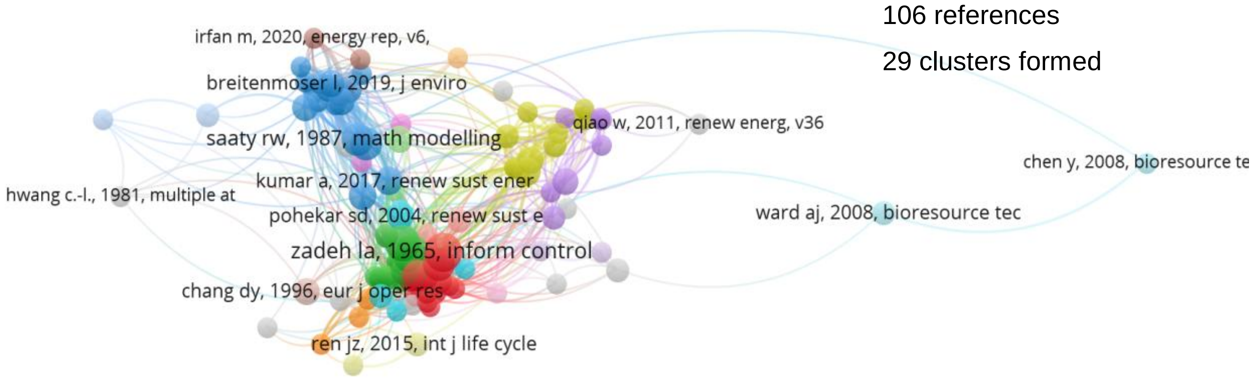
Measuring co-citations in the Web of Science (WoS) analysis, 4,518 references were cited, forming 26 clusters, with 106 references used in at least three articles. In the Scopus sample, 4,405 references were cited, forming 3 clusters, with only 11 references used in at least three articles.

Figure 5: Co-citation Web of Science.

4518 references cited

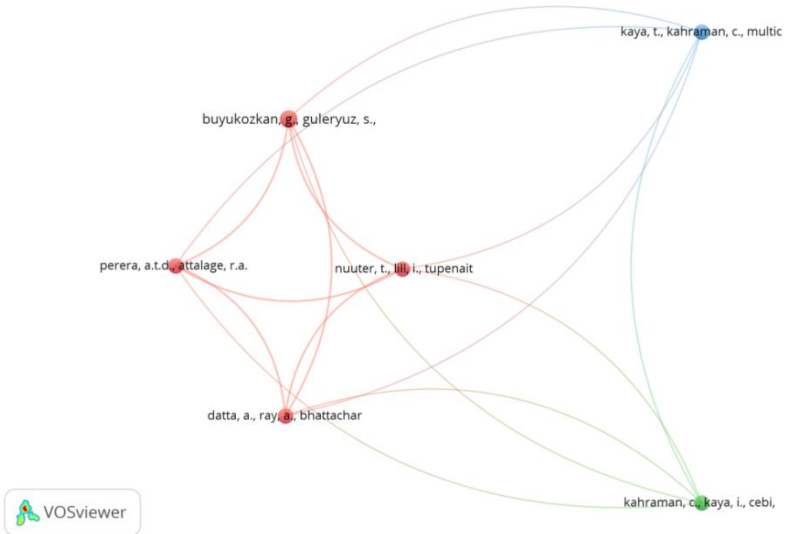
Cited more than 3 times – 106 references

29 clusters formed



Source: Authors, 2025.

Figure 6: Co-citation Scopus



4405 references cited

Cited more than 3 times – 11 references

3 clusters formed

Source: Authors, 2025.

It is observed that in the WoS 2024 and Scopus 2024 samples, the difference in the number of references is only 2.57%, with the Scopus sample being smaller. However, the WoS 2024 sample contains a significantly higher number of references cited in more than three articles, with three clusters of 17 references each, compared to one cluster with four references in the Scopus sample.

Table 2 lists the most cited references from the WoS 2024 and Scopus 2024 samples. The most frequently used reference is SAN CRISTÓBAL, J. R. (2011). It is noted that the most cited references are articles related to multicriteria decision-making and its methods: AHP, VIKOR, BWM, and TOPSIS.

Table 2: Most Cited References in Web of Science 2024 and Scopus 2024.

References	**Number of Citations**
SAN CRISTÓBAL, J. R.(2011).	545
AGHAJANI MIR, M.; TAHEREI GHAZVINEI, P.; SULAIMAN, N. M.; BASRI, N. E.; SAHERI, S.; MAHMOOD, N. Z.; JAHAN, A.; BEGUM, R. A.; AGHAMOHAMMADI, N.(2016).	172
IRFAN, M.; ELAVARASAN, R. M.; AHMAD, M.; MOHSIN, M.; DAGAR, V.; HAO, Y.(2022).	145
RAMANATHAN, R.(1995).	145
KHEYBARI, S.; KAZEMI, M.; REZAEI, J.(2019).	140

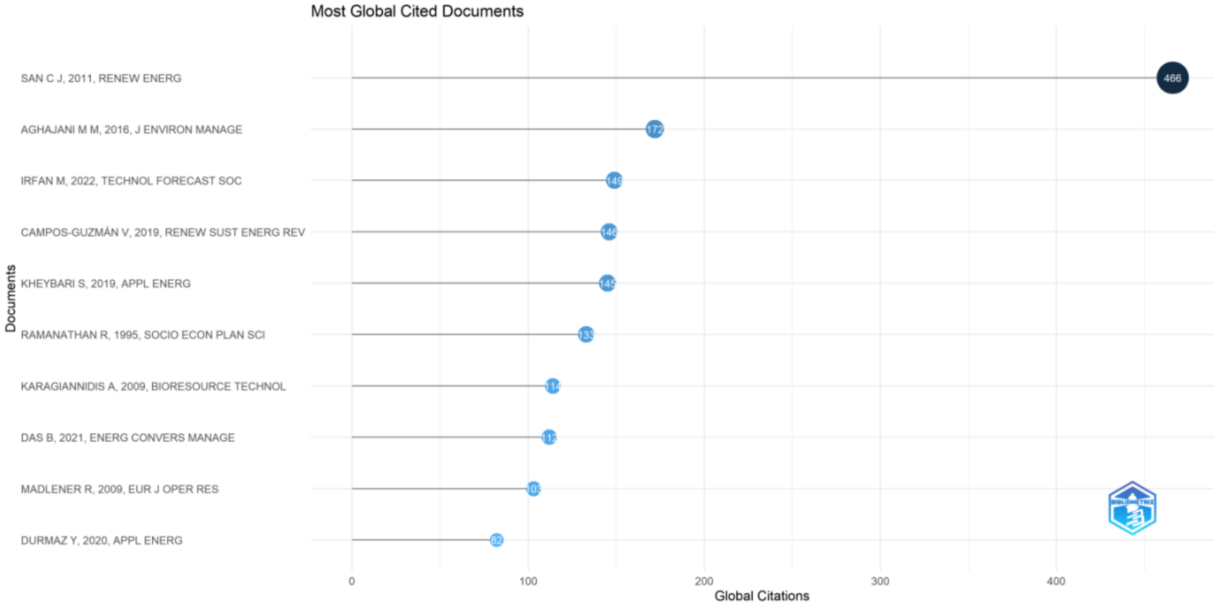
Source: Authors, 2025.

Subsequently, the two samples were unified using the open-source bibliometric tool Bibliometrix and its graphical interface Biblioshiny. From the initial documents, the software identified 196 documents, of which 51 were duplicates and therefore deleted, resulting in a total of 145 documents for analysis.Due to differences in formatting and information between the databases, Biblioshiny was unable to retrieve all metadata related to the variable CR (cited references) when the datasets were unified. It was observed that, individually, in the overview of the samples, the interface correctly identified the references in both Scopus and WoS, but information loss occurred during the unification process.

Considering the selected articles, its time span ranges from 1995 to 2024, covering 92 different journals and totaling 145 documents. Besides, the annual growth rate on the researched topic (*biogas and decision making*) was 10.69%, with contributions from 479 authors, of whom 5 are single authors. In this context, the international co-authorship accounts for 22.76%, with an average of 3.68 co-authors per document. A total of 462 author keywords were identified, while the average age of the articles is 5.2 years, and the average number of citations per document is 24.97.

Annual scientific production began with the publication of one article in 1995, 1997, and 2001, showing growth from 2010 onwards, reaching its peak in 2022 with 20 articles, dropping to 12 articles in 2023, and rising again in 2024.Graph 1 presents the graphical representation of the most globally cited documents. It is noted that the number of citations differs from the information previously provided by the VOSviewer software due to formatting differences between the databases used.

Graph 1: Most Globally Cited Documents



Source: Authors, 2025.

Among the ten most cited documents mentioned in Table 02, the top three references were also identified in the analysis previously conducted using VOSviewer software, which was performed individually for the WoS and Scopus samples. Figure 7 shows the representation of the participation of keywords, through Keywords Plus, in the analysis of the sample articles and their respective percentages.

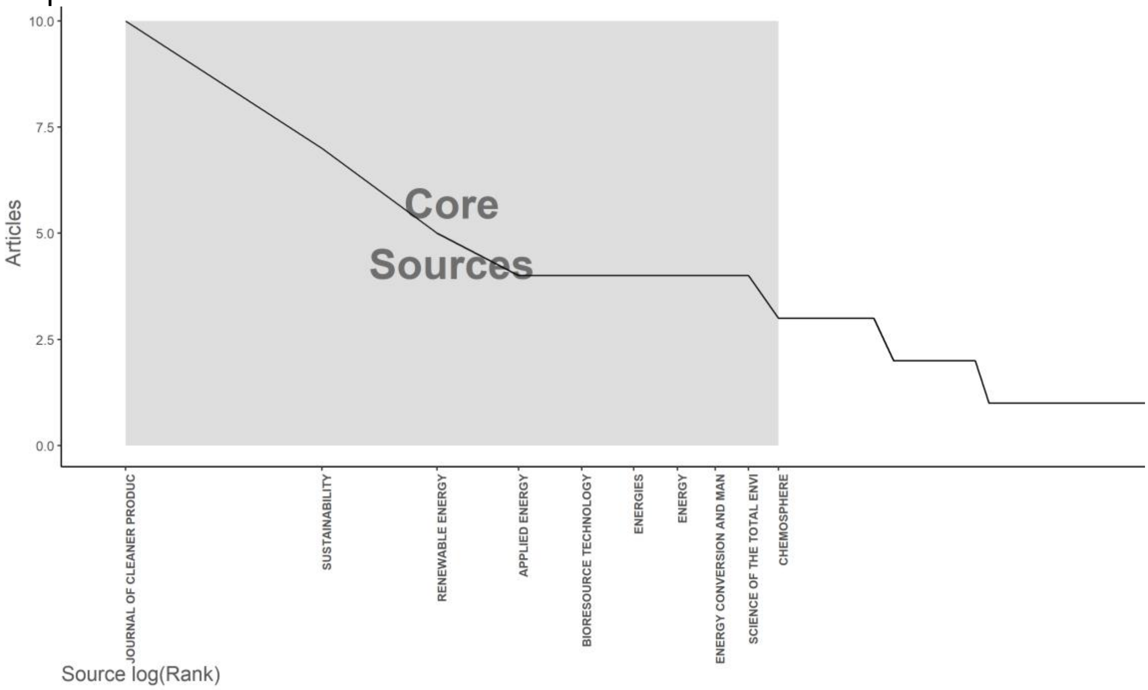
Figure 7: TreeMap of Keywords – Keywords Plus

Source: Authors, 2025.

In this stage, the keywords (Keywords Plus) were considered, with the most frequently mentioned being: *biogas* (50 occurrences) and *decision making* (42 occurrences). These keywords were also identified as the main ones in the analysis conducted using VOSviewer (Figure 7).

Bradford's and Lotka's bibliometric laws measure, respectively, the scientific productivity of journals and authors. These laws address distributions and censuses of scientific documents with similar properties. The interpretation of these analyses is based on the concepts of core and dispersion, where the core represents the group of elements that appears most frequently in a set of studied bibliographic references, while dispersion corresponds to the number of low-frequency elements in the same set (Café & Bräscher, 2008).Bradford's law is applicable to this analysis. Among the 92 journals examined, only 10 constitute the main sources on the topic and are located in Zone 1. Another 35 journals are in Zone 2, contributing to the topic but with less frequency, while 47 journals are in Zone 3, each with only one publication.The main journals are: Journal of Cleaner Production, Sustainability, Renewable Energy, Applied Energy, Bioresource Technology, Energies, Energy, Energy Conversion and Management, Science of the Total Environment, and Chemosphere (Graph 2).

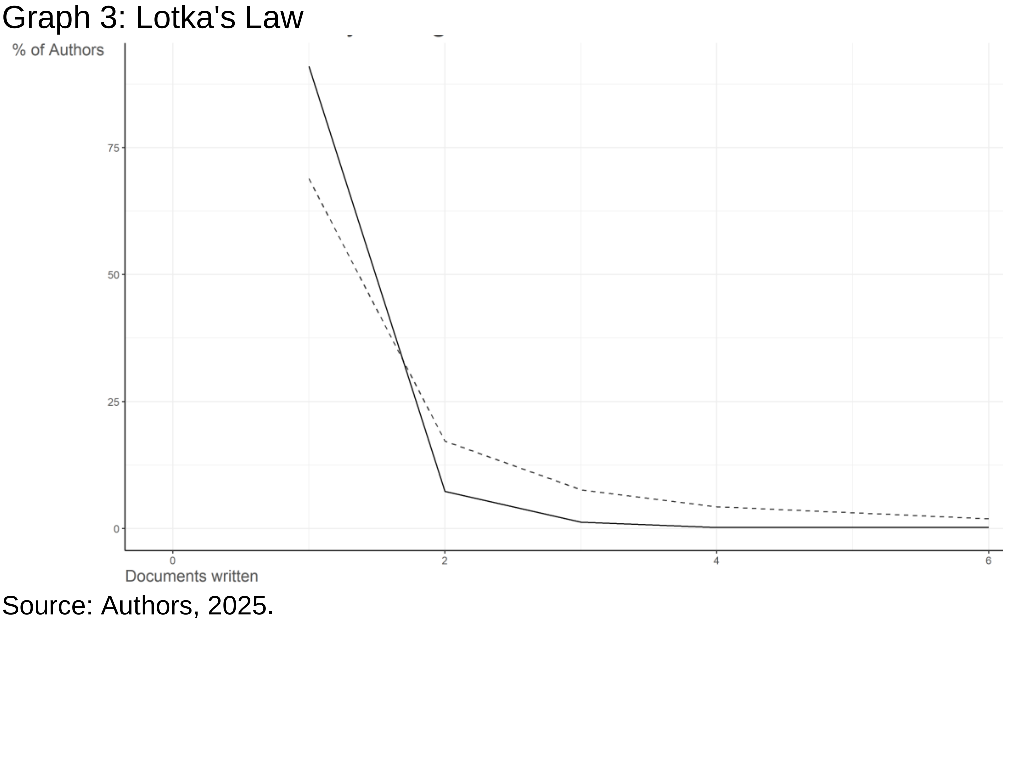
Graph 2: Bradford's Law



Source: Authors, 2025.

Lotka's Law is also applicable to the sample, as 436 authors produced only one document, 35 authors published two articles, only six authors produced three articles, one author published four articles, and similarly, only one author published six articles on the topic (Graph 3).

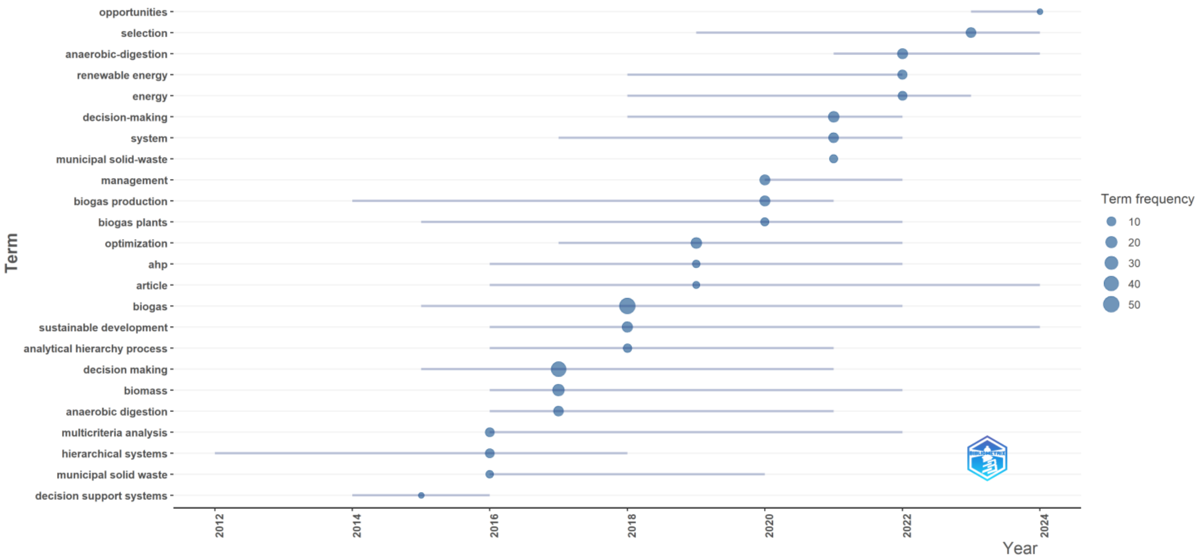
Graph 3: Lotka's Law



Source: Authors, 2025.

As a contribution to future research, this analysis identified the trending topics of Keywords Plus along the timeline from 1995 to 2024 (Graph 04). In 2024, the most frequently used keyword was “opportunities,” with 5 occurrences. In 2023, the most used keyword was “selection,” with 13 occurrences. In 2022, “anaerobic-digestion” was the most frequent keyword, with 14 occurrences, followed by “renewable energy” with 11 occurrences and “energy” with 10 occurrences. In 2021, “decision making” was the most frequently used keyword, with 17 occurrences.This analysis will assist researchers in refining their searches related to biogas and decision-making, as well as in selecting appropriate keywords.

Graph 4: Trending Topics - Keywords Plus

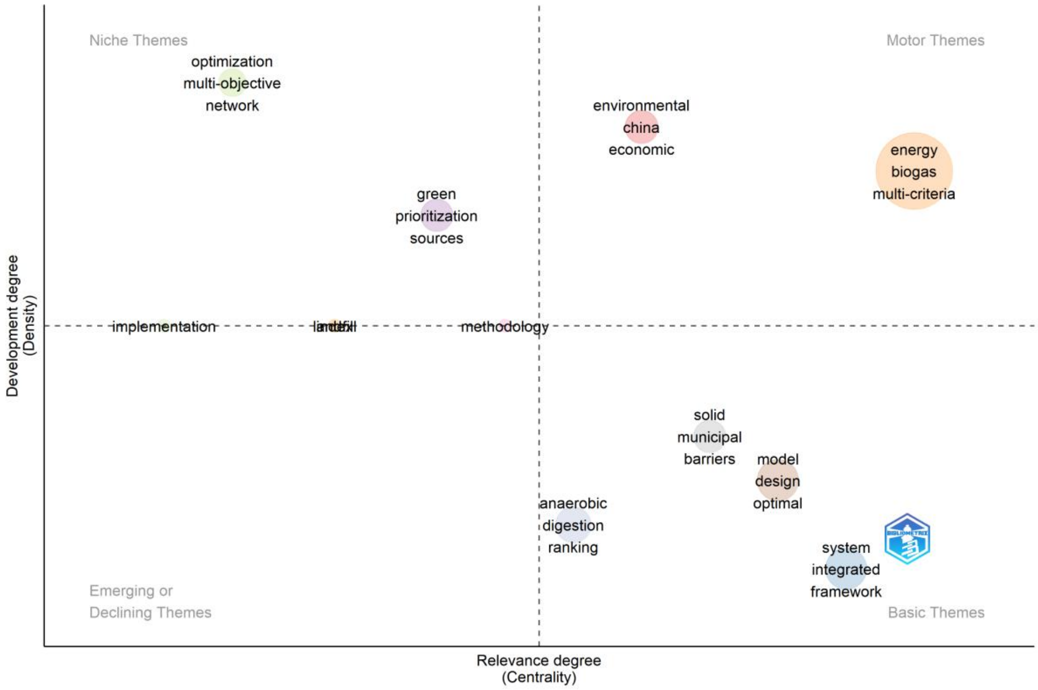


Source: Authors, 2025.

The thematic maps (Graphs 05 and 06) were generated based on the titles and Keywords Plus of the 92 analyzed articles, considering the 250 most frequently used keywords with a criterion of at least 30 occurrences. The thematic map graphically represents, in map and/or network format, the most commonly used terms in the selected publications, allowing for an assessment of the level of proximity (dependency or relationship) or connection between the networks (Silva et al., 2022).

Themes are classified based on centrality and density. Centrality measures the volume of work related to the theme, while density measures the importance of the theme within the dataset analyzed. Each quadrant of the thematic map represents a category.Themes are classified based on the co-occurrence of words in the titles and Keywords Plus, which are then plotted on a 2D graph where the X-axis measures centrality and the Y-axis measures density. The greater the co-occurrence of words belonging to other themes in research topics, the higher the theme's centrality. Similarly, stronger co-occurrences of words within a research topic indicate greater density (Santos; Lopes; Cruz, 2022).

Graph 5: Thematic Map –Titles

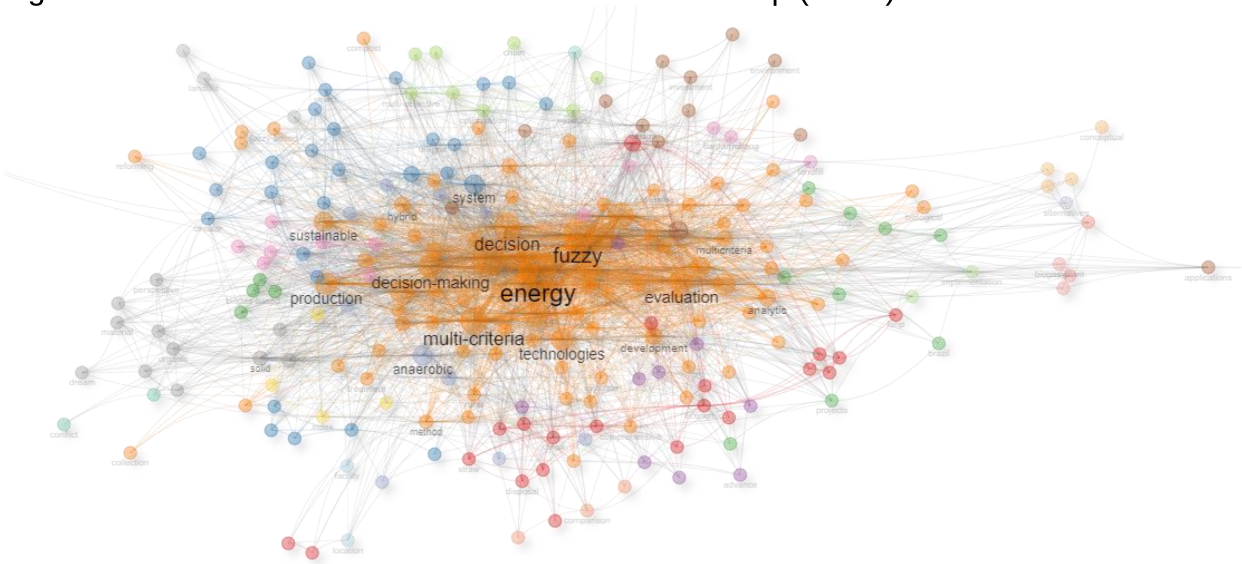


Source: Authors, 2025.

Thematic Map - Titles: In the basic themes (lower-right quadrant) of the title-based selection, the clusters identified are: "integrated system structure," "optimized model design," "municipal solid barriers," and "anaerobic digestion classification." Among these, "integrated system structure" is the theme with the highest centrality, while "municipal solid barriers" shows the highest density in this quadrant.

As motor themes (upper-right quadrant), the clusters "biogas multicriteria energy," identified as the theme with the highest centrality and density, and "environmental China economic," classified as a motor theme with high density but lower centrality, stand out.In the upper-left quadrant, highly specialized themes are addressed, forming clusters such as "multi-objective network optimization," which has the highest density, and "green prioritization sources," which demonstrates the highest centrality.In the lower-left quadrant are relatively developed and marginal themes, which are either emerging or declining. In this selection, no titles are exclusively found in this quadrant; instead, the clusters are located between the upper-left and lower-left quadrants. These clusters include "implementation," "landfill," and "methodology" (Graph 05).

Figure 8: Word Co-occurrence Network - Thematic Map (Titles)



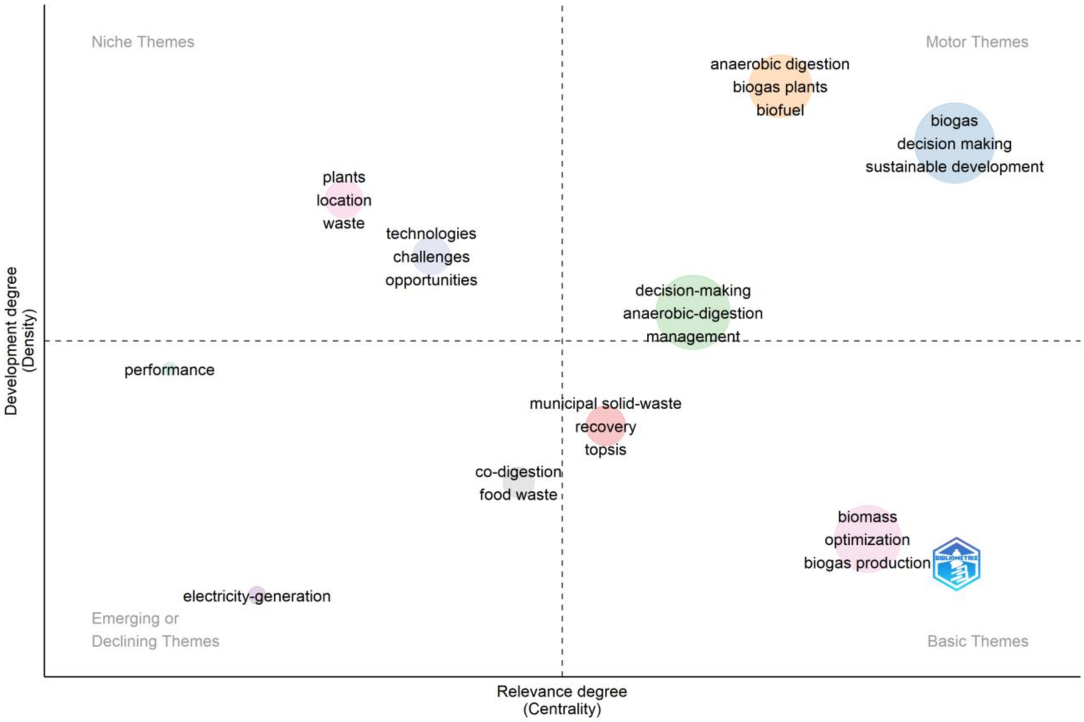
Source: Authors, 2025.

In Figure 8, the thematic network of the thematic map – titles, displays the words and their co-occurrences used in the map's construction. All elements of the same color group together into a single thematic cluster, allowing for a quick identification of trends. It is noted that the largest and most central words are "energy" and "fuzzy."The network related to the thematic map, generated from the article titles, highlights the central words: "energy" with 50 occurrences, "biogas" with 43 occurrences, "multi-criteria" with 32 occurrences, "fuzzy" with 31 occurrences, and "analysis" with 30 occurrences. A total of 86 words were mentioned in the analysis.

In Graph 6, the basic themes (lower-right quadrant) of the title-based selection include clusters such as: "biomass optimization - biogas production," with the highest centrality, and "municipal solid waste," with the highest density. The theme "decision-making – anaerobic digestion – management" is considered a basic cluster but is emerging to become a motor theme. As motor themes (upper-right quadrant), the clusters "biogas – decision-making – sustainable development," identified as the theme with the highest centrality, and "anaerobic digestion – biogas plants – biofuels," classified as a motor theme with high density but lower centrality, stand out.

In the upper-left quadrant, highly specialized themes are addressed, with clusters such as: "waste plant location," which has the highest density, and "technologies – challenges – opportunities," which shows the highest centrality.In the lower-left quadrant are relatively developed and marginal themes, which are either emerging or declining. The theme "performance" has the highest density among others in this quadrant but shows low centrality. “Electricity generation” and “food waste co-digestion” are also present in this quadrant.

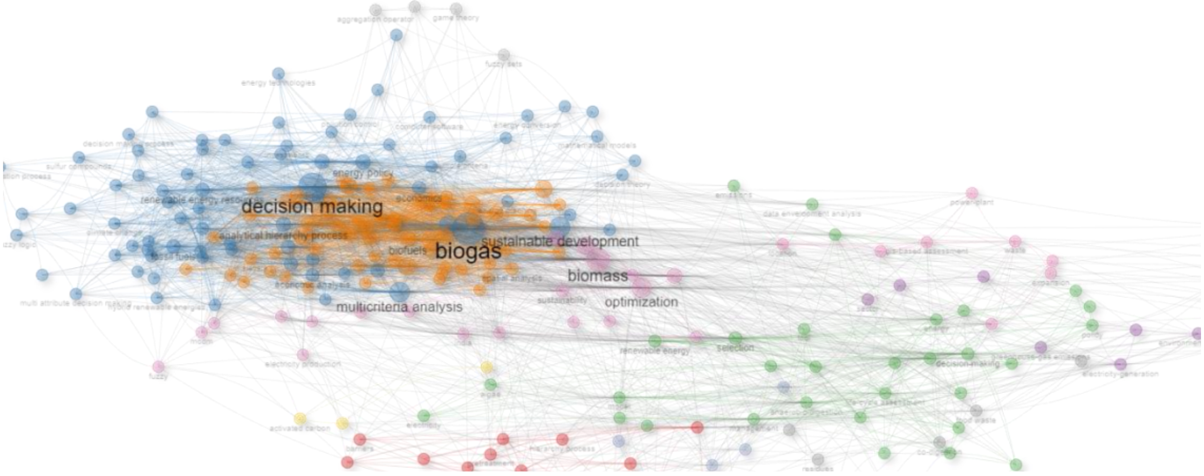
Graph 6: Thematic Map - Keywords Plus



Source: Authors, 2025.

In Figure 9, the network related to the thematic map highlights the central words: “biogas,” with 42 occurrences; “decision making,” with 35 occurrences; “decision-making,” with 17 occurrences; “biomass,” with 17 occurrences; and “optimization,” also with 17 occurrences. A total of 70 words were mentioned in the analysis. The thematic network of the thematic map – Keywords Plus – is observed. It is notable that the term “decision making” strongly connects with “biogas” and “biomass,” reflecting its relationship with decisions about renewable energy and sustainability, which are central themes in the field of study.

Figure 9: Word Co-occurrence Network - Thematic Map Keywords Plus.



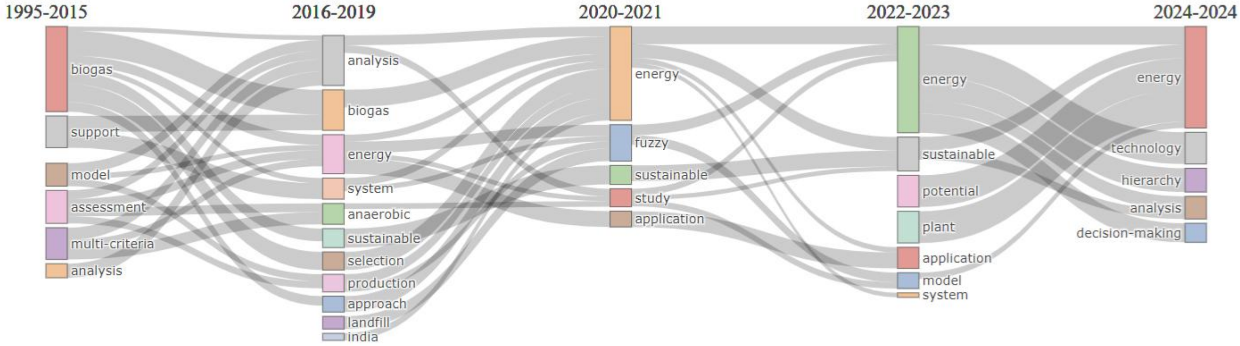
Source: Authors, 2025.

Figure 10 shows the progression of various themes over the years through title-based selection. Each rectangle represents a theme, and its size reflects the number of publications related to that theme. The width of the connections is determined by the common index between connected themes. It is noted that the thematic evolution presented by the Biblioshiny graphical interface is represented by triangles, named based on the highest degree of keywords (Xu, Lei, & Qin, 2022).

In slice 1 (1995–2015), the most prominent theme was “biogas.” In slice 2 (2016–2019), the highlights were “analysis,” “biogas,” and “energy.” In slice 3 (2020–2021), the notable themes were “energy” and “fuzzy.” In slice 4 (2022–2023), the leading theme was “energy,” as it also remained in slice 5 (2024), where “energy” continues to be the primary theme. The term “energy” appears from Slice 2 through Slice 5, while “sustainable” is present in slices 2, 3, and 4.

Themes such as “fuzzy,” “sustainable,” “application,” and “decision making” emerged from 2020 onwards, demonstrating an evolution in methodologies in the field of biogas and decision-making. It is observed that, at the beginning of the analysis, the term “biogas” was more prominent but was replaced by the term “energy” starting in 2020.The terms present in 2024 – “energy,” “technology,” “hierarchy,” “analysis,” and “decision-making” – reinforce the scientific production and the relevance of this topic.

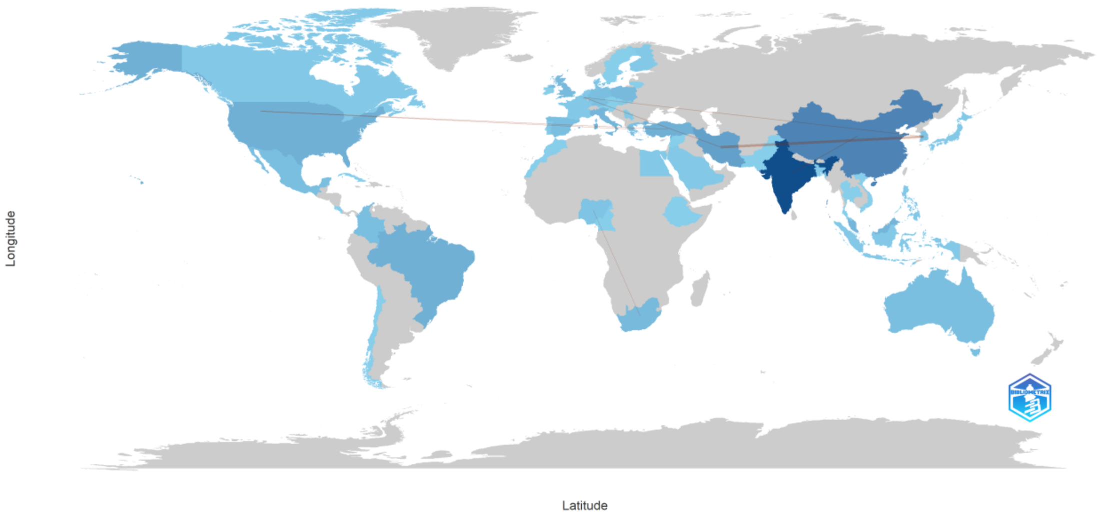
Figure 10: Thematic Evolution Map (1995–2024) – Titles.



Source: Authors, 2025.

Figure 11 presents the collaboration map between countries. The identified collaborations are as follows: Iran and South Korea have three collaborations; Belgium and South Korea, two collaborations; India and China, two collaborations; Iran and Belgium, two collaborations; South Africa and Nigeria, two collaborations; and Turkey and the United States, two collaborations.

Figure 11: Country Collaboration Map.



Source: Authors, 2025.

The findings above provide researchers in the field with deeper insights into the research agenda related to biogas and decision-making, enabling contributions to the area in developing and expanding topics.

5. DISCUSSION

In this section, we explore the characteristics of publications on biogas and decision-making, presenting some suggestions. We analyzed, in general, the structure of publications, citations, keywords, cooperation networks, and other information.In the analysis using VOSviewer software, there was an observed increase of 107.18% in the number of authors and 158.59% in the number of clusters in the Scopus sample compared to WoS.

Among the keywords, “biogas” and “decision making” stood out. Despite a difference of only 10 articles between the samples, the number of keywords in Scopus was 98.21% higher than in WoS.Analyzing co-citations, the difference in the number of references between the samples was only 2.57%, with Scopus presenting fewer references. However, the WoS sample had a significantly higher number of references cited in more than three articles, with three clusters of 17 references each, compared to one cluster of four references in Scopus.

The most cited references were related to articles on multicriteria decision-making and its methods: AHP, BWM, TOPSIS, and VIKOR. The most referenced work was by SAN CRISTÓBAL, J. R., titled *Multi-criteria decision-making in the selection of a renewable energy project in Spain: The Vikor method,* published in *Renewable Energy* in 2011. Other relevant works applied methods such as TOPSIS, VIKOR, AHP, and G-TOPSIS, as well as integrated models of goal programming. These references, are essential for new researchers seeking to deepen their understanding of biogas and multicriteria decision-making.

Using the Biblioshiny graphical interface, 145 documents were analyzed. The time span of the analyzed articles ranged from 1995 to 2024, covering 92 different journals. The annual growth rate on the topic (biogas and decision-making) was 10.69%. International co-authorship accounted for 22.76%, with an average of 3.68 co-authors per document.Annual scientific production began modestly, with one article published in 1995, 1997, and 2001. From 2010 onward, the topic gained relevance, reaching its peak production of 25 articles in 2022.

The most globally cited publications were: SAN C J. (2011, *Renewable Energy*); AGHAJANI M. M. (2016, *Journal of Environmental Management*); and IRFAN M. (2022, *Technological Forecasting and Social Change*). These articles serve as guides for in-depth studies on biogas and decision-making.

The most relevant Keywords Plus analyzed via Biblioshiny were: “biogas,” “decision making,” and “biomass.” The bibliometric laws of Bradford and Lotka, which measure the scientific productivity of journals and authors, respectively, were applicable to the analyzed sample. The main journals identified by Bradford’s Law were:*Journal of Cleaner Production, Sustainability, Renewable Energy, Applied Energy, Bioresource Technology, Energies, Energy, Energy Conversion and Management, Science of the Total Environment,* and *Chemosphere.*

The trending topics of Keywords Plus indicated that the most used word in 2024 was “opportunities,” with five occurrences; in 2023, “selection,” with 13 occurrences; and in 2022, “anaerobic-digestion,” with 14 occurrences. This analysis helps researchers refine their searches on biogas and decision-making.

Another highlight for future studies are the two thematic maps generated: one from article titles and another from Keywords Plus. Both identify “biogas” and “decision making” as motor themes, highlighting their high relevance and development in the field. Themes such as “biomass,” “biogas production,” “municipal solid barriers,” and “municipal solid waste” appear as basic themes in both maps but still require further development. Niche topics like “optimization” and “waste management” appear as specialized topics but have limited relevance in the overall context. Emerging themes identified only in the Keywords Plus map include “performance,” “electricity generation,” and “food waste co-digestion.”

This mapping provides researchers with a perspective on the evolution of biogas and decision-making topics, highlighting relevant themes and assisting in understanding current and future trends. The analysis allows for the identification of emerging areas, knowledge gaps, and guidance for future work, contributing to the advancement of the field. Furthermore, collaboration networks reveal strong connections between themes such as “energy,” “biogas,” “multicriteria,” and “decision-making,” which hold significant representation in the field. In the context of international collaboration, Iran and South Korea stand out with three collaborations.

6. CONCLUSION

After analyzing the Web of Science and Scopus databases to explore the field of biogas and decision-making, 145 articles related to the topic were identified between 1995 and 2024. Initially, 1,216 articles were reviewed, and after reading and evaluation, 196 articles were selected for analysis in VOSviewer and 145 articles for analysis in Bibliometrix and Biblioshiny.

The most cited publications are articles related to multicriteria methods. As a contribution of this study, the analyses identified motor themes in the field of biogas and multicriteria decision-making, including “biogas” and “decision making.” Among the basic and foundational themes are terms such as “biomass,” “biogas production,” “municipal solid barriers,” and “municipal solid waste,” which represent subjects for further exploration by researchers interested in this area.

The analyses provide guidance for researchers in the field, directing and informing future investigations based on the findings presented in the thematic map of motor, basic, emerging, and niche areas. These contributions can serve as a guide for researchers to gain a better understanding of the topic and delve deeper into underdeveloped aspects of the field.

For future research, it is suggested that studies address topics such as optimizing biogas production from biomass, municipal solid barriers, ideal model design, and municipal solid waste recovery using the multicriteria TOPSIS method. These topics have the potential to significantly contribute to the growth of the biogas and multicriteria decision-making field.

APPLICATION OF A MULTICRITERIA DECISION MODEL FOR THE SELECTION OF CONVERSION PATHWAYS FOR BIOFUEL PRODUCTION AND MANAGEMENT IN A MEDIUM-SIZED MUNICIPALITY IN THE STATE OF PARANÁ

ABSTRACT

Biogas and biofuels have emerged as viable alternatives to meet the targets established by the Paris Agreement. Considering the numerous variables involved in biogas production and the need to understand growth opportunities, technological improvements, and policies aimed at stabilizing the sector, a bibliographic review was conducted, analyzing 145 scientific articles. This analysis revealed a research gap related to biogas, energy generation, and the application of multicriteria decision-making methods. This study aims to contribute to filling this gap through the application of a multicriteria model designed to assist public decision-makers in selecting among three conversion pathways for biogas and biofuel production: pyrolysis, covered lagoon biodigester, and continuous stirred-tank reactor (CSTR) biodigester. These alternatives were evaluated based on environmental, social, economic, and technical criteria, applying the AHP (Analytic Hierarchy Process) and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) methods. The AHP method was used to rank the criteria and their respective sub-criteria, while the TOPSIS method helped select the alternative closest to the “ideal positive solution” among the conversion routes analyzed. The ranking results showed that environmental and social criteria received the highest scores compared to technical and economic criteria.

Keywords: multicriteria decision-making method; biofuels; conversion route.

7. INTRODUCTION

The world's current energy supply is largely derived from non-renewable energy sources—fossil fuels. These fuels have limited supply and high costs and contribute significantly to greenhouse gas (GHG) emissions and air pollution. A sustainable way to mitigate the environmental, social, and economic problems associated with these non-renewable energy sources is through the promotion of renewable energies, particularly biomass, and the conversion of waste into bioenergy (Mulu; M'Arimi; Ramkat, 2021).

The increase in GHG emissions over recent years requires Brazil to intensify its efforts to meet its GHG reduction targets under the Paris Agreement by 2025. Since 2003, methane recovery initiatives through biogas generation in waste management have been observed. In 2022, 526 thousand tons of methane (CH_4) were recovered in 51 sanitary landfills, representing a 5% increase compared to the previous year. Biogas recovery is responsible for avoiding the emission of 20% of all methane generated in final waste disposal (Observatório do Clima, 2023).

The Brazilian government has committed to reducing its GHG emissions by 37% by 2025 and contributing to a 43% reduction by 2030, compared to estimated 2005 levels [3]. Brazil also agreed to increase the share of sustainable bioenergy in its energy matrix by 18%, restore 12 million hectares of forests, and achieve 45% of renewable energy use by 2030 (Trindade etal., 2019).

Brazil has a competitive advantage due to the lower cost of crops and industrial residues. There is significant potential to scale up the industrial exploitation of biogas, particularly from agro-industrial waste. The main commercial applications of biogas include electricity generation through combustion in generator sets, biomethane production (after CO_2 and contaminant removal) to replace natural gas, especially in transportation, and the use of residual materials as fertilizers (Milanez et al., 2018).

The use of biogas through the conversion of solid waste into energy is relatively recent in Brazil. This sector is still in the process of consolidation and is subject to constant regulatory and policy changes. The greatest challenges in harnessing biogas for energy production are linked to the development of actions by the private sector, government, and research and development institutions. These factors further hinder the political, social, environmental, and technical structuring of the biogas sector in Brazil (Mito, 2022).

According to the CIBiogás (2025) report, in 2022, Brazil had 885 existing and operational biogas plants, with a cumulative production of 2,886,462,729.75 Nm^3/year. Regarding the number of existing biogas plants by state in 2022, Minas Gerais ranks first with a total of 224 existing plants and 25 new plants, followed by Paraná with 139 existing plants and 29 new plants. In third place is Santa Catarina, with 55 existing plants and 15 new plants, while São Paulo ranks fourth with 54 existing plants and seven new plants. Goiás comes fifth, with 52 existing plants and 12 new plants. Although São Paulo accounts for 74 biogas plants and ranks fourth in terms of the number of installations, it is the largest biogas-producing state, with a total production of 1,016,642,220.10 Nm^3/year. For biogas production in the Southern Region of Brazil, the main substrate source used for biogas generation comes from municipal solid waste and sewage, followed by industrial and agricultural residues. The primary use of the biogas is for electricity generation (CIBiogás; 2025).

The main forms of energy conversion are direct combustion (with or without physical processes, such as drying, sorting, compression, and cutting/breaking), thermochemical processes (gasification, pyrolysis, liquefaction, and transesterification), or biological processes (anaerobic digestion and fermentation) (Silva; Trevisan, 2019). Biomass is then transformed into various energy products, such as heat, electricity, liquid fuels, and gaseous fuels (Zanette, 2009).

This study focuses on the thermal conversion process of pyrolysis and the biological conversion process of digestion, aiming at the generation of biogas and liquid and gaseous biofuels (bio-oil and syngas) (Bridwater, 2006).

Among the conversion processes, pyrolysis has proven to be a promising technology for obtaining renewable fuels. It is a thermochemical process that involves heating organic materials in the absence of oxidizing agents. The final products of the pyrolysis process depend on several factors: pyrolysis temperature, heating rate, condensation temperature, the nature of the feedstock, and particle size (Farias; da Silva Guerra; Machado, 2020).

Pyrolysis is an analysis or decomposition reaction that occurs under the action of high temperatures. When the raw material is exposed to these high temperatures, the molecular structure of the compound breaks down due to the heat in an environment with little or no oxygen. The process is energy self-sustaining, as the chemical decomposition produces more energy than it consumes. Also known as carbonization, pyrolysis thermally decomposes carbon-containing materials, such as wood, agricultural waste, and any other organic matter, resulting in three phases: a solid phase (charcoal), a gaseous phase, and a liquid phase called the pyroligneous fraction (extract or bio-oil) (Moura, 2012).

The temperatures applied during the pyrolysis process influence the production of each phase (char, gas, or liquid). Lower temperatures combined with longer vapor residence times favor the production of charcoal, high temperatures and long residence times increase the conversion of biomass into gas, and moderate temperatures with short vapor residence times are ideal for liquid production. Fast pyrolysis for liquid production is particularly advantageous due to the ease of storage and lower transportation costs compared to solid biomass (Bridwater, 2006).

Biogas is a gas rich in methane (CH_4), carbon dioxide (CO_2), and other minor compounds, such as hydrogen sulfide (H_2S), nitrogen (N_2), water vapor (H_2O), and ammonia (NH_3). It is produced through the anaerobic digestion of industrial effluents, animal manure, and/or sewage sludge (Soares et al., 2022). This is a complex process that depends on the activity of various microorganisms that transform the organic matter in the substrates into biogas through biochemical reactions, acting synergistically and in proto-cooperation [8]. Biogas generation depends on several factors, including the type of waste used, the methane content, and the quality of the biodigester fertilizers (Milanez et al., 2018).

The process takes place in the absence of oxygen in equipment known as biodigesters. It offers advantages, such as production from locally available organic waste, generation near the consumption site, which avoids large investments or pipelines, and the conversion of environmental liabilities into energy assets. Designing a biodigestion plant involves several steps, from selecting and conditioning the raw material to the reactor itself and subsequent stages of separation and purification of the generated products (CiBiogás, 2025).

The biodigester is the main component of a biodigestion plant, where residual or cultivated biomass is converted by the action of microorganisms. There are different types of biodigesters or anaerobic reactors, including Upflow Anaerobic Sludge Blanket (UASB) reactor, Continuous Stirred Tank Reactor (CSTR),Covered

Lagoon or Plug-Flow Reactor, Fixed-Bed Anaerobic Reactor, Rotating-Bed Anaerobic Reactor, Fluidized-Bed Anaerobic Reactor, and Solid-Phase Reactor (Soares et al., 2025).

The CSTR reactor was developed to achieve a high reaction rate, applying engineering principles to reduce the hydraulic retention time by using mixing, heating, and strategies to retain microorganisms within the reactor. The covered lagoon biodigester, also known as the Canadian model or BLC, is the least technologically advanced. It is designed to operate with a total solid content of 0.5% to 5% and a hydraulic retention time of 30 to 60 days, making it suitable for warm climate regions.

The complete mix biodigester, which is a continuous stirred tank reactor (CSTR), features a higher technological level, operates with a solids content of 12% to 15%, and requires a minimum liquid retention time of 20 days. It is suitable for all types of climates and allows for the co-digestion of feedstocks (a mixture of two or more complementary substrates) (Soares et al., 2025).

The CSTR biodigester model is more complex. The Continuous Stirred Tank Reactor (CSTR) was designed to handle large volumes and is characterized by its stirring system, which keeps the contents homogenized while controlling parameters, such as temperature, pH, and biomass level (CiBiogás, 2025).

The Covered Lagoon Biodigester (BLC) is commonly found in rural areas and is installed by excavating a tank in the ground, which is then waterproofed and covered with a geosynthetic material (a synthetic or natural polymer product in the form of a sheet or strip), such as PVC (polyvinyl chloride) and HDPE (High-Density Polyethylene). This is considered a low-tech model characterized by its low permeability to fluids and gases. It has a rectangular shape, and its slope and installation depend on the soil characteristics of each property (CiBiogás, 2025).

Multicriteria Decision Analysis (MCDA) methods aim to support decision-makers in choices involving multiple criteria, providing guidance for more effective and consistent decisions. It is an inherently complex process. MCDA addresses three main decision-making problems: selection, classification, and ranking. The first two are more commonly studied, while the third provides a way to handle MCDA problems that require alternatives to be assigned to ordered categories (Andretta Junior; Piratelli; Pacheco, 2022).

A study by San Cristobal (2011) analyzed decision making using the VIKOR method, a decision approach that considers multiple conflicting objectives across social, economic, technological, and environmental factors. The study assessed the specific measure of proximity to the ideal solution. The VIKOR method was applied alongside AHP to compare sustainable energy generation alternatives, including wind, hydro, solar thermal, solar thermoelectric, photovoltaic, biomass, biogas, and biofuels. The most advantageous option identified was a biomass power plant with co-firing in a conventional power plant.

Aghajani Mir et al. (2016) applied the TOPSIS decision-making method to determine the best municipal solid waste (MSW) management approach by comparing and ranking different scenarios. The defined and compared MSW treatment scenarios showed that the optimal decision involves a combination of recycling, anaerobic digestion, and landfill with electricity generation.

Similarly, Irfan (2022) used AHP and G-TOPSIS methods to analyze the energy barriers of biomass. The main barrier identified was technological and infrastructural, followed by economic and financial barriers, political and institutional obstacles, cultural and behavioral factors, and meteorological challenges.

Ramanathan and Ganesha (1995) proposed a model for domestic energy resource allocation. The suggested model included natural gas, firewood, and solar thermal energy for cooking; biogas and electricity generated from firewood for water pumping; and all electricity generation technologies for lighting and operating household appliances. Grid electricity was preferred only for lighting.

Based on a set of criteria, Kheybari, Kazemi, and Rezaei (2019) identified the best location for a bioethanol plant. Using the three dimensions of sustainability (economic, environmental, and social), they applied the Best–Worst Method (BWM) to calculate the overall score for each province, identifying Khuzestan Province as the most suitable location for bioethanol production in Iran.

The Analytic Hierarchy Process (AHP) method was developed in the 1970s by Thomas Saaty and can be applied in various fields of knowledge due to its ability to incorporate both qualitative and quantitative data into the analysis (Andretta Junior; Piratelli; Pacheco, 2022).

Saaty (1987) describes AHP as a general measurement theory used to derive ratio scales from discrete and continuous paired comparisons. Measurements can be obtained from actual data or from a fundamental scale that reflects the relative strength of preferences and feelings. AHP finds broad applications in multicriteria decision making, planning, resource allocation, and conflict resolution. Generally, a hierarchical model of a problem starts with the goal, followed by criteria and sub-criteria (which are subdivisions of the criteria), leading to the selection of alternatives.

The Technique for Order of Preference by Similarity to Ideal Solution(TOPSIS) was developed by Hwang and Yoon in 1981. It was designed to select the best alternative based on the shortest Euclidean distance from the positive ideal solution and the farthest from the negative ideal solution. The chosen alternative should be as close as possible to the “positive ideal” and as far as possible from the “negative ideal” (Andretta Junior; Piratelli; Pacheco, 2022).

Implementing a biogas project involves several stages, including feasibility studies, plant planning, and operation. For the sustainable development of the biogas value chain, it is essential to understand the sector’s capacities and strategies to support stakeholders and decision-makers. This knowledge enables the identification of growth opportunities, technological improvements, and policies to stabilize the sector. A robust political, regulatory, and technological framework is crucial to sustaining and incentivizing the sector. Once consolidated, public policies will directly influence the development and strengthening of renewable energy sources (Mito, 2022).

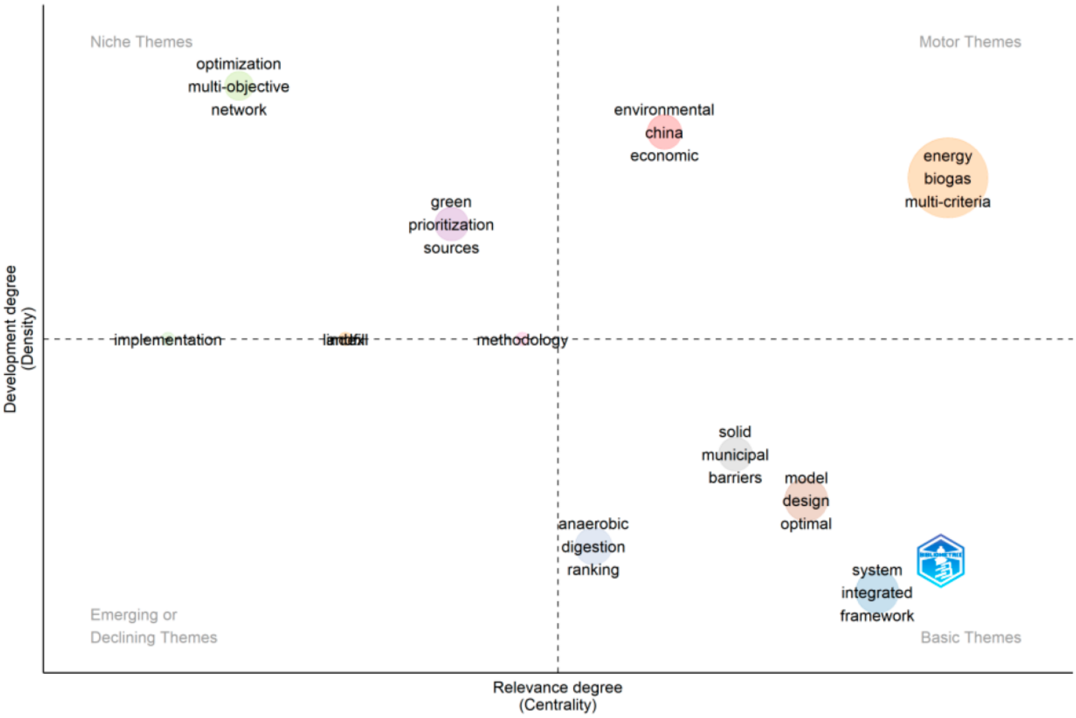
The success of biogas generation is directly linked to the design and sizing of the biodigestion plant, while inefficiency is often related to improper plant sizing, bioreactor loading, substrate agitation, and temperature control within the bioreactors (De Souza, 2015). Given the numerous variables involved in biogas and biofuel production, this study aims to apply a multicriteria model to assist public decision-makers in selecting among three conversion pathways: pyrolysis, covered lagoon biodigester, and continuous stirred-tank reactor (CSTR) biodigester. The analysis is based on environmental, social, economic, and technical criteria, applying the multicriteria methods AHP (Analytic Hierarchy Process) and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) to rank the criteria and determine which of the technologies is the most advantageous for biogas and biofuel production.

8. MATERIALS AND METHODS

This study aims to assist public decision-makers by analyzing environmental, economic, social, and technical criteria related to biogas and biofuels. The methodological approach employs the multicriteria AHP method for ranking the criteria and the TOPSIS method for selecting the best conversion pathway. The objective is to guide public managers in decision making for the implementation of biogas plants at the municipal level, considering the key factors for choosing among the conversion routes: pyrolysis, anaerobic digestion using the covered lagoon biodigester model, and the CSTR biodigester.

A bibliographic review was conducted with 145 articles from the Scopus and Web of Science databases. Through the analysis of these articles using Bibliometrix software version 4.3.0 and Biblioshiny function, a thematic map was generated based on the article titles. A research gap was identified related to biogas, energy generation, and the application of multicriteria decision-making methods as core themes in the field. Additionally, basic themes to be further developed were identified, including municipal solid barriers, ideal design models, and integrated system structures (Figure 12).

Figure 12: Thematic map—titles.



Source: Authors, 2025.

With the identified research gap, the study aimed to determine the key parameters for decision making in biogas production projects. Yamaji et al.(2024) conducted a systematic analysis of scientific articles addressing decision making and biogas, compiling 58 analyzed articles that identified 499 distinct sub-criteria. These sub-criteria were subsequently grouped and classified, resulting in 39 sub-criteria covering four dimensions, which in this paper are referred to as decision-making criteria: environmental, economic, social, and technical.

For this study, five sub-criteria were selected for each main criterion, totaling 20 sub-criteria for analysis. These sub-criteria were chosen based on the results of the project model proposed by Yamaji et al. (2024), as presented in Table 3.

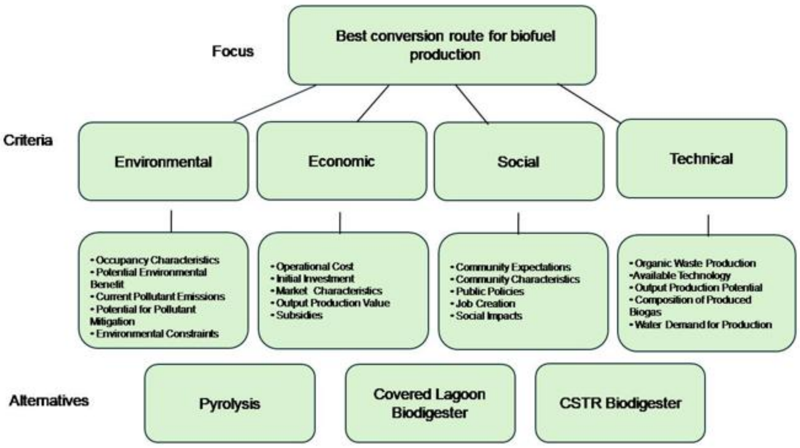
Table 3: Criteria and sub-criteria—decision making and biogas.

	Criteria/Dimensions			
	Environmental	Economic	Social	Technical
Sub-criteria	ENV01 Occupancy Characteristics	ECO01 Operational Cost	SOC01 Community Expectations	TEC02 Organic Waste Production
	ENV02 Potential Environmental Benefit	ECO02 Initial Investment	SOC02 Community Characteristics	TEC03 Available Technology
	ENV03 Current Pollutant Emissions	ECO03 Market Characteristics	SOC03 Public Policies	TEC04 Output Production Potential
	ENV04 Potential for Pollutant Mitigation	ECO06 Output Production Value	SOC04 Job Creation	TEC08 Composition of the Produced Biogas
	ENV06 Environmental Constraints	ECO09 Subsidies	SOC05 Social Impacts	TEC11 Water Demand for Production

Source: Adapted from Yamaji et al., 2024.

After defining the criteria, the weight allocation was carried out by a biogas specialist using the Analytic Hierarchy Process (AHP) and a fundamental scale that reflects the relative strength of preferences and perceptions. In the decision hierarchy (Figure 13), the focus is set as the “best conversion route for biofuel production”, based on the following criteria: environmental, economic, social, and technical, along with the 20 sub-criteria for selecting among the alternatives of pyrolysis, covered lagoon biodigester, and CSTR biodigester. To model subjective decision-making processes based on multiple criteria within a hierarchical system, the structure must be based on three principles: (a) decision hierarchy, (b) pairwise comparative judgment of alternatives and criteria, and (c) consistency assessment of the results (Martínez –Gómes, 2016).

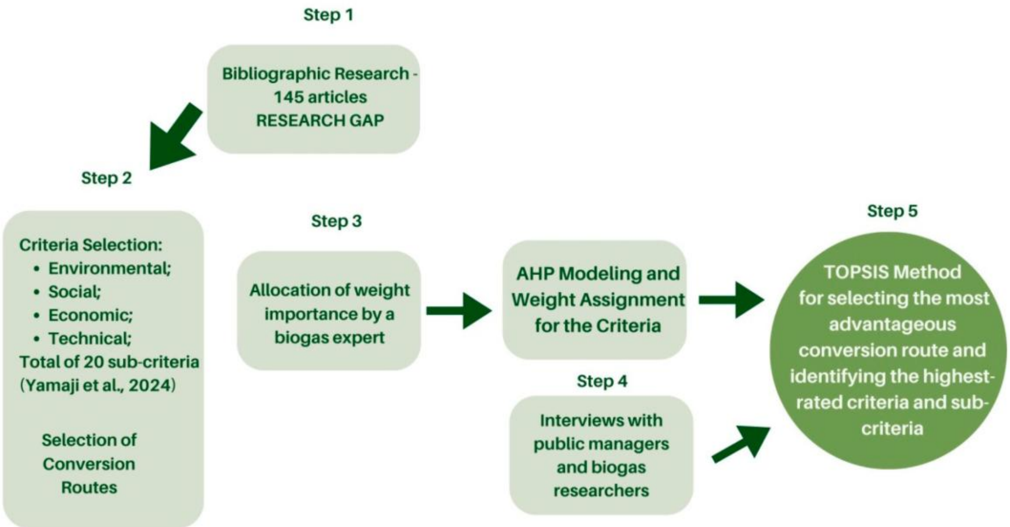
Figure 13: Decision hierarchy.



Source: Authors, 2025.

After calculating the weights of each criterion using the AHP method, a questionnaire was created via Google Forms for public managers and biogas researchers to evaluate each sub-criterion related to each alternative on a scale from 0 to 10, where 0 represents highly disadvantageous and 10 represents highly advantageous. Following the evaluations, the TOPSIS method was applied, which is a technique for ordering preferences by similarity to the ideal solution (Figure 14).

Figure 14: Methodology steps.



Source: Authors, 2025.

The TOPSIS method consists of selecting the alternative that is closest to the positive ideal solution and farthest from the negative ideal solution, where the highest-ranking alternative is considered the best choice (Tzeng; Huang, 2011).

The objective of applying this methodology is to determine the best conversion route alternative for biofuel production among pyrolysis, covered lagoon biodigester, and CSTR biodigester. The TOPSIS method procedures can be described as follows: a set of alternatives (*A*), a set of criteria (*C*), where (*X)* denotes the set of ratings, and (*W*) represents the information set that denotes the performance ratings (Table 4).

Table 4: TOPSIS information table.

A	C_1	...	C_m
A_1	x_{11}	...	x_{1m}
$\vdots$	$\vdots$	$\vdots$	$\vdots$
A_n	x_{n1}	...	x_{nm}
W	w_1	...	w_m

Source: Adapted from Tzeng; Huang, 2011.

After constructing the TOPSIS information table, the normalized and weighted decision matrix (N_{ij}) is calculated, as shown in Equation (1).

Equation (1): Normalized and Weighted Decision Matrix N_{ij}.

$$r_{ij}(v) = \frac{v_{ij}}{\sqrt{\sum_{j=1}^{n} v_{ij}^2}} \qquad i = 1, \ldots, m(critérios); \quad \mathrm{j = 1, \ldots, n\ (alternativas)}$$

$$N_{ij} = w_j r_{ij}(v)$$

Source: Tzeng; Huang, 2011.

Next, the Positive Ideal Point (PIP) and Negative Ideal Point (NIP) of the ideal solution are calculated according to Equation (2).

Equation (2): Calculation of the Positive Ideal Point and Negative Ideal Point.

$$PIP = A^+ = \{N_1^+(v), N_2^+(v), \ldots, N_i^+(v), \ldots, N_m^+(v)\ \}$$
$$= \left\{\max_j v_{ij}(v) | i \in I_1, \min_j v_{ij}(v) | i \in I_2 \mid i = 1, \ldots, n\right\}$$

$$PIN = A^- = \{N_1^-(v), N_2^-(v), \ldots, N_i^-(v), \ldots, N_m^-(v)\ \}$$
$$= \left\{\min_j v_{ij}(v) | i \in I_1, \max_j v_{ij}(v) | i \in I_2 \mid i = 1, \ldots, n\right\}$$

Source: Tzeng; Huang, 2011.

After calculating the NIP and PIP, the distance between the elements of the decision matrix and the ideal solutions is measured, as shown in Equation (3).

Equation (3): Distance between the elements of the decision matrix and the ideal solutions

$$D_j^+ = \sqrt{\sum_{i=1}^{m}\left[N_{ij}(v) - N_i^+(v)\right]^2}, j=1,2,\ldots,n$$
$$D_j^- = \sqrt{\sum_{i=1}^{m}\left[N_{ij}(v) - N_i^-(v)\right]^2}, j=1,2,\ldots,n$$

Source: Tzeng; Huang, 2011.

As the final step, the closeness coefficient (CCj) is calculated for each alternative, as shown in Equation (4).

Equation (4): Closeness Coefficient (CCj) for each alternative

$$CA_j = \frac{D_j^-}{D_j^+ + D_j^-}$$

Source: Tzeng; Huang, 2011.

9. RESULTS

This section presents the results of this study, including the matrices generated by the pairwise comparisons of the AHP methodand the tables produced by the TOPSIS method.

The calculation of weights for criteria and sub-criteria in the AHP reveals that the classical approach does not impose restrictions on the multiplication of the pairwise comparison matrix of criteria by the pairwise matrices of sub-criteria. As a result, information tends to spread across all base matrices used for computing the respective weights. However, the residuals from these multiplications introduce biases in the final weights, reflecting inter-criterion influences. In the context of the problem addressed in this study, each alternative (plant) has sufficiently distinct applications across the adopted criteria (dimensions), namely, environmental, economic, social, and technical aspects. Therefore, one of the specific objectives of the proposed methodology is to generate criterion-specific (dimension-specific) weights that are linearly independent. This enables the selection of an alternative (plant) to be evaluated in terms of the importance of each individual criterion, without the results being affected by inter-criterion influence. Achieving this configuration requires an appropriately adjusted mathematical modeling, as detailed below.

The selected evaluation criteria were environmental, economic, social, and technical. A total of 20 sub-criteria were assessed, including occupancy characteristics, potential environmental benefit, current pollutant emissions, potential for pollutant mitigation, environmental constraints, operational cost, initial investment, market characteristics, output production value, subsidies, community expectations, community characteristics, public policies, job creation, social impacts, organic waste production, available technology, output production potential, composition of produced biogas, and water demand for production.

According to the hierarchical model proposed in this study, there are three plants evaluated based on four criteria, each composed of five sub-criteria. These sub-criteria must be compared relative to each other by an expert and also evaluated by decision-makers. This results in a total of 60 sub-criteria to be compared, applying a 1 to 9 scale to assess their relative importance.

In this scenario, we have a matrix M (Figure 4) with dimensions 60 × 60, totaling 3600 comparisons to be calculated by the volunteer expert. Considering that AHP defines the cells opposite the main diagonal of this matrix as the inverse of the value (1/vi), the number of required comparisons is reduced to 1200.

Figura 15: Matrix M model..

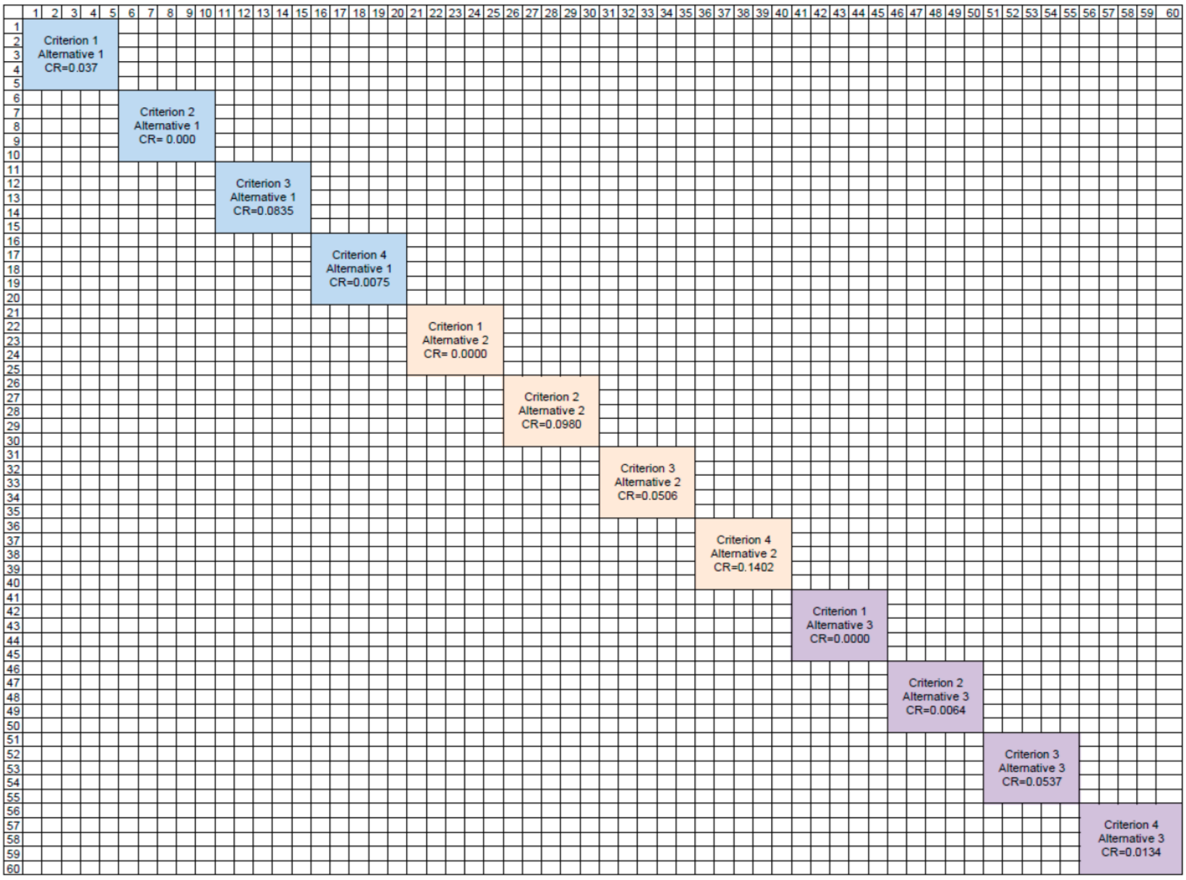
$$M = \begin{bmatrix} 1 & \cdots & v_n \\ \vdots & \ddots & \vdots \\ \frac{1}{v_n} & \cdots & 1 \end{bmatrix}$$

Source: Authors, 2025.

At this point, it is important to highlight the characteristics of the sub-criteria adopted from Yamaji et al. (2024), which follow the hierarchical structure illustrated in Table 3. The concept introduced by Saaty (1987) implies that comparisons are made only among sub-criteria within the same criterion and belonging to the same plant.

This approach creates a filtering effect on the data, meaning that only a series of 12 sub-matrices with dimensions of 5 × 5, aligned along the main diagonal of the original matrix M, are actually subject to the pairwise comparison process by the expert. As a result, the workload is reduced to 402 direct comparisons, as shown in Figure 16.

Figure 16: Schematic representation for calculating sub-matrices for pairwise 402 comparison and their respective consistency ratios. For reference, acceptable values remain around 0.10. The blue color represents the pyrolysis conversion route, the orange color represents the covered lagoon biodigester and the purple color represents the CSTR biodigester.



Source: Authors, 2025.

Each of these 12 sub-matrices with 5 × 5 dimensions represents the pairwise comparison of one criterion within a specific plant. The next step requires normalizing the internal values of these 12 sub-matrices (by dividing each value vi by the sum of the respective column of the sub-matrix).

Finally, by multiplying each original sub-matrix (row) by its normalized version (column), a sequence of 12 vectors (with 5 dimensions) is generated. These vectors are then organized into groups by criterion (across different plants), concluding with the calculation of an average vector for each criterion, which is also normalized to form the final weights of each sub-criterion (and its respective hierarchical criterion) Table 5.

Table 5: Normalized weights of environmental, economic, social, and technical criteria.

Environmental Criterion Weight (ENV)	Economic Criterion Weight (ECO)	Social Criterion Weight (SOC)	Technical Criterion Weight (TEC)
0.039167	0.042194	0.041510	0.031618
0.060665	0.037305	0.033330	0.040068
0.039882	0.051905	0.049464	0.059879
0.060665	0.051905	0.056367	0.058660
0.060665	0.073110	0.069676	0.041965

Source: Authors, 2025.

The next step involved the evaluation by municipal managers, consultants, project supervisors, and researchers in the biogas sector from a medium-sized municipality in the state of Paraná. They assessed the criteria and sub-criteria presented in Table 1, rating each sub-criterion as either highly advantageous or highly disadvantageous for each conversion route alternative: pyrolysis, covered lagoon biodigester, and CSTR biodigester.

After collecting the participants' ratings, the average score for each sub-criterion was calculated, defining whether it represented a cost or benefit function, and organizing the averages by conversion route (pyrolysis, covered lagoon biodigester, and CSTR biodigester). It is important to note that sub-criterion TEC11, which assesses water demand for production, is not applicable to the pyrolysis conversion route. To avoid errors in the model's calculations, a value of 0.01 was assigned to this cell (Table 4).

Table 6: Average scores by conversion route, sub-criteria weights, and cost or benefit function.

	Cost or Benefit Function	Weights	Pyrolysis	Covered Lagoon	CSTR
ENV01—Territorial Occupancy Characteristics	Higher, Better	0.03917	7.25	7.75	4.25

ENV02—Potential Environmental Benefits	Higher, Better	0.60665	7.25	8.25	6.5
ENV03—Current Pollutant Emissions	Higher, Better	0.03988	6.75	7.5	5
ENV04—Potential for Pollutant Emission Mitigation	Lower, Better	0.06067	7	8.5	5.75
ENV06—Environmental Constraints	Higher, Better	0.06067	6.25	7.75	5.75
ECO01—Operational Cost	Lower, Better	0.04219	6	5.25	7.25
ECO02—Initial Investment	Lower, Better	0.03731	6.25	6.25	7.5
ECO03—Market Characteristics	Lower, Better	0.05191	5.25	7.75	5.75
ECO06—Output Production Value	Higher, Better	0.05191	5.75	7.75	5.5
ECO09—Subsidies	Higher, Better	0.07311	6.5	6.25	6.75
SOC01-Community Expectations	Higher, Better	0.04151	6.5	7	6.25
SOC02-Community Characteristics	Higher, Better	0.03333	6.75	7.5	5.75
SOC03-Public Policies	Higher, Better	0.04946	6.75	8	6.5
SOC04-Job Creation	Higher, Better	0.05637	7	8.5	6.25
SOC05-Social Impacts	Higher, Better	0.06968	7.5	8.25	6.75
TEC02-Organic Waste Production	Higher, Better	0.03162	8.25	8.25	6
TEC03-Available Technology	Higher, Better	0.04007	6.75	7.75	6.75
TEC04-Output Production Potential	Higher, Better	0.05988	8.5	9.25	5.5
TEC08-Composition of Produced Biogas	Higher, Better	0.05866	7.25	8.75	6
TEC11-Water Demand for Production	Higher, Better	0.04197	0.01	6.5	8.25

Source: Authors, 2025.

The next step was to calculate the normalized and weighted decision matrix (Nij), as presented in Equation (1). The values of rij, vij, and Nij were computed for the matrix calculation, as shown in table 7.

Table 7: Cost and benefit calculation, vij of each alternative, rij, and vij.

Cost or Benefit Directly and Inversely Proportional v_{ij}			**r_{ij}**			**N_{ij}**		
Pyrolysis	**Covered Lagoon**	**CSTR**	**Pyrolysis**	**Covered Lagoon**	**CSTR**	**Pyrolysis**	**Covered Lagoon**	**CSTR**
0.93548	1.00000	0.54839	0.63419	0.67793	0.37177	0.02484	0.02655	0.01456
0.87879	1.00000	0.78788	0.56808	0.64644	0.50931	0.34463	0.39216	0.30898
0.74074	0.66667	1.00000	0.52468	0.47221	0.70832	0.02093	0.01883	0.02825
0.82353	1.00000	0.67647	0.56350	0.68426	0.46288	0.03419	0.04151	0.02808
0.92000	0.74194	1.00000	0.59425	0.47923	0.64592	0.03605	0.02907	0.03918
0.87500	1.00000	0.72414	0.57822	0.66082	0.47852	0.02440	0.02788	0.02019
1.00000	1.00000	0.83333	0.60921	0.60921	0.50767	0.02273	0.02273	0.01894
0.67742	1.00000	0.74194	0.47789	0.70546	0.52340	0.02480	0.03662	0.02717
0.74194	1.00000	0.70968	0.51767	0.69773	0.49516	0.02687	0.03622	0.02570
0.96296	0.92593	1.00000	0.57707	0.55487	0.59926	0.04219	0.04057	0.04381
0.92857	1.00000	0.89286	0.56940	0.61320	0.54750	0.02364	0.02545	0.02273
0.90000	1.00000	0.76667	0.58122	0.64580	0.49511	0.01937	0.02152	0.01650
0.84375	1.00000	0.81250	0.54784	0.64929	0.52755	0.02710	0.03212	0.02609
0.82353	1.00000	0.73529	0.55286	0.67133	0.49362	0.03116	0.03784	0.02782
0.90909	1.00000	0.81818	0.57544	0.63298	0.51789	0.04009	0.04410	0.03608
1.00000	1.00000	0.72727	0.62883	0.62883	0.45733	0.01988	0.01988	0.01446
0.87097	1.00000	0.87097	0.54897	0.63029	0.54897	0.02200	0.02525	0.02200
0.91892	1.00000	0.59459	0.61982	0.67451	0.40106	0.03711	0.04039	0.02402
0.82857	1.00000	0.68571	0.56420	0.68093	0.46692	0.03310	0.03994	0.02739
1.00000	0.00154	0.00121	1.00000	0.00154	0.00121	0.04196	0.00006	0.00005

Source: Authors, 2025.

After completing these calculations, Equation (2) was used to calculate the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS), and Equation (3) was applied to measure the distance between the elements of the decision matrix and the ideal solutions (Table 8 and Table 9).

Table 8: Calculation of the positive ideal solution (PIS) and negative ideal solution (NIS).

Sub-Criteria	PIS	NIS
ENV01—Territorial Occupation Characteristics	0.02655	0.01456
ENV02—Potential Environmental Benefits	0.39216	0.30898
ENV03—Current Pollutant Emissions	0.02825	0.01883
ENV04—Potential for Pollutant Emission Mitigation	0.04151	0.02808
ENV06—Environmental Constraints	0.03918	0.02907
ECO01—Operational Cost	0.02788	0.02019
ECO02—Initial Investment	0.02273	0.01894
ECO03—Market Characteristics	0.03662	0.02480
ECO06—Output Production Value	0.03622	0.02570
ECO09—Subsidies	0.04381	0.04057
SOC01—Community Expectations	0.02545	0.02273
SOC02—Community Characteristics	0.02152	0.01650
SOC03—Public Policies	0.03212	0.02609
SOC04—Job Creation	0.03784	0.02782
SOC05—Social Impacts	0.04410	0.03608
TEC02—Organic Waste Production	0.01988	0.01446
TEC03—Available Technology	0.02525	0.02200
TEC04—Output Production Potential	0.04039	0.02402
TEC08—Composition of Produced Biogas	0.03994	0.02739
TEC11—Water Demand for Production	0.04196	0.00005

Source: Authors, 2025.

Table 9: Distance between the decision matrix elements and the ideal solutions.

Pyrolysis	Covered Lagoon	CSTR	Pyrolysis	Covered Lagoon	CSTR
	D+			D−	
0.0528	**0.0442**	**0.0999**	**0.0594**	**0.0909**	**0.0144**

Source: Authors, 2025.

After calculating the positive and negative ideal points, the distance between the elements of the decision matrix and the ideal solutions was computed, as presented in Equation (3). The values obtained from this calculation are shown below:

To classify and rank the most advantageous conversion route, the closeness coefficient (CC) was calculated for each alternative according to Equation (4). The most advantageous alternative ranked (Table 10) first is the covered lagoon biodigester, followed by pyrolysis in second place, and the CSTR biodigester in third place.

Table 10: Result of the most advantageous alternative.

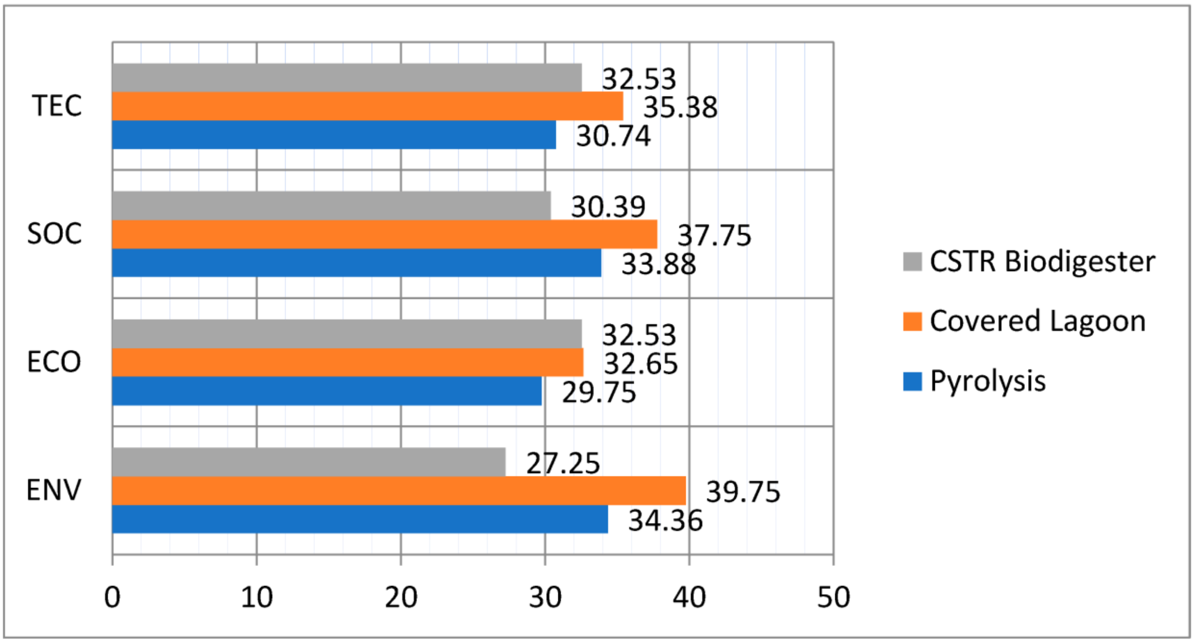
RESULT		
Pyrolysis	**Covered Lagoon**	**CSTR**
0.52970	0.67269	0.12593
2	**1**	**3**

Source: Authors, 2025.

Among the evaluated criteria, the environmental criterion received the highest score of 100.35, followed by the social criterion with 100.33. The technical criterion ranked third with 97.04, and the economic criterion ranked last with a total of 91.28.

The ranking of the criteria based on the decision-makers' evaluation is presented in Graph 7:

Graph 7: Ranking of criteria by alternatives.



Source: Authors, 2025.

Covered Lagoon Biodigester: environmental, social, technical, and economic.

Pyrolysis: environmental, social, technical, and economic.

CSTR Biodigester: technical, economic, social and environmental.

By evaluating the criteria and sub-criteria individually and analyzing the scores given by each decision-maker, it is noted that in the ranking of criteria, the environmental and social dimensions received very similar scores, followed by the technical criterion, with the economic criterion ranking last. For the covered lagoon alternative, the environmental and technical criteria stood out.

By evaluating each sub-criterion individually and aggregating the scores provided by each decision-maker, Table 11 was generated.

Table 11: Scores sub-criterion.

Sub-Criteria	**Scores**
SOC05 Social Impacts	29.96
ECO09 Subsidies	27.47
TEC04 Output Production Potential	26.69
ENV02 Potential Environmental Benefits	25.55
ENV04 Potential for Pollutant Emission Mitigation	24.68
TEC08 Composition of Produced Biogas	24.53
SOC04 Job Creation	23.52
ENV06 Environmental Constraints	22.81
SOC03 Public Policies	20.23
ECO06 Output Production Value	19.26
ECO03 Market Characteristics	18.97
TEC11 Water Demand for Production	17.65
TEC03 Available Technology	16.18
SOC01 Community Expectations	15.69
ECO01 Operational Cost	14.92
ENV03 Current Pollutant Emissions	14.49
ECO02 Initial Investment	14.30
ENV01Territorial Occupation Characteristics	13.83
TEC02 Organic Waste Production	13.60
SOC02 Community Characteristics	12.63

Source: Authors, 2025.

Among the five highest-rated sub-criteria, we have:

SOC05—Social Impacts: expected impacts on the community, such as improvements in public health, quality of life, decent work, and the promotion of the local economy;

ECO09—Subsidies: tax or credit incentives granted by the government for the project;

TEC04—Output Production Potential: estimated quantity of output production;

ENV02—Potential Environmental Benefits: environmental benefits anticipated by the project, such as increased use of biofertilizers, waste reinserted into the economic chain, and impact on global warming;

ENV04—Potential for Pollutant Emission Mitigation: the amount of pollutant emissions avoided through the implementation of the project.

These analyses can support public managers during the research and implementation phases of a biogas and biofuel plant, providing guidance on the most relevant criteria and sub-criteria to consider during the initial stages of planning, construction, and site selection.

10. DISCUSSION

The promotion of renewable energy will assist Brazil in meeting its established targets for reducing greenhouse gas emissions—up to 37% by 2025 and 43% by 2030—thus contributing to the national goals under the Paris Agreement. The sustainable development of the biogas value chain requires the support of key stakeholders and decision-makers in the energy sector to identify growth opportunities, technological improvements, and policy measures aimed at stabilizing the sector and addressing the various bottlenecks highlighted in this study. These include the need for the approval of specific policies and regulations, broader dissemination of data on biogas production potential, the presence of qualified companies in the sector, greater clarity on financing mechanisms, increased development of R&D projects, and the creation of viable business models for the segment, among others.

Opportunities already identified should be seized, such as the expansion of vocational training programs, stronger collaboration between universities and companies in the sanitation sector, the development of intermunicipal consortia, the decentralization of municipal energy supply, and increased competitiveness in the sanitation sector. The results of this study aim to support public managers in implementing new biofuel conversion projects by guiding them on the most relevant criteria for selecting among the available routes, namely: pyrolysis, covered lagoon biodigester, and CSTR biodigester.

Among the proposed alternatives for biogas and biofuel conversion, the covered lagoon biodigester was identified as the most advantageous option, followed by pyrolysis, and lastly, the CSTR biodigester. This outcome may be attributed to the fact that this type of biodigester is the most commonly used for biogas production in Brazil and involves less technical complexity compared to the CSTR model.

The covered lagoon biodigester model is the most commonly used system. It features a low technological level and is easy to construct and operate. Due to its simplicity, it is widely employed in rural properties and agro-industrial facilities, and it can process a variety of substrates, such as waste from animal slaughterhouses, starch production, and swine farming [27]. This type of biodigester is characterized by a masonry base, a gas holder made of flexible PVC membrane, and a plastic tarp lining in its fermentation chamber, which, due to its larger surface area exposed to the sun, increases biogas generation on hot days. The model can be applied in both small and large-scale properties, as well as agro-industrial projects. It is the most widespread model in Brazil. Its horizontal construction and suitability for shallow soils reduce the risk of groundwater contamination. This model has a medium level of construction complexity and is easy to operate. It is economically viable, with low initial investment, maintenance costs, and payback period compared to other models [28].

Based on the criteria established and the feedback from respondents regarding the conversion routes that come closest to the ideal solution, the environmental criterion was ranked as the most important, followed by social, technical, and, finally, economic. This reveals that when considering biogas and biofuel generation, many decision-makers initially focus on the environmental and social benefits of the project. Although the implementation of biogas and biofuel plants typically begins with technical and economic assessments, this analysis indicates that environmental and social criteria should take precedence in the decision-making process.

11. CONCLUSIONS

This study aimed to apply a multicriteria decision-making model in a medium-sized city in the state of Paraná, with the objective of assisting public decision-makers in choosing among the conversion routes pyrolysis, covered lagoon biodigester, and CSTR biodigester for the production of biogas and biofuels, based on an analysis of environmental, social, economic, and technical criteria. These criteria and alternatives were evaluated using the multicriteria methods AHP and TOPSIS.

The contribution of this study lies in guiding and supporting municipal public managers in selecting the covered lagoon biodigester as the most advantageous conversion route in a scenario similar to the one analyzed (a medium-sized municipality). Regarding the evaluated criteria, it was observed that environmental and social criteria received higher scores than the technical and economic ones. Concerning the sub-criteria, the authors ranked the scores individually assigned by decision-makers, which can assist in determining which sub-criteria should be prioritized in public management analyses.

In light of the theoretical foundation, this study presented the AHP (Analytic Hierarchy Process) calculations, including the decision hierarchy, pairwise sub-matrices, and normalized weights by criterion. With the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method, average scores from decision-makers for each conversion route were used to calculate sub-criteria weights, cost and benefit functions, the normalized and weighted decision matrix, positive and negative ideal points, distances between matrix elements and ideal solutions, and the closeness coefficient. Based on the multicriteria decision-making calculations, the most advantageous alternative was biogas and biofuel generation using the covered lagoon biodigester, followed by pyrolysis in second place and the CSTR biodigester in third.

This study presents some limitations. One is the adjustment required for criterion TEC11, which addresses water demand for production; since the pyrolysis route does not use water, a placeholder value of 0.01 was assigned to enable model calculations. Another limitation is that if any criteria or sub-criteria suggested in this study are modified, it is necessary to recalculate the AHP weights and rerun the TOPSIS method to determine the most advantageous conversion route.

For future research, conducting a comparative analysis of other MCDA methods is recommended, such as the application of AHP throughout the entire process, and comparisons among methods, such as Fuzzy ARAS, CODAS, COPRAS, EDAS, and OCRA. Further investigation should include sensitivity and stability analyses of the proposed approach in different applications and with larger datasets. This model can also serve as a guideline for the implementation of biogas and biofuel plants by carefully measuring and analyzing each criterion and sub-criterion using the covered lagoon biodigester as the conversion route, and assessing the universality and adaptability of this conversion route in diverse contexts. In a second phase, a comparative analysis among the three conversion routes can be conducted, evaluating indicators and limitations, provided they are located in the same region and use the same biomass inputs.

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