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MULTICRITERIA DECISION-MAKING IN BIOGAS PROJECTS

Londrina

2023

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Londrina
2023

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Londrina, February 27, 2024.

Multicriteria Decision-Making in Biogas Projects

Abstract:

Decision making in biogas production projects from organic waste involves considerate a variety of criteria and that may vary according to the priority and need of the decision maker. Given this context, the present study aims to propose multicriteria decision-making models for evaluating biogas production from organic waste projects, divided into two articles: the first is an integrative review of the international scientific literature and the second is a proposition of six models for decision making according to the stage of the biogas cycle. A total of 58 articles were utilized, from which 497 decision-making criteria were identified. These criteria were classified into 39 sub-criteria grouped under four main categories: economic, environmental, social, and technical. The results suggest that there is a predominance of technical and economic criteria in decision making in biogas. In the second article, based on the systematization of data in the integrative literature review carried out in the first article, it was possible to identify which criteria are most used for each phase of the biogas cycle. Through this cross-analysis, six distinct multi-criteria decision-making models were proposed, one for each project phase: site selection, biodigester type, project initiation, project cycle, initial phase, and final phase. These models strive to achieve a balance among the environmental, social, economic, and technical aspects by equalizing the number of sub-criteria within each aspect.

Keywords: Biogas; Indicators; Multicriteria decision making; Integrative literature review; MDCA.

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1 INTRODUCTION

The use of biogas as a renewable energy source has garnered considerable attention in recent times due to its potential to address various environmental, energy, and waste management challenges. The production of biogas from organic waste introduces a complex decision-making process that involves the careful consideration of diverse criteria, which can vary in importance according to the preferences and necessities of decision-makers. Considering the complexity of this decision context, this dissertation undertakes the task of formulating multicriteria decision-making models to evaluate biogas production from organic waste projects. This exploration is divided into two distinct articles, each with a unique focus and purpose but linked by the main topic and contribution.

The first article's objective is to analyze, through an integrative bibliographic review, the indicators considered in a decision-making process for the evaluation of biogas production projects from organic waste to present relations. Building upon the insights garnered from the integrative literature review, the second article has the objective to construct specific multi-criteria decision-making models for each phase of evaluating biogas production projects from organic waste. It delves into the proposition of six distinct multicriteria decision-making models. These models correspond with the six phases of the biogas production cycle: localization, biodigester type, project, cycle, initial phase, and final phase.

The following sections of the paper are organized as follows: Articles 1 and 2, each containing their own abstract, introduction, theoretical framework, methodological procedures, results, discussion, and concluding remarks. Subsequently, final considerations about all the research are provided.

2 ARTICLE 1

Decision-Making in Biogas Production Projects: Paradigms and Prospection

Abstract: The decision to implement a biogas production project involves the evaluation of multiple variables, such as the problem to be solved, the biodigester, business model, investment, and final products. An integrative literature review was carried out, in which 58 articles were obtained and relevant criteria for decision-making in biogas production projects from organic waste were identified. Three stages were considered in the analysis of the biogas production cycle: initial, plant, and final, as well as the economic, environmental, and social aspects that influence the decision. In general, the publications are dispersed over 30 different journals. The methodology used in most studies is empirical, quantitative, and descriptive, with data collected mainly from secondary sources. From the studies, 499 original criteria were identified, which were classified into one of four categories: economic, environmental, social, and technical, which cover a total of 39 sub-criteria. Economic and technical criteria were the most frequent in publications, while environmental and social criteria were less common and less prioritized. This suggests that there is a tendency to prioritize economic and technical dimensions over environmental and social dimensions in the analysis of the articles found. Finally, a preliminary decision-making model based on the findings is proposed.

Keywords: biogas; indicators; dimensions of sustainability; multicriteria decision-making; integrative literature review.

2.1 INTRODUCTION

The world's waste production is 2.5 billion tons per year, and about a third of it does not have a treaty or an environmentally safe destination, especially in low-income countries [1; 2]. In 2016, waste disposed in open-air landfills released more than 1.5 billion tons of carbon dioxide into the atmosphere, in addition to posing a risk to the health of people who work and live near these sites [2].

Despite this, of the total waste produced by humans, most (44%) corresponds to organic waste, which can be reused in different ways, such as composting or biogas production, for example [1;2]. In addition, it is estimated that world production will increase to 3.4 billion tons and carbon dioxide emissions to 2.6 billion tons per year by 2050 [3].

In this sense, in Brazil, in August 2010, Law 12,305 was enacted, which establishes the National Solid Waste Policy (NSWP). This regulation provides for the principles and objectives of waste management for the country, considering sustainable development, systemic waste management, and the promotion of good working conditions and income for waste collectors, to which Brazilian municipalities must adapt. In addition to Brazil, other countries have also sought to regulate the management of urban solid waste and the production of biogas from these materials [4].

In the European Union, for example, the 2008/98/EC directive established a hierarchy in waste management, prioritizing prevention, reuse, recycling, and energy recovery, the latter being an alternative for the treatment of waste that could not be valued in another form. Already in Germany and Sweden, public policies have encouraged biogas production from organic waste with the construction of biogas centers and incentive actions for selective collection and waste separation [5,6]. These initiatives have contributed to the reduction of greenhouse gas emissions, renewable energy generation, and waste use as a resource [7].

Biogas produced from urban or rural solid waste is a potential alternative for natural gas replacement, which is a fossil and non-renewable fuel. This discussion has been raised these days, especially in the international scenario, due to the natural gas crisis caused by the Russian invasion of Ukraine in early 2022, which caused instability and uncertainty in the market for this product, whose main supplier to Europe is Russia. The continent has prepared for a winter where there is a possibility of energy shortages, especially for domestic heating [8].

In view of this context, it is understood that biogas is a potential solution to be considered as an alternative to at least four categories of problems: sanitation, carbon emission, energy, and public management. The reuse of organic waste provides an ad-equate and environmentally advantageous destination for garbage while reinserting it in the production chain. Regarding energy problems, there is the dependence on the electricity of hydroelectric dams and fossil fuels, both oil and natural gas, for use in cars. Regarding carbon emissions, biogas production is a way to generate carbon cred-its, that is, to compensate activities that release greenhouse gases into the atmosphere.

Biogas production also allows the transition to the circular economy, the third and last stage of the evolution of economic cycle models, which, at first, is linear, that is, resources from nature are transformed, marketed, consumed, and waste is removed from nature and discarded. Then, the savings of recycling, where part of the waste is reused, are finally circular, when, in addition to recycling part of the materials in new productive cycles, all waste will be reinserted in the economy, that is, reused and monetized [9,10].

In addition, the incorporation of organic waste reuse for biogas production con-tributes to the progression of municipalities to current conceptions such as Smart Cities, which represents a concept of city that values and mobilizes its resources and active in an optimized way [11].

Considering these aspects, it is understood that deciding whether to pursue or not a biogas project involves several variables, from the problem that we seek to solve, the cost of the project, the business model, and the financing of the enterprise, to the final products of biogas production, which can be sold or used in the production cycle itself.

Such a project can work on several fronts, including the pursuit of Sustainable Development Goals (SDGs), such as improving the current condition of SDG 7: clean and accessible energy; SDG 8: decent work and economic growth; SDG 9: industry, in-novation, and infrastructure; SDG 11: sustainable cities and communities; SDG 13: action against global climate change; and SDG 17: partnerships and means of implementation [12].

More than merely representing a trace of innovation and modernity, this type of project allows, at one time, an intelligent local productive arrangement integrated with social aspirations for greater efficiency in public administration and care for the environment.

In this context, the research problem is: What are the criteria considered in a decision-making process for the evaluation of biogas production projects from organic waste? Given the complexity and relevance of this theme, this study aims to analyze, through an integrative bibliographic review, the indicators considered in a decision-making process for the evaluation of biogas production projects from organic waste to present relations.

Among the variables analyzed are study focus, indicators, dimensions of sus-tainability, year of publication, and country of publication. To this end, the following specific objectives were listed: i) review the scientific literature related to biogas and decision-making; ii) identify criteria pertinent to decision-making in biogas projects.

Given this scenario, this research aims to fill the scientific knowledge gap of pro-duction in decision-making models in biogas projects considering the following aspects: social (work and waste management, impact on citizens), environmental (waste disposal, environmental impact), economic and financial (investment, maintenance, return), technical (preparation of waste for biodigestion, waste digestion method, necessary and available technology), public management (project, operation model, public budget), and logistics (distance between waste and plant collection, transportation cost).

The practical justification of this study is due to its contribution around biogas projects. The evaluation model can be applied in different municipalities, public managers and other professionals can take advantage of the proposed model and adapt it according to the priorities and conditions sought (techniques, amount of waste, and budget) that exist in their reality.

2.2 Decision Making in Biogas Production

The first experiences with biogas for energy use took place in China and India, where food remains and other wastes were used in the early twentieth century. At this time, the main objective was the reduction of sludge in urban centers; however, after the oil crisis in the 1970s, biogas became a promising alternative to replace this fossil fuel that is limited in nature, besides the decreased gases that cause the greenhouse effect from its burning [13].

In recent decades, there has been an increase in the production of urban solid waste (MSW), which, in addition to taking up space in landfills, has contaminating potential for soil and water and releases greenhouse gases in its decomposition process. About half of solid urban waste (MSW) is composed of organic matter, i.e., the remains of food and animal waste, or biomass, which can be reused in a biogas plant and transformed into energy and biofertilizers [2,14]. The debate regarding sustainability was present during COP 26 on the objectives of containing global warming, stopping deforestation, and encouraging technology and innovation, in which Brazil pledged to zero the emission of methane by 2030 [15].

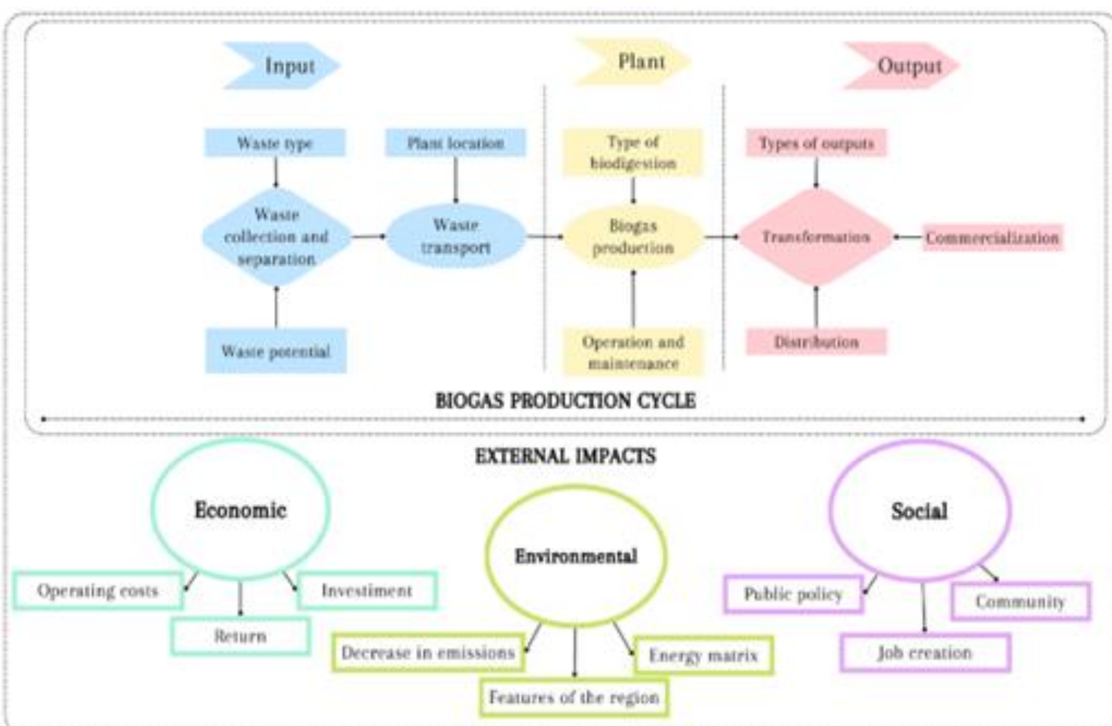
In the context of decarbonization and the improvement of weather conditions, one of the alternatives to contribute to this goal is biogas. Brazil has the potential to explore various alternative energy matrices to hydroelectric, such as wind, solar, and biomass. However, currently about 75% of electricity in the country is produced by hydroelectric plants, a system that has weaknesses as it depends on the volume of water available in reservoirs, which in turn are subject to rain conditions that have changed over the past decades, generating uncertainties in national energy security [13].

Biogas also contributes to the transition from the linear to the circular economy as it transforms environmental liabilities into energy assets, that is, it reinserts the waste that would be the end of the economic chain in the production cycle by monetizing their reuse products. A treatment plant transforms environmental passive MSW into energy assets such as biomethane, vehicular compressed natural gas (CNG), electric or thermal energy, biomethane and biofertilizers [1,14]. Regarding the inputs of the plants, it is known that the substrates used for biogas production are divided into 3 classes according to their origin: agriculture, industry, landfills, and sewage treatment stations.

In Brazil, the main source of substrate used for biogas production in biodigestion systems is agriculture, which represents 79% of plants in operation in the country. On the other hand, their contribution to the total volume of biogas is only 11%. Already, plants that process urban solid waste or effluent from sewage treatment stations rep-resent 9% of plants in operation but account for 73% of the biogas produced in the country [13].

Therefore, to decide on the feasibility of a biogas project, several aspects related to its conception, construction, operation, and maintenance must be considered, as well as the benefits and conveniences arising from such a venture. Figure 1, exposed below, presents decision points in the production of biogas.

Figure 1. Decision points in the production of biogas



Source: the author, 2023.

Three steps inherent to the biogas production cycle are listed: initial, plant, and end. The initial stage occurs before the waste reaches the biogas plant, i.e., the very production of the waste, its collection, separation, and transport to the plant. At this stage decision points are linked to the quantity and type of waste produced by suppliers, whether citizens, sanitary companies, or rural properties. Already in the plant the production of biogas in a biodigester occurs, which depends on the type of technology chosen and is appropriate for the design, costs, and labor needed to operate and maintain this plant during its useful life. In the final stage, plant exits are produced, which depend on the interest of the project, such as electricity, biofertilizer, or vehicle gas, which can be monetized or not [13,14].

In addition to the biogas production cycle, the external impacts that influence the weighting of such a project are presented, which are divided into three areas: economic, environmental, and social. Among the economic decision points are the value of the initial investment, the return on investment, and the cost of operation of the plant. The environmental sphere contains the impacts arising from the decrease in carbon emissions in the atmosphere, energy matrix exchange, and analysis regarding the adequacy of the region to receive a biogas plant. Lastly, it concerns the social decision points related to the jobs generated by the plant, the impact on the local community, and the existence or absence of public policies and government incentives for biogas enterprises [14].

2.3 Materials and Methods

In this study, itis performed an integrative review of the literature. The objective of this type of review is the integration of empirical or theoretical literature to provide a broader understanding of a particular phenomenon by integrating opinions, concepts, or ideas from research and, as a result, presenting the consolidation of research constructs and design as well as scientific gaps for developing future studies [17]. The procedures followed four research steps: data collection, classification development, classifications, and results analysis, as shown below.

2.3.1 Step 1

Searching the web of science database, 161 articles were found using the keywords "biogas" and "decision making" with full text open for viewing. Then all articles were downloaded in PDF format and listed according to the order presented on the platform, whose criterion was of the highest relevance.

Two articles were discarded for being in a foreign language other than English or Portuguese. After reading the summaries of the other 159 articles, those that had no adherence to the theme of this research were discarded, such as decision-making articles on other topics or research on biogas in which there was no decision-making, for example, leaving the remaining 58 articles.

Subsequently, we tabulated the information regarding thirteen characteristics of the articles according to three areas: publication, focus and methodology. In publica-tion was collected the year of publication, journal, genre of the authors, and country of study. About the focus: objective, part of the cycle, and type of waste. In methodology: nature, approach, purpose, data collection (primary data is data obtained directly by researchers for the article in question and secondary data is obtained by researchers from databases, public or private documents issued for a primary purpose other than research), and data analysis method, as well as the keywords of each of the articles. In another spreadsheet, the criteria used by the researchers in their work to analyze deci-sions in biogas were tabulated.

2.3.2 Step 2

A classification system was developed with logically structured coding from the data collected from the articles. For the categorization of the "objective" variables, the principles of content analysis methodology were used [16]. The classification of articles is presented in Tables 1 (publication and methodology) and 2 (focus). The focus characteristics were classified by collecting the original objectives in a separated spreadsheet and grouped with other objectives based on the similarities between them.

Then, the name of the objective classification was decided in such a way that it covered all the common objectives of that group and, at the same time, made explicit the main characteristic of that objective and how it differs from the others. For example: the objectives “decide which is the best alternative (AD biogas plant) from technical, environmental, and economic perspectives” and “determine the most suitable sites for locating biogas plants using dairy manure as feedstock, specifically in the Entre-Douro-e-Minho Region in Portugal" were both classified as "Assist in decision making in biogas".

For the criteria and subcriteria classification, presented in Tables 3 (environmental and economic) and 4 (social and technical), the originals criteria identified in the articles were collected in a separated spreadsheet and then classified according to similarities between the other articles criteria's. After this grouping, the names of the classifications were chosen. In one article, for example, one of the criteria was "Land area required" and in the other "Biogas plant size", both were classified as "TEC06 - Available Area for the Plant". This process was repeated for all article's original criteria.

2.3.3 Step 3

In this phase, the classification system is applied to the selected articles to provide structure to the existing knowledge on the theme studied and, later, to present a scien-tific production profile and the main results of the analyzed articles.

2.3.4 Step 4

At this stage, the analysis of the results is performed, starting with the general panorama of publications, the verification of the characteristics of the articles, the subscribers for decision-making in biogas and the crossing between these data. The re-sults obtained are discussed in greater depth, and it is possible to identify the research gaps, opportunities, and challenges for future studies. Also, a preliminary deci-sion-making model is proposed based on the research findings.

Table 1. Classification and description of publications and methodologies.

Part of the review	Topic	Code	Alternative
Publication	Journal	Sustainability	
		Energies	
		Applied energy	
		Biomass and Bioenergy	
		Energy, Sustainability and Society	
		Environmental & Climate Technologies	
		Journal of cleaner production	
		Renewable Energy	
		Waste Management	
		Water	
		Outros	
	Country	Germany	
		England	
		China	
		Finland	
		U.S	
		Sweden	
		Ukraine	
		Africa	
		Brazil	
		India	
		Poland	
		Others	
Metodology	Nature	Empirical	
		Theoretical	
	Approach	Quantitative	
		Qualitative	
	Purpose	Descriptive	
		Exploratory	
	Data collect	Primary	
		Secondary	
	Data analysis	ANA01	Multi-Criteria Decision Analysis (MCDA)
		ANA02	Descriptive statistics
		ANA03	Mathematical model
		ANA04	Life-Cycle Assesment (LCA)
		ANA05	Geographic Information System (GIS)
		ANA06	Anaerobic Digess Model (ADM1)
		ANA07	Inferential Statistics
		ANA08	Others

Source: the author, 2023.

Table 2. Classification and description of objectives, waste types and part of the cycle

Topic	**Code**	**Alternative**	**Description**
Objective	OBJ01	Assist in decision making in biogas	Articles focus on raising characteristics, quantitative or qualitative that assist in decision making related to biogas production
	OBJ02	Identify perspectives in biogas production	Articles focus on identifying possibilities related to biogas production, either in the expansion of the existing network or verification of investment opportunities.
	OBJ03	Explore energy arrays and/or disposal of alternative waste	Articles focus on exploiting relevant aspects for decision making regarding alternative energy production, such as biogas, solar or wind, for example.
	OBJ04	Measure efficiency of biogas production	Articles focus on quantifying biogas production from different perspectives, such as measuring the presence of microorganisms or certain chemical compounds and potential for transforming biogas into energy.
	OBJ05	Develop an MCDA in biogas	Articles focus on the development of an MCDA model for biogas production.
	OBJ06	Compare biogas production systems	Articles focus on comparing the productivity of different types of waste or biodigestion technologies.

Residue type	RES01	Organic waste	**Topic**	**Code**	**Alternative**
	RES02	Animal manure	**Part of the cycle**	POC01	Cycle
	RES03	Residual waters		POC02	Final
	RES04	Food remains		POC03	Projct
	RES05	Manure and organic waste		POC04	Initial
	RES06	Several		POC05	Localization
	RES07	Not applicable		POC06	Biodigester type

Source: the author, 2023.

Table 3. Classification, coding and description of sub-criteria

Criteria	Code	Sub-criteria	Description
Environmental	ENV01	Characteristic of territorial occupation	More or less favorable characteristics of the municipality or region in which the project aims to be undertaken, as a demographic density, proximity to areas of environmental preservation, river springs.
	ENV02	Potential environmental benefits	Environmental benefits provided for by the project, such as an increase in the use of biofertilizers, residues reinserted in the economic chain, impact on global warming.
	ENV03	Current pollutant emission	Number of greenhouse gas emissions with the current destination of organic waste.
	ENV04	Potential for pollutant emission mitigation	Amount of pollutant emission avoided from the implementation of the project.
	ENV05	Energy impact	Substitution in the current energy matrix or availability of energy to the community / rural population through the project.
	ENV06	Environmental restrictions	Environmental restrictions provided for in the project, such as bad smell, noise and/or visual pollution, impairment of preservation areas.
	ENV07	Current waste treatment	Current disposal of organic waste, more or less environmentally correct or advantageous.
Economic-financial	ECO01	Operational cost	Costs of plant operation and maintenance, labor and transportation of inputs and outputs.
	ECO02	Initial investment	Estimated monetary value for the initial investment of the project.
	ECO03	Market characteristics	Market characteristics that may be more or less conducive to the project, such as competitiveness, market share, interest rate, opportunity cost, inflation.
	ECO04	Waste Transport Cost	Cost of transport of organic waste to the plant.
	ECO05	IRR	Return rate
	ECO06	Value of output production	Monetary value of plant output production.
	ECO07	Lifespan	Estimated project life time.
	ECO08	Risk	Risk involved in the project.
	ECO09	Subsidies	Tax or credit incentives granted by the government for the project.
	ECO10	Valuation of the Enterprise	Estimated monetary value of the project when implemented.
	ECO11	Exits price	Estimated market price of outputs chosen for production from biogas.
	ECO12	Payback	Time required to recover the initial investment.
	ECO13	Cost of current waste disposal	Cost of the disposal of current organic waste in the municipality or region.
	ECO14	Depreciation	Loss of gradual value of the biogas plant.

Source: the author, 2023.

Table 4. Classification, coding and description of social and technical sub-criteria

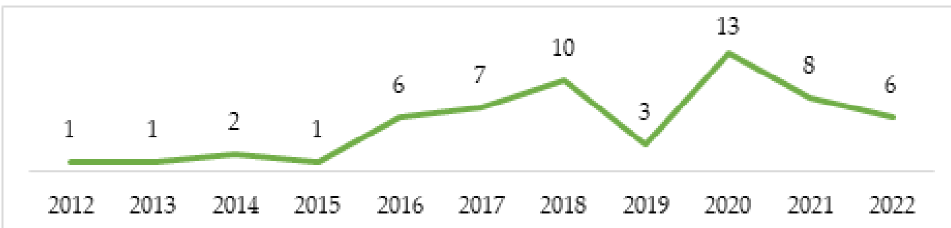
Critério	Code	Subcriteria	Description
Social	SOC01	Community Expectation	Perception and expectations of the community (stakeholders) regarding the project.
	SOC02	Community Characteristics	Character istics more or less conducive to the implementation and acceptance of the project, such as qualified labor, level of education, local leadership and organizations operating in the sector.
	SOC03	Public Policy	Legislation for biogas projects, public incentive programs.
	SOC04	Job Generation	Expected number of direct and indirect jobs generated by the project.
	SOC05	Social Impact	Expected impacts on the community, such as increased public health, quality of life, decent work, promotion of the local economy.
Technical	TEC01	Organic Waste Composition	Chemical composition of organic waste available for production, which may be more or less suitable for this purpose.
	TEC02	Organic Waste Production	Amount of waste produced in the municipality that will be available for biogas production.
	TEC03	Available Technology	Technology available for the plant, type of biodigester, which may be more or less suitable for the quantity and type of waste in the project.
	TEC04	Potential Production of Outputs	Estimated quantity of output production.
	TEC05	Potential Production of Biogas	Estimated amount of biogas production.
	TEC06	Available Area for the Plant	Area available for construction of the plant and suitability of location in relation to waste collection and delivery/distribution of outputs.
	TEC07	Efficiency Degree	Level of efficiency of the plant in using waste to produce biogas.
	TEC08	Produced Biogas Composition	Quality of the chemical composition of the biogas produced in the plant, which may have greater or lesser potential for conversion into outputs.
	TEC09	Outputs Demand	Estimated demand for project outputs.
	TEC10	Plant Energy Demand	Energy demand required for biogas production.
	TEC11	Production Water Demand	Amount of water required for the biogas production cycle.
	TEC12	Production Redidue	Waste generated by biogas production.
	TEC13	Biodigestion Cycle	Time required to complete the biogas production cycle, from the input of waste to the output of the chosen products (outputs).

Source: the author, 2023.

2.4 Discussion

This section presents the results of the collection and manipulation of the data from the articles found, according to the year of publication, the keywords, the characteristics of the publications, and the decision-making criteria found. The Figure 2 shows the year of publication of articles:

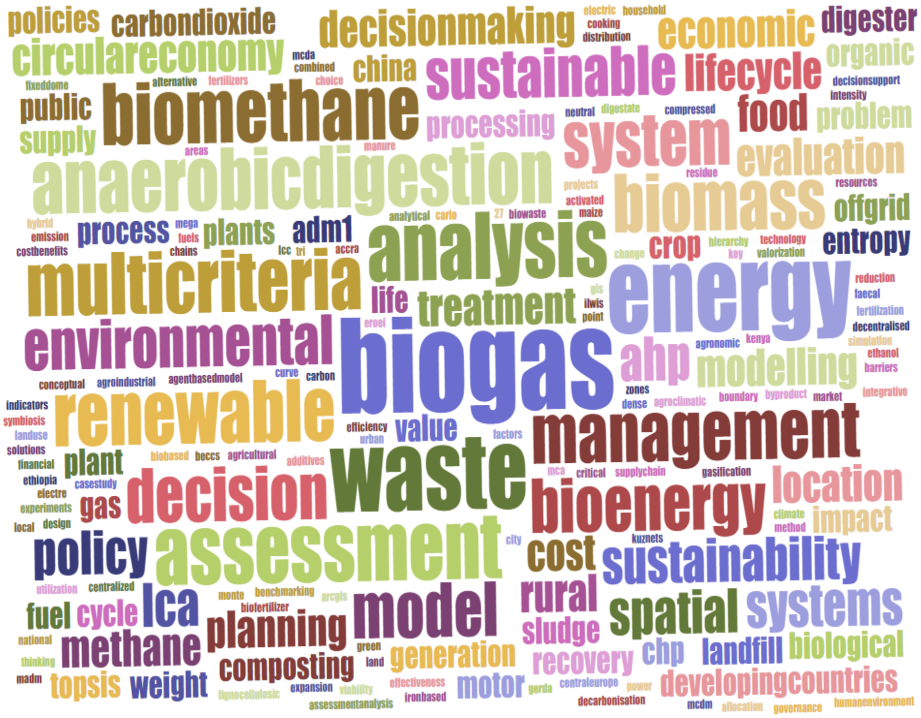
Figure 2. Year of publications.



Source: the author, 2023.

As can be seen, the articles began to be published in 2012, with only one published work, as well as in the two subsequent years. In 2016, the number of publications grew to six articles. In 2020, there will be the largest quantity, 13 works. The Figure 3 shows a cloud of words elaborated from the keywords found in the articles:

Figure 3. Keywords cloud.

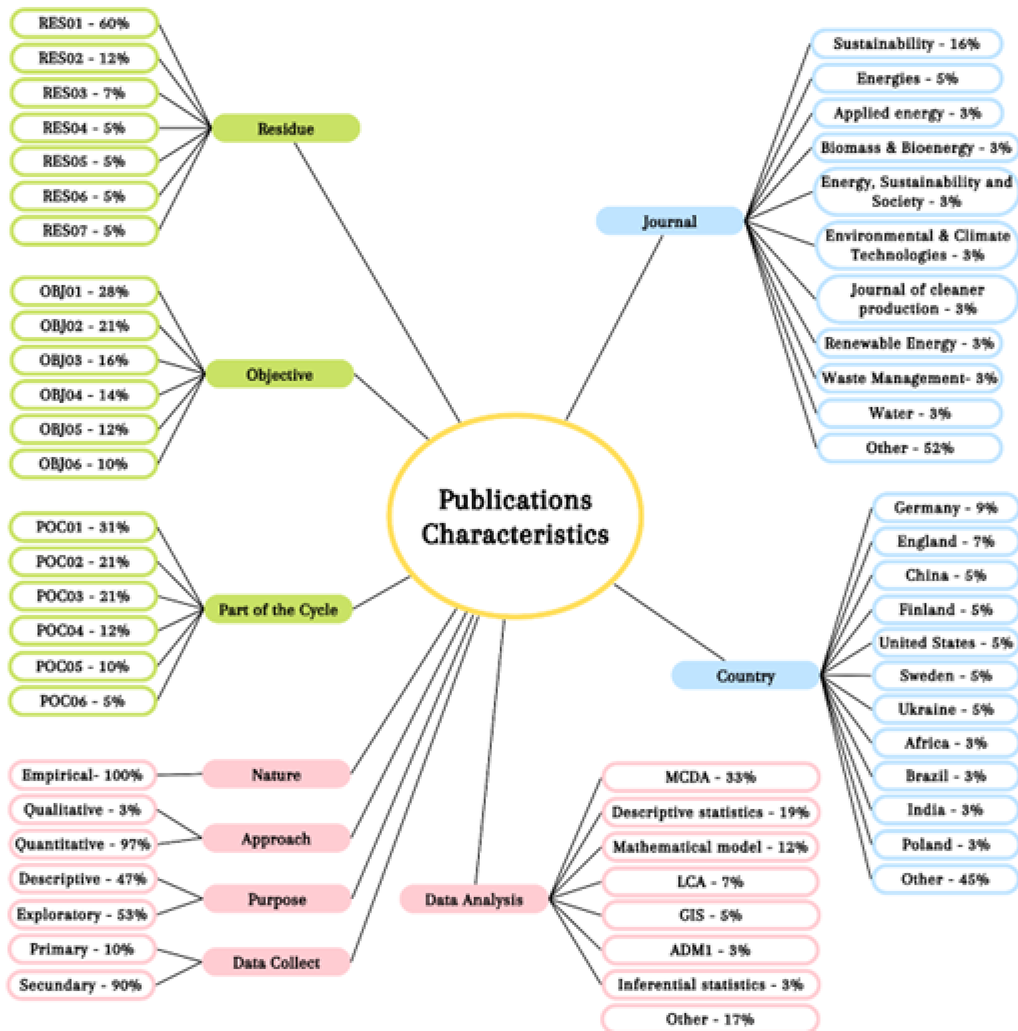


Source: the author, 2023.

The word cloud serves as a visual representation of the most frequently used keywords in the analyzed articles. It complements the descriptive summary of the findings and provides a quick and intuitive way to grasp the dominant themes and topics within the literature and allows for easy identification of patterns and relationships between keywords. The relative size and positioning of the words reflect their frequency and prominence, enabling readers to quickly grasp the overall distribution of topics. There were 310 keywords in the 58 articles. The word "biogas" appears with bigger frequency (in 20 different articles), which is expected because it’s one of the terms used in the search for articles. However, the second most prominent word is "waste" (10 times), followed by "renewable" (8 times). The terms "biomethane,", "multicriteria," and "anaerobic digestion" appear seven times each, while "energy" and "sustainable" appear six times in different articles.

Figure 4 presents the classification of publications, providing information on authorship, country of origin, focus, and methodology of studies, as well as the criteria used in decision-making in biogas projects.Figure 4 presents the classification of publications, providing information on, authorship, country of origin, focus, and methodology of studies, as well as the criteria used in decision-making in biogas projects.

Figure 4. Publications characteristics.



Source: the author, 2023.

The publications are dispersed across a wide range of journals, with 30 of the 58 articles (52%) published in unique journals. This suggests that biogas research is still in its early stages of development and that there is a need for more consolidation and collaboration across different research groups. The remaining 28 articles (48%) are concentrated in 10 other journals, with Sustainability publishing the highest number of articles (9). The concentration of a significant number of articles in Sustainability, a journal dedicated to sustainable development, further highlights the growing recognition of biogas as a key technology for achieving sustainability goals.

Europe is the leading region for biogas research, with Germany and England contributing the most articles (9% and 7%, respectively). Other significant contributors include

China, Finland, the United States, Sweden, and Ukraine (5% each). However, most articles (45%) were conducted in countries that were not repeated. This distribution suggests that biogas research is concentrated in a relatively small number of developed countries. While there is some research activity in other parts of the world, including Africa, Asia, and America, it is less significant. Despite this imbalance in global biogas research, biogas has the potential to make a significant contribution to sustainable development in all countries. It is important to invest in biogas research and development in developing countries to ensure that all people have access to this technology.

Regarding the focus of the studies, the fact that the most common objective is to assist in decision-making suggests that researchers are primarily focused on developing tools and resources to help people make informed decisions about biogas projects. The distribution of article objectives suggests that biogas research is focused on both developing the technology itself and making it more accessible and affordable for people around the world and indicates that researchers are committed to realizing the full potential of biogas as a sustainable energy source.

The relatively high proportion of articles focused specifically on decision-making suggests that there is a need for more practical and accessible resources to support biogas deployment, while the interest in exploring energy matrices and/or alternative waste disposal highlights the potential of biogas to play a role in integrated waste management and renewable energy systems. The focus on measuring efficiency and comparing production systems suggests that researchers are working to improve the performance and cost-effectiveness of biogas technology.

The distribution of articles by biogas project and production phase provides insights into the areas where researchers are paying the most attention. The fact that most articles focus on the entire biogas production cycle suggests that researchers are taking a holistic approach to biogas development. The focus on the final phase of production (POC02) and the evaluation of biogas projects (POC03) also highlights the importance of ensuring that biogas projects are successful and sustainable over the long term.

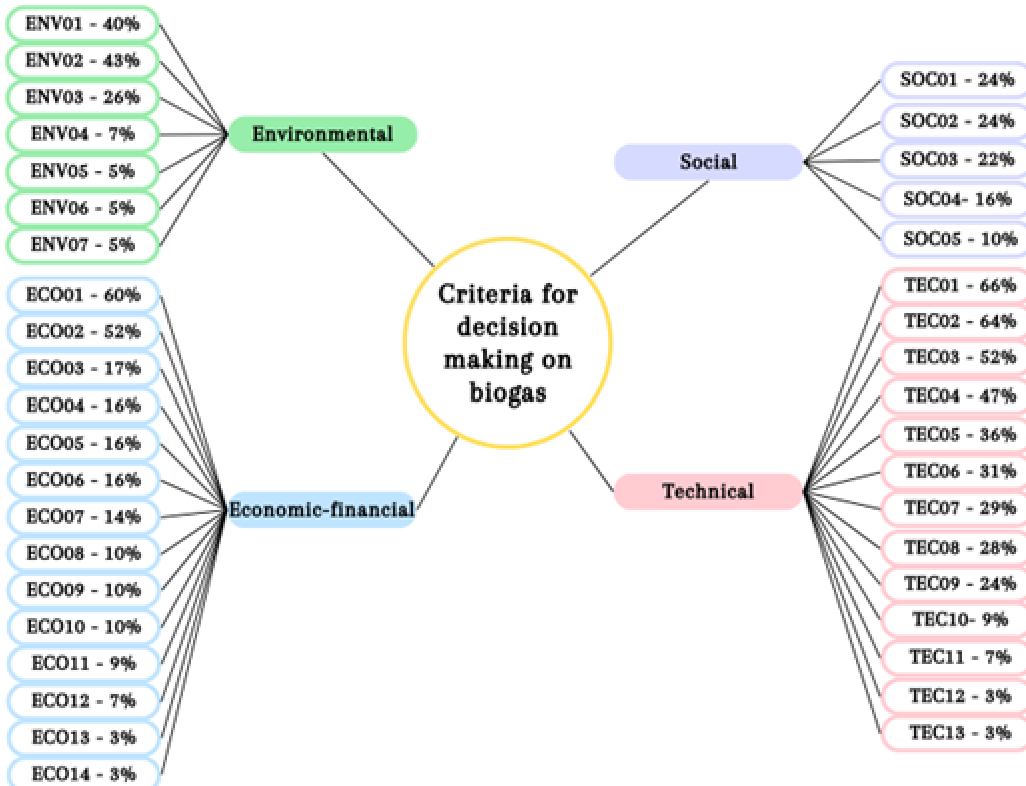
The high proportion of empirical and quantitative research suggests that researchers are committed to generating evidence-based, measurable and quantifiable knowledge in the field of biogas technology and its applications. Also, the high proportion of descriptive research suggests that researchers are interested in understanding the current state of biogas development and identifying areas for further improvement. The use of MCDA as the most common data analysis method is also understandable, given its suitability for complex decision-making problems such as biogas project evaluation and that researchers are recognizing the importance of considering multiple factors in biogas decision-making. Furthermore, the diversity of other methods used in biogas research suggests that the field is open to innovation and new approaches.

The percentages presented in Figure 5 represent the frequency of each sub-criterion within the analyzed articles. The analysis reveals that economic and technical criteria are the most frequently considered in biogas sustainability assessments, since that economic and technical sub-criteria are the most prevalent, with 14 and 11 sub-criteria, respectively, compared to 7 environmental and 5 social sub-criteria. This suggests a significant imbalance in the frequency of sub-criteria across different categories. This suggests that decision-makers may prioritize economic viability and technical feasibility over environmental and social factors. While economic and technical considerations are undoubtedly important, it is crucial to ensure that environmental and social impacts are also adequately evaluated to promote sustainable biogas development.

Among the environmental sub-criteria, potential environmental benefits are the most frequently considered, followed by land occupation and pollution emissions. This indicates that decision-makers are aware of the potential environmental impacts of biogas projects, but there may be room for more in-depth consideration of specific environmental factors, such as greenhouse gas emissions, water resource impacts, and biodiversity impacts.

The social category has the least number of sub-criteria, highlighting the limited attention given to social impacts. These sub-criteria are less frequently considered compared to economic, technical, and environmental factors. This suggests that social impacts may not be given as much weight in biogas sustainability assessments. It is important to recognize that biogas projects can have significant social implications, including impacts on local communities, employment opportunities, and social equity.

Figure 5. Criteria used for decision-making in biogas projects.



Source: the author, 2023.

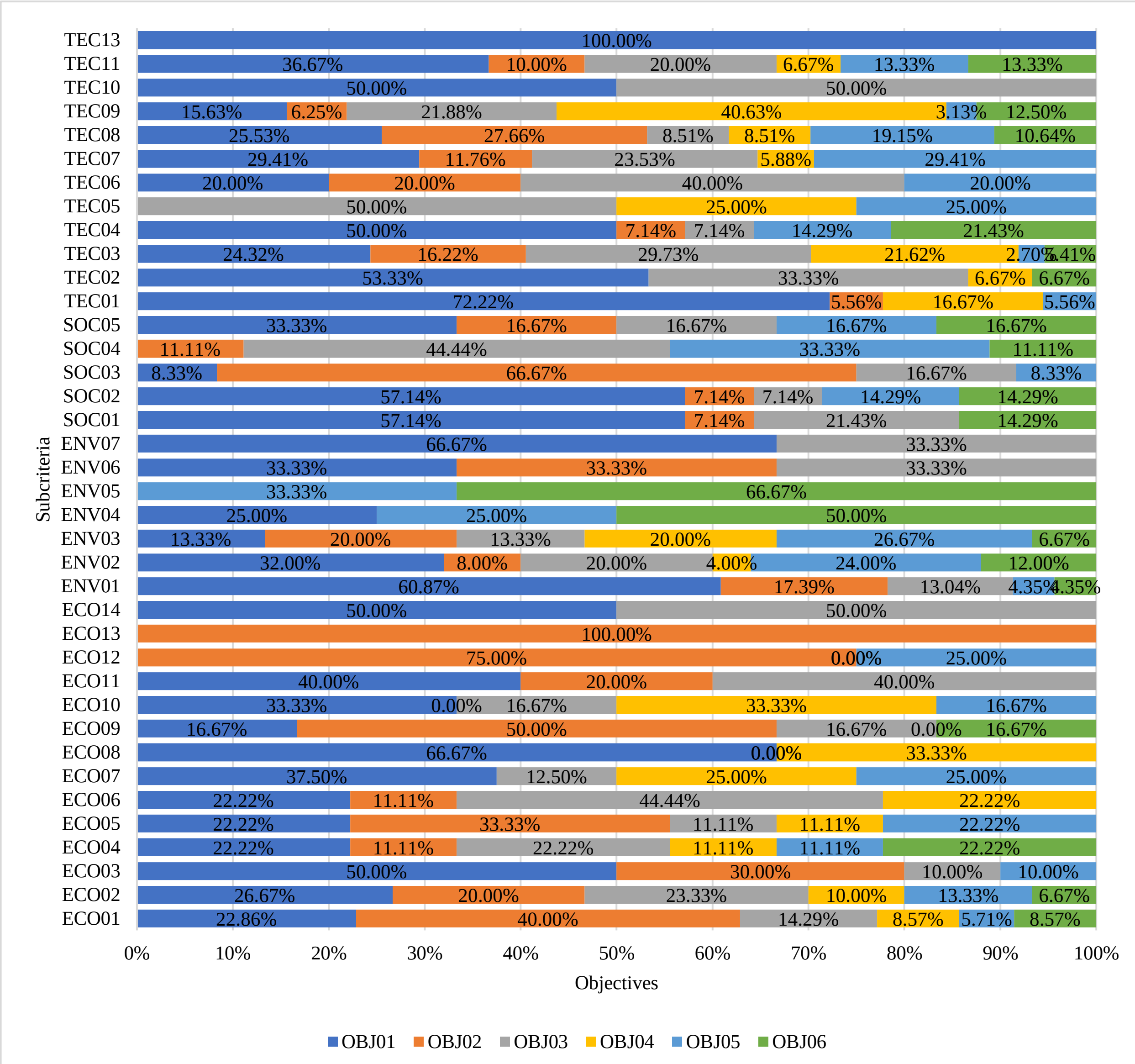
The technical category is focused on sub-criteria related to waste feedstock characteristics, available technology, and output production potential. This indicates that technical feasibility is crucial for biogas project success. This is observed as well in the economic category, which is dominated by sub-criteria related to costs and financial aspects, such as operating costs, initial investment, and internal rate of return. This suggests that economic viability is a major consideration for biogas projects.

Within each category of sub-criteria, there is a range of importance. For instance, operating costs and initial investment are the most common economic sub-criteria, while community expectations, community characteristics, and public policies are the most frequent social sub-criteria. This suggests that decision-makers may prioritize certain aspects within each category based on their specific priorities and context.

The findings of this analysis suggest that there is a need for more holistic and balanced approaches to biogas sustainability assessments. Figure 6, 7 and 8 below shows the crossing of sub-criteria and articles focus (objective, part of the cycle and residue type):

The subcriteria that are most associated with the objective of assisting in decision-making in biogas (OBJ01) are biodigestion cycle (TEC13), wich was only found in this objective, composition of organic waste (TEC01), and the environmental subcriteria of Characteristic of territorial occupation, lifespan and risk (ECO01, ECO07 and ECO08). This may reflect the priority of the researchers in evaluating the economic and technical feasibility of biogas projects. The subcriteria that are most associated with the objective of identifying perspectives in biogas production (OBJ02) are cost of current waste disposal, depreciation (ECO12 and ECO13) and public policy (SOC03). This may suggest that the researchers with this objective are trying to understand the potential impacts of biogas projects on the environment and society.

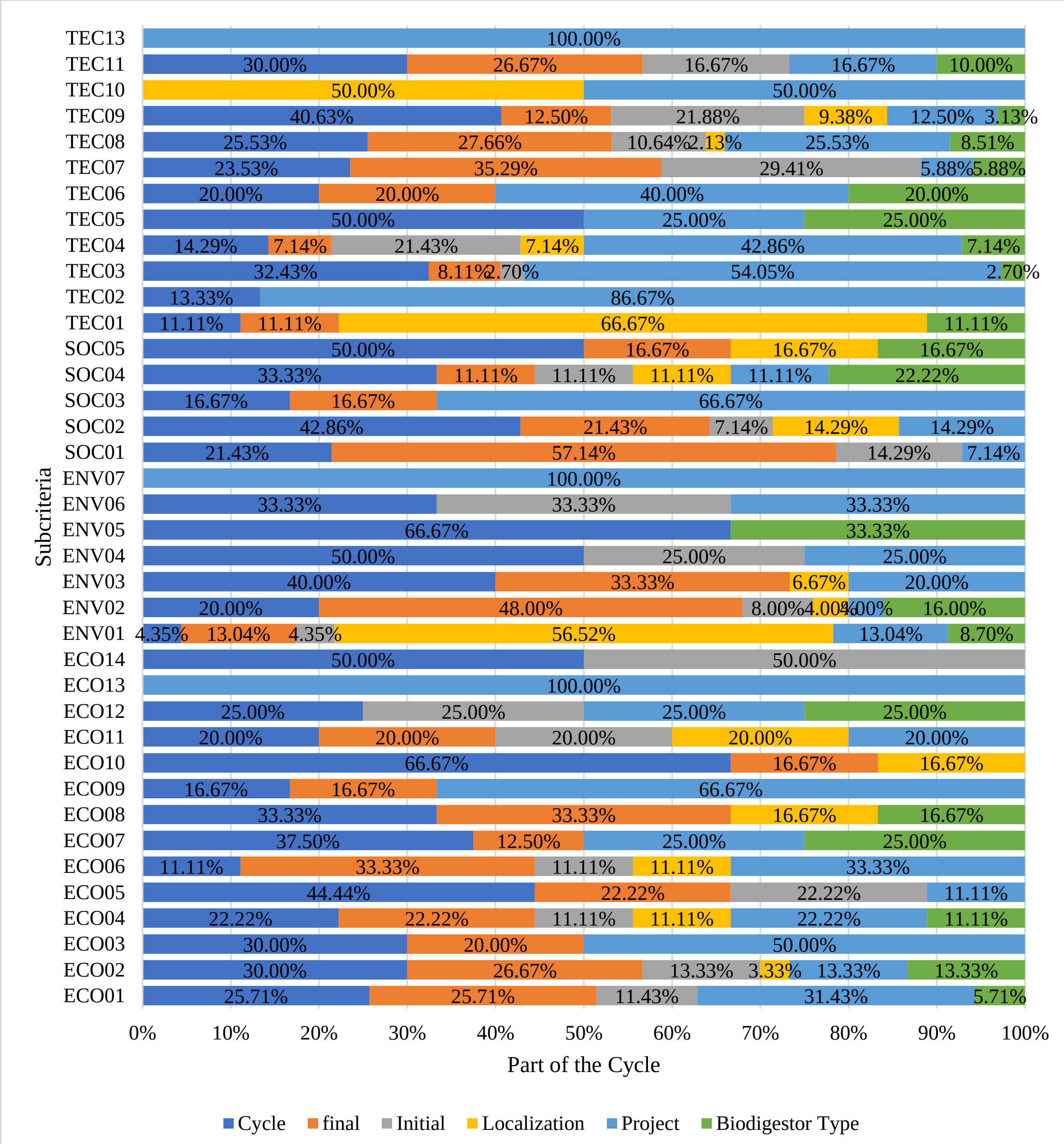
Figure 6. Crossing analysis of sub-criteria and objective.



Source: the author, 2023.

Regarding the objective of exploring energy matrices and/or alternative waste disposal (OBJ03), the most common subcriteria are potential of biogas production, plant energy demand (TEC05 e TEC10) and depreciation (ECO14). This reflects the importance of technical feasibility of a new waste destination. No social subcriteria were found in articles that were measuring the efficiency of biogas production (OBJ04). Instead, the most common subcriteria in these articles were technical and economic.

Figure 7. Crossing analysis of sub-criteria and part of the cycle.



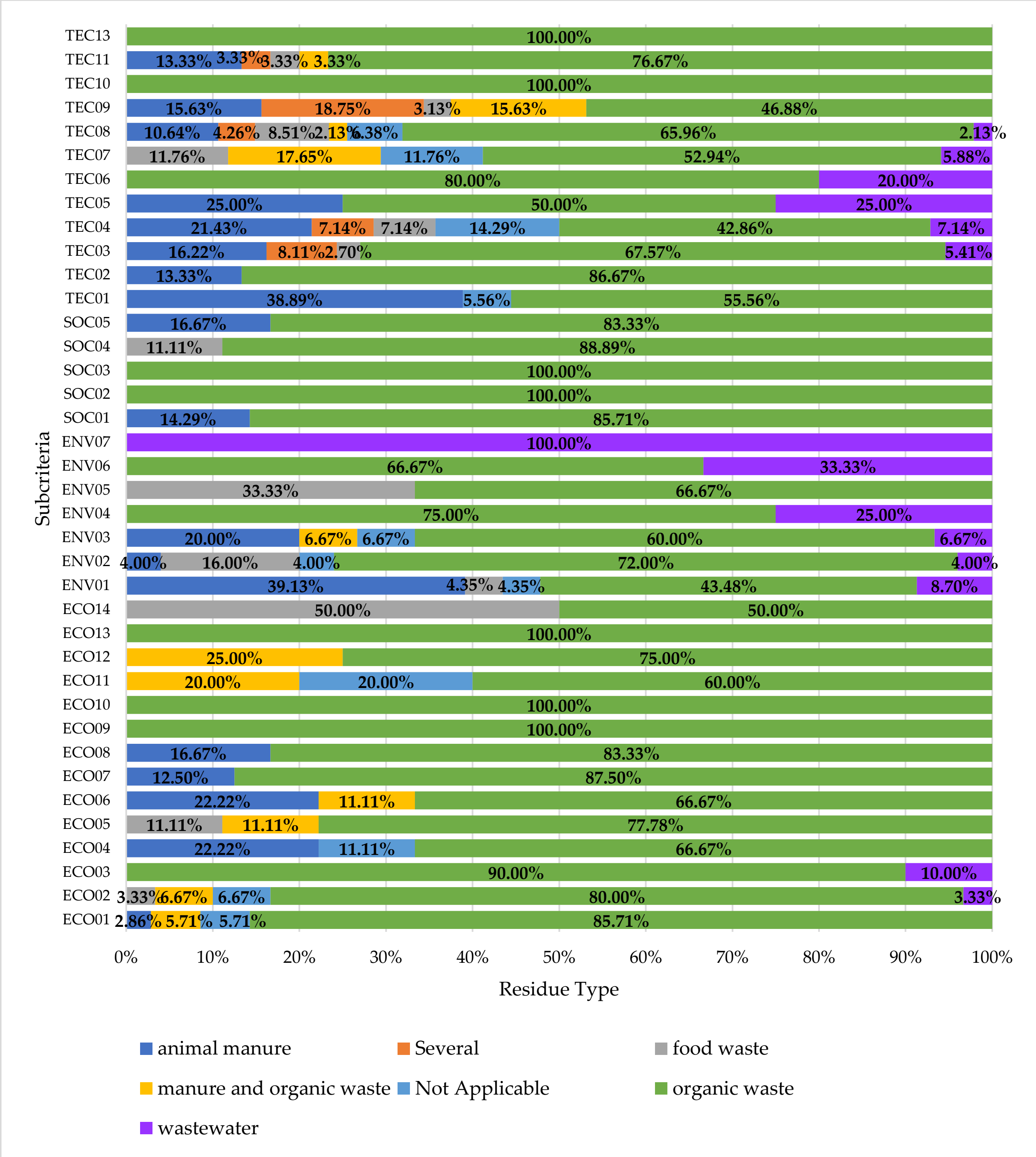
Source: the author, 2023.

The crossing suggests that the subcriteria that are most important for different objectives vary according to the objective of the articles. However, there are some common subcriteria for all six objectives, such as the economic operational cost, initial investment, and residue transportation cost (ECO01, ECO02 and ECO04), the environmental potential environmental benefits and Current pollutant emission (ENV02 and ENV03). Four technical subcriteria are common to all objectives: available technology, produced biogas composition, outputs demand and production biogas demand (TEC03, TEC08, TEC09 and TEC11) This suggests that these subcriteria are essential for developing decision-making frameworks for biogas projects in different circumstances. No social subcriteria was found in all the six objectives, what may suggest that certain purposes do not consider social considerations for evaluating biogas projects.

The most common sub-criteria for all residue types are operating cost (ECO01) and initial investment (ECO02). Other common sub-criteria include composition of organic waste (TEC01), production of organic waste (TEC02) and potential environ-mental benefits (ENV02) for all residue types. All social subcriteria are concentrated in organic waste and most of them were not found in articles that used wastewater, organic waste with animal manure or several residue types. The sub-criterion related to job generation (SOC04) is the only one used in articles with food waste.

Additionally, it is important to recognize that certain sub-criteria may be more important for certain stakeholders. For example, community expectations (SOC01) and community characteristics (SOC02) may be more important for local communities, while public policies (SOC03) and output demands (TEC09) may be more important for government agencies and businesses.

Figure 8. Crossing analysis of sub-criteria and residue type

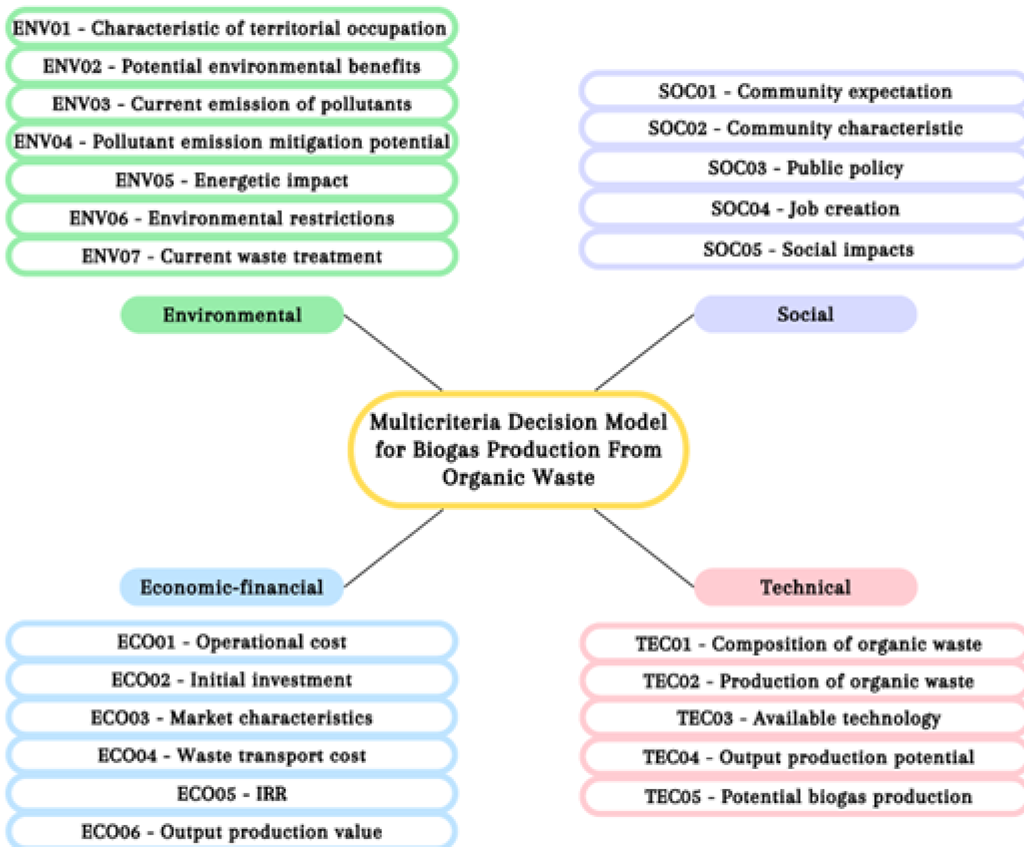


Source: the author, 2023.

2.4.1 Theoretical Findings

For practical contribution in the field of biogas-related decision-making from organic waste, a multicriteria decision-making model was made based on the findings of the research raised and thus suggested minimum criteria for consideration in different possible contexts involving the production cycle of biogas.

Figure 9. Theoretical proposition of a multicriteria decision model for biogas production.



Source: the author, 2023.

For the choice of model sub-criteria, beyond the frequencies found in the articles on the subject, there was an attempt to balance the technical, economic, and financial spheres, with priority given to technical criteria to the detriment of social and environmental criteria, which compromises the sustainability of this type of project. This emphasis on technical criteria is likely since technical aspects are often more easily measurable and quantifiable than environmental or social impacts. As a result, technical criteria may receive more attention in decision-making processes, even though environmental and social factors are also crucial for ensuring the sustainability of biogas projects. Since the integration of social justice and equity considerations into bio-gas sustainability assessments can promote more inclusive and equitable decision-making processes, the proposition incorporates both, quantitative and qualitative factors, to help decision-makers make informed choices that prioritize environmental and social sustainability, while also ensuring technical feasibility and economic viability. From these findings, Figure 9 exposed below shows the theoretical proposition of a multicriteria decision model for biogas production from organic waste. The sub-criteria that stood out in the publications analyzed were listed: environmental (7), social (5), economic (6), and technical (5).

At first, the five sub-criteria were most often established in the articles analyzed, but in environmental instances, the energy impact, environmental restrictions, and current waste treatment are the same frequency (ENV05, ENV06, and ENV07; 5%), and therefore, they were kept in the proposition. The same happened in the economic and financial sub-criteria IRR and production value of outputs (ECO05 and ECO06; 16%). However, it is noteworthy that the theoretical proposition has a preliminary character and, therefore, needs later empirical proof according to the multicriterial decision-making methodology so that weights are established for subcriteria as well as verification of the adherence of the model in a single decision-making situation in bio-gas projects.

2.4.2 Syntesis

Decision-making in a biogas production project involves several variables, from the problem to be solved, the project cost, the business model, and funding, to the final products of biogas production. Thus, this research sought to respond to the problem of the criteria considered in a decision-making process to evaluate biogas production projects from organic waste. To achieve the general objective, the scientific literature on the decision-making of biogas projects was reviewed so that it was possible to identify relevant criteria for a successful decision in this type of context.

For the analysis of the biogas production cycle, three steps were considered: initial, plant, and end, as well as the cycle. The initial stage includes the production, collection, separation, and transport of waste, while in the plant, biogas production occurs in a biodigester. In the final stage, exits such as electricity, biofertilizer, or vehicle gas are produced. External impacts were also integrated that influenced the decision to implement a biogas project, i.e., economic, environmental, and social aspects.

When checking the years of publications, it is understood that the peak research on the subject was between 2018 and 2020, presenting a slight drop in the following years. From the keywords found in the articles, it can be concluded that there is a wide range of topics that the authors are investigating, as identified in the analysis of the objectives of the studies. Keywords suggest that there is a vast diversity in the topics in which the researchers attempt, as was also identified in the analysis of the objectives and methodology of the studies.

Noteworthy are the terms of biogas efficiency and technology (in a technical and/or chemistry emphasis of biodigesters), public policies (in a bias of how the government can facilitate or make it difficult to implement this type of solution), and economic viability (which is also revealed in the amount and frequency of economic and financial criteria in publications).

Expressions of social aspects signal embezzlement in impact analysis in local communities; equity and social justice issues, for example. This can lead to an incomplete understanding of the challenges and opportunities of biogas implementation and negatively affect decisions based on this data. There is also significant concern about the search for solutions to environmental problems, manifested in terms of renewable energy sources, agroindustrial and sewage waste processing, biomethane production, and the use of agricultural waste.

Other keywords reveal the methodologies used in articles, such as mathematical models, integrated systems modeling, cost-effective analysis, and MCDA decision-making itself, which indicate the need for integrated and holistic approaches to the theme. In short, the conjuncture demonstrates a strong relationship between decision-making in biogas and sustainability and sustainable development.

The analysis of the journals in which the publications were made indicates that, although the publication Sustainability concentrates the largest number of articles published on the subject, there is a dispersal of studies on biogas in different scientific publications, which may occur due to the diversity of perspectives itself under which the research was conducted and also a positive aspect for the dissemination of the theme in different areas. On the other hand, it can also make it difficult to obtain a consolidated view on the subject.

In terms of geographical location, Europe's dominance in biogas research is likely due to several factors, including its strong tradition of environmental protection, its commitment to renewable energy, and its well-developed research infrastructure. The relatively low level of biogas research activity in developing countries reveals a few challenges, including limited funding, lack of expertise, and poor access to research facilities. It is important to address these challenges to promote more equitable global biogas research and development. This could be achieved through international collaboration, capacity building programs, and targeted funding for research in developing countries.

The wide dispersal of articles across different journals and countries suggests that biogas research is a diverse field that attracts interest from a variety of academic disciplines. It also indicates that researchers are approaching biogas from a range of perspectives, priorities, and goals.

The field of biogas research is still relatively young and researchers are focused on developing a strong foundation of knowledge and understanding. The methodology used in most articles is empirical, quantitative, and descriptive. Data collection was mainly secondary, and analysis methods include MCDA and descriptive statistics, which is consistent with research in the decision-making field. The focus on the entire biogas production cycle suggests that researchers are aware of the need to consider all aspects of the process, from feedstock collection to biogas utilization. The interest in the final phase of production and evaluation of biogas projects highlights the importance of ensuring that biogas projects are sustainable and successful over the long term. The relatively low proportion of articles focused on the initial phase of production suggests that there is a need for more research on how to optimize feedstock collection, preparation, and pretreatment.

The limited research on the decision of the location of the biogas plant and the type of plant biodigester suggests that there is a need for more guidance for practitioners on how to select the best options for their specific needs and context, where the researches were made, since most articles leaned over real practical problems in which a decision related to biogas was demanded, and consequently, the objectives and criteria reflect the priorities and problems found in each context and not establish the establishment of a generic decision-making model in biogas projects.

All 499 original criteria found in the 58 selected articles were classified according to one of the four criteria, and 39 sub-criteria were listed for the research. The largest number of sub-criteria found in the articles are economic and technical criteria. Of the environmental sub-criteria, the most frequent is potential environmental impacts.

The pollution criterion issued in the current scenario was identified in 26% of the articles. Economic and financial subcriteria, operating costs, and initial investment are the most common in more than half of the articles. Sub-criteria in the social sphere are less common, with community expectation, community characteristics, and public policies being more common. Technical criteria, organic waste composition, and organic waste production are the most frequent.

However, there is a greater concern with the economic and financial criteria and the technical aspects in relation to environmental and social aspects, which could be verified both in the number of subcribers of classifications and their frequency in publications.

2.5 CONCLUSIONS

From the results presented, it can be inferred that there is a greater concern with the economic and financial criteria in relation to environmental and social aspects, which is reflected both in the number of subcriteria of classifications and their frequency. These results may suggest that, in the analysis of the articles found, there is a tendency to prioritize the economic and technical dimensions to the detriment of the environmental and social dimensions, which may indicate an inequality in the approach to sustainable development.

The practical contribution of the research takes place in the theoretical proposition of the decision-making model, which sought to list minimal criteria to be considered in a decision-making process by a public manager or business analyst, for example. The model's flexibility allows it to be tailored to specific decision-making contexts and project phases, ensuring its applicability in a variety of biogas production scenarios. Also, incorporating both quantitative and qualitative criteria, the model can help decision-makers avoid making decisions solely based on financial or technical considerations, thereby promoting more sustainable and equitable decision-making processes. This study provides a comprehensive overview of the criteria considered in decision-making processes for biogas production projects from organic waste. The identification and classification of 39 sub-criteria into four main categories (environmental, economic, financial, technical, and social) offers a valuable resource for researchers and practitioners in the field of biogas sustainability assessments. The development of a preliminary multicriteria decision model represents a significant step towards standardizing and improving decision-making processes in biogas project development.

Study results are limited to articles available on Web of Science open access, therefore, they may not reflect the entirety of the scientific literature in the field. It is suggested for future research to construct multicriteria decision models specific for each part of the biogas production cycle (project, initial, cycle and final) to facilitate decision-making according to the objectives and priorities of the person responsible for the analysis. In addition, it is convenient to test the constructed decision-making model by subjecting it to an empirical situation in which a decision is made in biogas projects. Then, investigations of the relative importance of different sub-criteria in various decision-making contexts would enhance the practical utility of the model.

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3 ARTICLE 2

Proposal of Multicriteria Decision-Making Models for Biogas Production

Abstract: While biogas production offers promising solutions for waste management, energy diversification, and sustainable development, effective project implementation requires comprehensive evaluation criteria that encompass diverse aspects, such as the problem to be addressed, biodigester technology selection, business model development, investment considerations, and final product utilization. A preliminary study involving an integrative review of 58 articles yielded 499 unique criteria. These criteria were categorized into four groups: economic, environmental, social, and technical, encompassing a total of 39 subcriteria. Six stages of the biogas production cycle were considered in the analysis: project, initiation, biodigester type selection, location determination, operational cycle definition, and final product utilization. The analysis revealed that existing decision-making models often prioritize technical and economic considerations while neglecting broader social and environmental perspectives. This paper addresses this gap by proposing, for the first time, stage-specific, multicriteria decision-making (MDCA) models tailored to each phase of a biogas production cycle. These models empower project managers and policymakers to optimize resource allocation, minimize the environmental impact, maximize social benefits, and ensure project viability and profitability. The models' adaptability allows for tailored prioritization based on specific project requirements and contexts. This groundbreaking research fills a critical void in biogas decision making by bridging the gap between existing technical and economic model limitations and the growing need for truly sustainable project development.

Keywords: biogas; multicriteria decision making; MCDA; models proposition.

3.1 INTRODUCTION

Biogas, a clean-burning gaseous mixture primarily composed of methane and carbon dioxide, arises from the anaerobic digestion of organic materials by microorganisms. This natural process, occurring in landfills and controlled digesters, unlocks the energy potential stored within organic waste, which includes sewage sludge, agricultural residues, and food scraps. The resulting biogas can be directly utilized for heat generation, electricity production, or transportation fuel, replacing fossil fuels, and contributing to decarbonization efforts.

In the face of escalating environmental concerns and growing energy demands, biogas emerges as a beacon of hope. This versatile product of organic waste decomposition offers a multifaceted solution, tackling waste management challenges, diversifying energy sources, and fostering sustainable development. By harnessing the power of naturally occurring microorganisms, biogas production transforms organic waste into a renewable fuel source, minimizing landfill burdens and greenhouse gas emissions. This transformative potential extends beyond environmental benefits, unlocking economic opportunities through job creation and rural development while aligning with broader societal goals of energy security and environmental stewardship.

Biogas production holds immense potential in addressing a myriad of challenges, from effective organic waste management to the diversification of energy sources, ultimately contributing to sustainable development. However, unlocking this potential requires a strategic approach that extends beyond mere technical and economic considerations. Drawing upon an integrative literature review focused on “decision making in biogas”, the research identifies six crucial evaluation phases for a biogas production project: project, cycle, initial phase, the final phase, biodigester type, and location. Models specific for each phase are proposed based on these classifications, addressing the inherent complexities of decision making in biogas initiatives.

Despite the growing interest in biogas projects, many decision-making models tend to prioritize technical and economic factors, sidelining crucial social and environmental considerations. This oversight hampers the realization of truly sustainable biogas initiatives, limiting their potential benefits for both society and the environment.

The dynamic nature of biogas projects becomes evident when considering their varied applications, such as sustainable organic waste disposal, vehicular biogas production, electricity generation, and biofertilizer output. This diversity underscores the need for distinct multicriteria decision-making models tailored to different project objectives. These potential uses of biogas show the diversity of objectives that a decision-maker may consider when evaluating a biogas production project. Consequently, distinct multicriteria decision-making models that support these varying requirements are needed. This can be verified by the fact that the most of the preliminary study articles focused on the entire biogas production cycle, while only a few dealt with the biodigester type or the location of the biogas plant, as shown in Table 5.

Problems of this nature involve multiple criteria, alternatives, and preferences that interfere with the decision-making process. Considering the subjectivity inherent in the decision-making process, in which there are pre-determined alternatives, most references are uncertain or there is a divergence of opinions between decision-makers [1]. On this subject, multicriteria methods stand out as a tool to assist in decision making. Decision making is a function that aims to resolve or dissolve the conflict of trade-offs between the multiple criteria adopted.

Table 5. Part of the biogas cycle from the literature.

Project	**Cycle**	**Final**	**Location**
Ammenberg J et al. 2018 [2]	Roubík H et al. 2018 [3]	Kalinichenko A Havrysh V Perebyynis V 2016 [4]	Bojesen M Boerboom L Skov-Petersen H 2015 [5]
Kalinichenko et al. 2017 [6]	Chodkowska-Miszczuk et al. 2020 [7]	Berhe M et al. 2017 [8]	Silva S Alcada-Almeira L Dias L C 2014 [9]
Chrispim M C et al. 2020 [10]	Iannou-Ttofa et al. 2020 [11]	Konneh K V et al. 2021 [12]	Soha T Hartmann B 2022 [13]
Li F et al. 2016 [14]	Lindfors A et al. 2019 [15]	Gandhi P et al. 2018 [16]	Ciapala B et al. 2017 [17]
Pehlken A et al. 2020 [18]	Barragán-Escadón A et al. 2020 [19]	Kluczek A 2018 [20]	Laasasenaho K et al. 2019 [21]
Obileke K et al. 2020 [22]	Wagner M et al. 2018 [23]	Yang H et al. 2020 [24]	Khawaja C et al. 2021 [25]
Myšáková et al. 2016 [26]	Ugwu S Enweremadu C 2021 [27]	Tonrangklang et al. 2022 [28]	**Biodigester Type**
Dyer A et al. 2021 [29]	Cheraghalipour et al. 2022 [30]	Gunaratne T et al. 2016 [31]	Rupf G et al. 2017 [32]
De Medina-Salas L et al. 2018 [33]	Zhang W et al. 2018 [34]	Hagman L Feiz R 2021 [35]	Rao B et al. 2014 [36]
Kaneesamkandi Z et al. 2020 [37]	Arodudu O T et al. 2017 [38]	Perez-Camacho M N Curry R 2017 [39]	Feiz R Et al 2020 [40]
Biernaski I Silva C 2018 [41]	Verhoog R et al. 2016 [42]	Oshea et al. 2021 [43]	**Initial**
Chaher N E H et al. 2020 [44]	Sadhukhan J 2022 [45]	Rahmam M M et al. 2013 [46]	Lhano T et al. 2021 [47]
	Horschig T et al. 2019 [48]		Bhatt A H Tao L 2020 [49]
	Agbejule et al. 2021 [50]		Bartoli A et al. 2020 [51]
	Gaida D et al. 2012 [52]		Meng L et al. 2020 [53]
	Smith J U et al. 2015 [54]		Sadhukhan J 2014 [45]
	Ddiba A K et al. 2022 [55]		Segundo-Aguilar et al. 2021 [56]
	Poggio D et al. 2016 [57]		Bar R Ehrensperger A 2018 [58]

In this sense, multicriteria decision making allows decision makers to simultaneously consider the environmental, social, environmental, and technical aspects of biogas projects. According to the studies presented in Table 5, biogas projects impact not only the energy efficiency and economic forecasts but also play an important role in sustainable waste management, mitigating environmental impacts, and promoting social development. By balancing these different aspects, multicriteria decision making can contribute to the implementation of more effective and sustainable biogas projects.

The article's central question emerges from this context: What are the most suitable multicriteria decision-making models for each phase of the evaluation of biogas production projects from organic waste? To answer this question, the article outlines specific objectives: (i) identify significant criteria for each phase; (ii) analyze the coherence and relevance of existing models; (iii) propose decision-making criteria for each stage of the biogas production cycle.

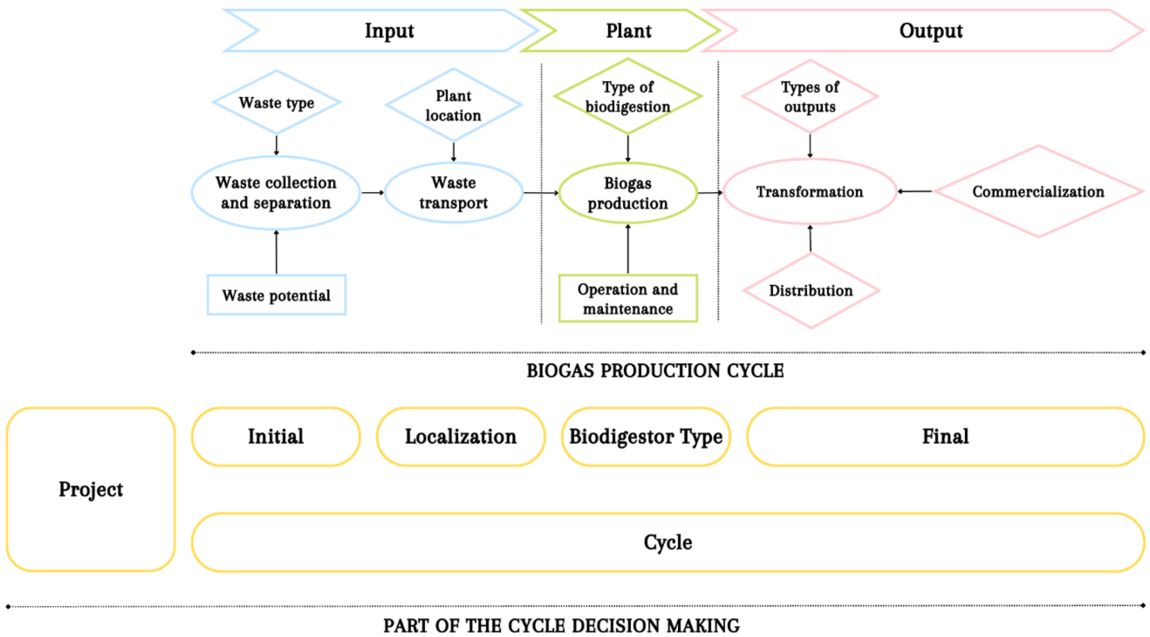
Navigating through the nuances of each stage from project initiation to location determination, operational cycle definition, and final product utilization, the research emphasizes the importance of weighing technical, financial, societal, and environmental considerations. This comprehensive approach fills a critical knowledge gap, introducing multicriteria decision-making models tailored to each phase of the biogas production cycle and addressing the limitations observed in the recent literature.

Furthermore, the article emphasizes the practical significance of its work by catering to the needs of public administrators involved in the decision-making processes. By considering economic, technical, environmental, and social factors, particularly in addressing sanitation challenges, organic waste disposal, energy matrix diversification, and sustainable development, the research aims to facilitate informed and balanced decisions.

In conclusion, the article offers a holistic framework for evaluating biogas projects, bridging the gap between technical and economic model limitations and the imperative for sustainable project development. By presenting a multifaceted perspective, the authors envision a future in which biogas realizes its potential as a catalyst for positive change across environmental, social, and economic spheres. The production cycle, illustrated in Figure 1, encapsulates the phases and decision-making moments, providing a roadmap for the successful implementation of biogas projects from organic waste.

The biogas production cycle from organic waste starts with the separation, collection, and transportation of waste to the plant site, where it is introduced into the bio-digestion system and transformed into biogas. This biogas can subsequently be refined into various outputs, such as biofertilizer, biogasoline, or electricity [12]. Figure 10 illustrates the phases of biogas production: input, plant, and output, represented by arrows, along with some of the decisions to be made for each phase. These key phases guided the categorization of the part of the cycle focused on each of the articles used in this study: project, biodigester type, initial, cycle, plant location, and final. Project involves identifying the problem, feasibility studies, and technology selection; Biodigester-type selection involves choosing the appropriate digester type based on the feedstock, ca-pacity, and desired outputs; Initial phase involves the operational constraints, input availability, and costs; Location is the phase when factors such as land availability, regulatory compliance, and proximity to resources are considered; in Cycle, definition parameters for feedstock input, digester management, and product utilization are set; while the Final Product Utilization phase determines the use of biogas (electricity generation, heat production, vehicle fuel).

Figure 10. Biogas cycle production and decision making.



Source: the author, 2023.

These decisions include waste type [3], location [5,25], and output commercialization [24], depicted as diamonds. Significant indicators such as waste potential and plant operation and maintenance (represented by rectangles) can also signal project viability [19,30]. Below the cycle, the possible decision-making moments for such pro-jects are depicted: Project, which precedes the entire production cycle; Initial, Location, Biodigester type, and Final; and Cycle, which encompasses all the production phases (depicted as squares with rounded edges).

3.2 Materials and methods

Through a systematic examination of scientific articles addressing decision making in biogas within the international literature, the researchers conducted an integrative review. This form of review aims to amalgamate empirical and theoretical literature, offering a comprehensive comprehension of a specific phenomenon by harmonizing viewpoints, concepts, or ideas from various studies. Consequently, this approach culminates in the consolidation of research constructs and methodologies, while also highlighting scientific gaps that can guide future investigations [59].

The procedures encompassed data collection, classification development, the application of classifications, overall article analyses, and the formulation of decision-making models. Data collection began with a search on the Web of Science platform using a login linked with State University of Londrina. The keywords were "decision making" and "biogas," along with a filter for articles available in full text. A total of 161 articles were identified. Subsequently, articles that did not align with the re-search's scope or that were not in Portuguese or English were excluded, resulting in a final count of 58 articles.

Following this, the criteria employed by researchers in their examination of decision making in biogas, culminated in a compilation of 499 distinct subcriteria. These criteria and subcriteria classification, as presented in Table 2 (environmental and eco-nomic) and Table 3 (social and technical), involved compiling the original criteria identified in the articles into a separate spreadsheet and then classifying them based on similarities with other articles' criteria. Following this grouping, the classification names were chosen. For example, one article listed the criterion "Land area required" and another listed "Biogas plant size," both of which were classified under "TEC06—Available Area for the Plant." This process was repeated for all the original criteria from the articles. A total of 39 subcriteria were classified, spanning four dimensions of biogas decision making: economic, environmental, social, and technical.

Table 6. Environmental and economic subcriteria classification

	Code	Sub-criteria	Description
Environmental	ENV01	Characteristic of territorial occupation	More or less favorable characteristics of the municipality or region in which the project aims to be undertaken, as a demographic density, proximity to areas of environmental preservation, river springs.
	ENV02	Potential environmental benefits	Environmental benefits provided for by the project, such as an increase in the use of biofertilizers, residues reinserted in the economic chain, impact on global warming.
	ENV03	Current pollutant emission	Number of greenhouse gas emissions with the current destination of organic waste.
	ENV04	Potential for pollutant emission mitigation	Amount of pollutant emission avoided from the implementation of the project.
	ENV05	Energy impact	Substitution in the current energy matrix or availability of energy to the community / rural population through the project.
	ENV06	Environmental restrictions	Environmental restrictions provided for in the project, such as bad smell, noise and/or visual pollution, impairment of preservation areas.
	ENV07	Current waste treatment	Current disposal of organic waste, more or less environmentally correct or advantageous.
Economic	ECO01	Operational cost	Costs of plant operation and maintenance, labor and transportation of inputs and outputs.
	ECO02	Initial investment	Estimated monetary value for the initial investment of the project.
	ECO03	Market characteristics	Market characteristics that may be more or less conducive to the project, such as competitiveness, market share, interest rate, opportunity cost, inflation.
	ECO04	Waste Transport Cost	Cost of transport of organic waste to the plant.
	ECO05	IRR	Return rate
	ECO06	Value of output production	Monetary value of plant output production.
	ECO07	Lifespan	Estimated project lifetime.
	ECO08	Risk	Risk involved in the project.
	ECO09	Subsidies	Tax or credit incentives granted by the government for the project.
	ECO10	Valuation of the Enterprise	Estimated monetary value of the project when implemented.
	ECO11	Outputs price	Estimated market price of outputs chosen for production from biogas.
	ECO12	Payback	Time required to recover the initial investment.
	ECO13	Cost of current waste disposal	Cost of the disposal of current organic waste in the municipality or region.
	ECO14	Depreciation	Loss of gradual value of the biogas plant.

Source: the author, 2023.

Table 7. Social and technical subcriteria classification

	Code	Sub-criteria	Description
Social	SOC01	Community expectation	Community perception and expectations in relation to the project.
	SOC02	Community characteristic	More or less favorable characteristics for the implementation and acceptance of the project, such as qualified labor, education, local leadership and organizations operating in the sector.
	SOC03	Public policy	Legislation for biogas projects, public incentive programs.
	SOC04	Generation of jobs	Expected amount of direct and indirect jobs generated by the project.
	SOC05	Social impacts	Predicted impacts on the community, such as increased public health, quality of life, decent work, promotion of the local economy.
Technical	TEC01	Composition of organic waste	Chemical composition of organic waste available for production, which may be more or less conducive to this purpose.
	TEC02	Organic waste production	Quantity of waste produced in the municipality that will be available for biogas production.
	TEC03	Available technology	Technology available for the plant, type of biodigester, which may be more or less suitable for the amount and type of project residue.
	TEC04	Output production potential	Estimated amount of output production.
	TEC05	Potential biogas production	Estimated amount of biogas production.
	TEC06	Available area for plant	Area available for plant construction and location adequacy in relation to waste collection and delivery / distribution of outputs.
	TEC07	Degree of efficiency	Degree of plant efficiency in the use of waste for biogas production.
	TEC08	Composition of biogas produced	Quality of the chemical composition of biogas produced in the plant, which may have greater or lesser conversion to outputs.
	TEC09	Outputs demand	Estimated demand for project outputs.
	TEC10	Plant energy demand	Necessary energy demand for biogas production.
	TEC11	Water demand for production	Amount of water required for the biogas production cycle.
	TEC12	Waste production	Waste generated by biogas production.
	TEC13	Biodigestion cycle time	Time required to complete the biogas production cycle, from the entry of waste to the output of the chosen products (outputs).

Source: the author, 2023.

The MDCA models proposed in this study are underpinned by a selection of crucial parameters, each carefully chosen to encapsulate the multifaceted nature of decision making in biogas production projects. The rationale behind the inclusion of these parameters stems from an extensive review of 58 articles, ensuring a comprehensive representation of factors influencing project success. The following key parameters were identified: technical feasibility, economic viability, social impact, and environmental impact.

The technical feasibility parameter considers the technical viability of the biogas production process, encompassing aspects such as biodigester technology, waste feedstock characteristics, and process efficiency. The selection of this parameter reflects its recurring importance in the literature and its direct impact on the overall project success. Economic viability evaluates the economic aspects of biogas projects that are vital for sustainable implementation. Parameters such as cost–benefit analysis, return on investment, and financial feasibility were chosen to represent economic considerations. Social impact considers the social dimensions of biogas projects, and parameters related to community engagement, public acceptance, and social benefits were included. The importance of social aspects in decision making is highlighted in the literature, emphasizing the need for projects to align with community values and to enhance societal well-being. Environmental impact incorporated parameters of the environmental footprint of biogas production, such as greenhouse gas emissions, waste reduction, and ecological considerations. This reflects the imperative to address environmental sustainability and to minimize adverse ecological effects.

The selection of these crucial parameters was guided by their recurrent presence in the reviewed literature, affirming their significance in influencing decision-making processes in biogas projects. Additionally, the parameters were chosen to provide a holistic view that balances technical, economic, social, and environmental considerations. While the chosen parameters strive to encompass the diverse facets of biogas project evaluation, certain assumptions and limitations should be acknowledged. The availability of comprehensive and accurate data, especially for social and environmental aspects, may vary across different contexts, impacting the precision of the models. Furthermore, the weighting of parameters might be subject to project-specific variations, and the models assume a certain level of stakeholder engagement and data quality.

These considerations underscore the importance of interpreting the results within the context of the specific project and environment, acknowledging the inherent uncertainties and potential variations associated with the chosen parameters.

3.3 Results and Discussion

The propositions for biogas production projects from organic waste are presented below according to the phase of the biogas production cycle to which the multicriteria decision-making model refers project, biodigester type, initial, cycle, location, and final. It is important to note that the percentages presented in this research reflect the frequency with which each subcriteria appeared in the reviewed articles. While higher frequency suggests potential importance, it does not definitively establish it. Con-text-specific considerations, expert judgment, and the potential overlap between some criteria can also influence their significance. Additionally, while not directly employed in this study, importance weighting techniques could be used to further refine the models for specific applications in real-world scenarios, tailoring the decision-making process to individual project needs and priorities.

3.3.1 Project

The project phase model, presented in Table 8, has a higher number of subcriteria than the other models. This may reflect the complexity of factors that need to be considered in a project phase. The project phase model is more heavily weighted toward economic and technical subcriteria, which suggests that these are the most important factors during the project phase.

Table 8. Project model criteria

Code	Sub-criteria	Frequency (%)
TEC03	Available technology	15,87
TEC02	Organic waste production	10,32
TEC08	Composition of biogas produced	9,52
TEC04	Output production potential	4,76
TEC11	Water demand for production	3,97
ECO01	Operational cost	8,73
ECO03	Market characteristics	3,97
ECO02	Initial investment	3,17
ECO09	Subsidies	3,17
ECO06	Value of output production	2,38
SOC03	Public policy	6,35
SOC02	Community characteristic	1,59
SOC01	Community expectation	0,79
SOC05	Social impacts	0,79
SOC04	Generation of jobs	0,79
ENV03	Current pollutant emission	2,38
ENV01	Characteristic of territorial occupation	2,38
ENV07	Current waste treatment	2,38
ENV02	Potential environmental benefits	0,79
ENV04	Potential for pollutant emission mitigation	0,79
ENV06	Environmental restrictions	0,79

Source: the author, 2023.

The model comprises 85.68% of all the subcriteria found in articles regarding the project phase of biogas projects. Among these, the technical subcriteria “available technology” and “organic waste production” (TEC03; TEC02) represent 15.87% and 10.32% of the findings, respectively.

Given that the subcriteria “potential environmental benefit,” “potential for pollu-tant emission mitigation”, and “environmental restriction” (ENV02; ENV04; ENV06) share the same percentage frequency, these were retained in the model. In this case, the researcher acknowledges that it is not possible to rank the significance of these subcriteria in decision making for biogas production projects. Therefore, the MDCA model for biogas project analysis encompasses a total of 21 subcriteria.

3.3.2 Biodigester Type

Table 9 presents the model developed to evaluate the options of biodigester types, as well as the models for location and the initial phase, which embraces all the subcriteria found in the research dedicated to these specific decision-making aspects in biogas projects. However, in this case, nine technical subcriteria were included, as six of them exhibited the same percentage frequency. In the economic domain, six subcriteria were considered, with “initial investment” being the most frequent (11.11%), followed by “operational cost” and “lifespan” (5.56% each), and “waste transport cost”, “risk”, and “payback” (2.78%).

Table 9. Biodigester type model criteria

Code	Sub-criteria	Frequency (%)
TEC08	Composition of biogas produced	11,11
TEC11	Water demand for production	8,33
TEC01	Composition of organic waste	5,56
TEC09	Outputs demand	2,78
TEC04	Output production potential	2,78
TEC05	Potential biogas production	2,78
TEC07	Degree of efficiency	2,78
TEC03	Available technology	2,78
TEC06	Available area for plant	2,78
ECO02	Initial investment	11,11
ECO01	Operational cost	5,56
ECO07	Lifespan	5,56
ECO04	Waste Transport Cost	2,78
ECO08	Risk	2,78
ECO12	Payback	2,78
SOC04	Generation of jobs	5,56
SOC05	Social impacts	2,78
ENV02	Potential environmental benefits	11,11
ENV01	Characteristic of territorial occupation	5,56
ENV05	Energy impact	2,78

Source: the author, 2023.

Nevertheless, in the social and environmental domains, only two and three sub-criteria were found, respectively. In the social domain, “generation of jobs” (5.56%) and “energy impact” (2.78%) were identified, while in the environmental domain, “potential environmental benefit” (11.11%), “characteristic of territorial occupation” (5.56%), and “energy impact” (2.78%) were included.

3.3.3 Initial

The MDCA model for the initial phase, presented in Table 10, encompassed all the subcriteria found in the research studies that addressed this stage of biogas production. As the location and biodigester-type models suggest, there is a convergence of the cri-teria considered in this phase.

Table 10. Initial model criteria

Code	Sub-criteria	Frequency (%)
TEC09	Outputs demand	14,29
TEC08	Composition of biogas produced	10,20
TEC11	Water demand for production	10,20
TEC07	Degree of efficiency	10,20
TEC04	Output production potential	6,12
ECO01	Operational cost	8,16
ECO02	Initial investment	8,16
ECO05	IRR	4,08
ECO06	Value of output production	2,04
ECO04	Waste Transport Cost	2,04
ECO11	Outputs price	2,04
ECO12	Payback	2,04
ECO14	Depreciation	2,04
SOC01	Community expectation	4,08
SOC02	Community characteristic	2,04
SOC04	Generation of jobs	2,04
ENV02	Potential environmental benefits	4,08
ENV01	Characteristic of territorial occupation	2,04
ENV04	Potential for pollutant emission mitigation	2,04
ENV06	Environmental restrictions	2,04

Source: the author, 2023.

However, these indicators are predominantly focused on the economic scope. Within this context, eight economic subcriteria were considered, as five of them exhibited the same percentage frequency. Additionally, three social and four environmental subcriteria were included, as no further indicators related to these criteria were found in these articles. Furthermore, it was observed that approximately 50% of the subcriteria are concentrated in the technical area.

3.3.4 Cycle

The MDCA for evaluating the entire biogas cycle presented in Table 11 contains 20 subcriteria, 5 for each of the four criteria (technical, economic, social, and environmental), and this is the only model where no adaptation was necessary to the predetermined quantity for constructing the model. All the subcriteria included in the model account for 82.37% of all the subcriteria found in articles that dealt with the biogas production cycle.

Table 11. Cycle model criteria

Code	Sub-criteria	Frequency (%)
TEC09	Exits demand	9,56
TEC08	Composition of biogas produced	8,82
TEC03	Available technology	8,82
TEC11	Water demand for production	6,62
TEC07	Degree of efficiency	2,94
ECO02	Initial investment	6,62
ECO01	Operational cost	6,62
ECO10	Valuation of the Enterprise	2,94
ECO05	IRR	2,94
ECO07	Lifespan	2,21
SOC02	Community characteristic	4,41
SOC04	Generation of jobs	2,21
SOC05	Social impacts	2,21
SOC01	Community expectation	2,21
SOC03	Public policy	1,47
ENV03	Current pollutant emission	4,41
ENV02	Potential environmental benefits	3,68
ENV05	Energy impact	1,47
ENV04	Potential for pollutant emission mitigation	1,47
ENV01	Characteristic of territorial occupation	0,74

Source: the author, 2023.

Subcriteria were found with frequencies ranging from 0.74% to 9.56%, with the most common being the technical subcriteria “exists demand” and the least frequent being the environmental subcriteria “characteristic of territorial occupation” (TEC09; ENV01).

3.3.5 Plant location

The proposed MDCA model to analyze the location of the biogas production plant is presented in Table 12, and encompasses 17 subcriteria, which constitute 100% of the findings in these research studies, meaning that all the relevant subcriteria for this phase of biogas production were included. This model consists of three social and three environmental subcriteria. However, six economic subcriteria were incorporated, all of which exhibited the same percentage frequency (2.27%). Consequently, it was not possible to exclude any of them from the model.

Table 12. Plant location model criteria

Code	Sub-criteria	Frequency (%)
TEC01	Community expectation	27,27
TEC09	Outputs demand	6,82
TEC08	Composition of biogas produced	2,27
TEC04	Output production potential	2,27
TEC10	Plant energy demand	2,27
TEC12	Waste production	2,27
ECO02	Initial investment	2,27
ECO06	Value of output production	2,27
ECO04	Waste Transport Cost	2,27
ECO11	Outputs price	2,27
ECO08	Risk	2,27
ECO10	Valuation of the Enterprise	2,27
SOC02	Community characteristic	4,55
SOC04	Generation of jobs	2,27
SOC05	Social impacts	2,27
ENV01	Characteristic of territorial occupation	29,55
ENV02	Potential environmental benefits	2,27
ENV03	Current pollutant emission	2,27

Source: the author, 2023.

In this context, the environmental subcriteria “characteristic of territorial occupation” (ENV01) presented the highest percentage frequency within the entire model (29.55%), while the technical subcriteria “community expectation” (TEC01) ac-counted for 27.27% of the findings. This implies that, within the scientific literature, more than half of the decision-making indicators for determining the location of a biogas plant are concentrated in these aspects.

3.3.6 Final

As shown in Table 13, in articles that addressed the final phase of biogas production, subcriteria were included that account for 87.74% of the total found. No additional environmental subcriteria were found in articles dealing with the final phase of the biogas production cycle, and, consequently, only three environmental subcriteria were included. Therefore, the MDCA for the final phase is composed of 18 subcriteria, with 5 each in the technical, economic, and social aspects, and 3 in the environmental aspect.

Table 13. Final model criteria

Code	Sub-criteria	Frequency (%)
TEC08	Composition of biogas produced	12,26
TEC11	Water demand for production	7,55
TEC07	Degree of efficiency	5,66
TEC09	Outputs demand	3,77
TEC03	Available technology	2,83
ECO01	Operational cost	8,49
ECO02	Initial investment	7,55
ECO06	Value of output production	2,83
ECO05	IRR	1,89
ECO03	Market characteristics	1,89
SOC01	Community expectation	7,55
SOC02	Community characteristic	2,83
SOC03	Public policy	1,89
SOC04	Generation of jobs	0,94
SOC05	Social impacts	0,94
ENV02	Potential environmental benefits	11,32
ENV03	Current pollutant emission	4,72
ENV01	Characteristic of territorial occupation	2,83

Source: the author, 2023.

In this model, subcriteria were found with frequencies ranging from 0.94% to 12.26%. Of note are the social subcriteria “generation of jobs” and “social impacts,” as well as the technical subcriteria “composition of biogas produced” (SOC04; SOC05; TEC08). The environmental subcriteria “potential environmental benefits” also stands out, representing 11.23% of all the subcriteria found in articles related to the final phase of biogas production.

3.4 SYNTHESIS

The developed models have between 18 and 21 subcriteria. Three of these models (initial, location, and biodigester type) encompass all the most relevant subcriteria as found in the literature for their respective decision-making phases in biogas projects. This is likely because these phases are relatively well-defined, and the studies converge in relation to the decision-making criteria that should be considered. On the other hand, the MDCA for the cycle incorporates 82.37% of the subcriteria already utilized in existing research for project evaluations in biogas, which may be because these phases are less well-defined or there is less research on the decision-making criteria that should be considered.

Table 14. Models' criteria

Mode	Cycle	Final	Project	Initial	Localization	Biodigester Type	Media
TEC	5	5	5	5	6	9	**5.83**
ECO	5	5	5	8	6	6	**5.83**
SOC	5	5	5	3	3	2	**3.83**
ENV	5	3	6	4	3	3	**4.00**
Media	**5**	**4.5**	**5.25**	**5**	**4.5**	**5**	**4.88**

Source: the author, 2023.

To assess the current research's proposition of achieving a balance among technical, economic, social, and environmental aspects within the decision-making models, the number of subcriteria for each criterion are presented according to the six pro-posed models, along with their averages, as shown in Table 10. Also, Table 15 shows the presence of each subcriteria in the six different multicriteria models.

The technical subcriteria "composition of biogas produced" (TEC08) was present in all six models, with its frequency ranging from 2.33% in the location model to 12.38% in the final model. The subcriteria "community expectation" (TEC01) was only identified in the location model, appearing with a frequency of 27.91%.

In terms of the economic subcriteria, "initial investment" (ECO02) featured in all six models, most frequently in the biodigester-type model (11.11%) and least often in the location model (2.27%). The subcriteria "operational cost" was incorporated in five out of the six models, being most prevalent in the project model (8.73%).

The technical subcriteria "composition of biogas produced" (TEC08) was present in all six models, with its frequency ranging from 2.33% in the location model to 12.38% in the final model. The subcriteria "community expectation" (TEC01) was only identified in the location model, appearing with a frequency of 27.91%.

Table 15. MDCA synthesis

Criteria	Project	Biodigester-Type	Initial	Cycle	Plant Location	Final
ENV01	X	X	X	X	X	X
ENV02	X	X	X	X	X	X
ENV03	X			X	X	X
ENV04	X		X	X		
ENV05		X		X		
ENV06	X		X			
ENV07	X					
ECO01	X	X	X	X		X
ECO02	X	X	X	X	X	X
ECO03	X					X
ECO04		X	X		X	
ECO05			X	X		X
ECO06	X		X		X	X
ECO07		X		X		
ECO08		X			X	
ECO09	X					
ECO10				X	X	
ECO11			X		X	
ECO12		X	X			
ECO13						
ECO14			X			
SOC01	X		X	X		X
SOC02	X		X	X	X	X
SOC03	X			X		X
SOC04	X	X	X	X	X	X
SOC05	X	X		X	X	X
TEC01		X			X	
TEC02	X					
TEC03	X	X		X		X
TEC04	X	X	X		X	
TEC05		X				
TEC06		X				
TEC07		X	X	X		X
TEC08	X	X	X	X	X	X
TEC09		X	X	X	X	X
TEC10					X	
TEC11	X	X	X	X		X
TEC12					X	

In terms of the economic subcriteria, “initial investment” (ECO02) was featured in all six models, most frequently in the biodigester-type model (11.11%) and least often in the location model (2.27%). The subcriteria “operational cost” was incorporated in five out of the six models, being most prevalent in the project model (8.73%).

The social subcriteria “generation of jobs” (SOC04) was present in all models, although its frequency was relatively low across the board. Its occurrence ranged from 0.79% in the project model to 5.56% in the biodigester-type model. The "social impact" subcriteria was included in five of the six models, being absent only in the one ad-dressing the initial phase of biogas projects.

Environmental subcriteria "characteristic of territorial occupation" and "potential environmental benefits" (ENV01; ENV02) were also present in all models, with frequencies ranging from 0.79% in the project model to 11.43% in the final model for the former, and from 0.75% in the cycle model to 30.23% in the location model for the latter.

3.5 DISCUSSION

This study emphasizes the equilibrium of environmental, social, economic, and technical criteria in the decision-making process. The literature survey has exposed a lack of such a balanced approach in existing articles, highlighting the need for a sustainability evaluation of biogas production projects from organic waste.

It presents six decision-making models based on different phases of the biogas production cycle: project, cycle, final, initial, biodigester type, and location. These models, encompassing 17 to 21 subcriteria across environmental, social, economic, and technical categories, reflect a holistic view of project evaluation. Notably, certain sub-criteria consistently appeared across all models, such as the composition of biogas produced, initial investment, characteristics of territorial occupation, potential environmental benefits, and generation of jobs (TEC08; ECO02; ENV01; ENV02; SOC04). This consistency emphasizes their significance in project evaluation, irrespective of the specific phase of the cycle.

Despite efforts to balance the criteria, the proposed models exhibit some asymmetry, aligning with findings in the literature. Models for the final and initial phases, for instance, show fewer subcriteria under environmental and social considerations, while the biodigester-type model places a greater emphasis on technical and economic aspects.

The presented MDCA models offer a comprehensive framework for biogas project evaluation, catering to technical, economic, social, and environmental aspects. This adaptability allows project managers to make informed decisions that are aligned with the project's goals and stakeholder needs. The models' flexibility in assigning different weights to criteria enables customization to the specific context of each project, a valuable feature for addressing complex or unique requirements.

Illustrating the practical applicability of our research, it is possible to reference prominent biogas projects globally. The large-scale municipal waste digesters in Swedish cities showcase the potential of biogas for simultaneous urban waste management and energy generation. By transforming organic waste from households and businesses into biogas for electricity and heat generation, these digesters offer a compelling example of closed-loop resource management and circular economy principles, aligning with this research focus on promoting sustainable biogas solutions. This approach directly tackles the dual challenge of waste reduction and diversifying energy sources, addressing critical environmental concerns while contributing to energy independence at the local level. The utilization of biogas for both electricity and heat generation further maximize the project impact, demonstrating the efficiency and versatility of this renewable fuel source [60].

Similarly, the Biogas Bus Program in Nepal exemplifies how the proposed MDCA models could empower sustainable and socially responsible biogas project implementation. The program uses agricultural waste to fuel public buses, which directly ad-dresses waste management challenges while reducing air pollution and greenhouse gas emissions, contributing to both environmental sustainability and improved public health. This is an encouragement to promote biogas projects that generate positive impacts beyond solely energy production. Furthermore, the program's decentralized nature, focusing on small-scale digesters, empowers rural communities by creating local jobs and fostering energy independence. This aligns with incorporating social considerations into decision making, ensuring that biogas projects contribute to rural development and empower local communities [61].

These real-world examples demonstrate the versatility and positive impacts of biogas projects when considered through the lens of our proposed MDCA models. Such analyses could provide valuable insights into optimizing the integration of biogas systems into diverse environments, contributing to a more sustainable future.

Furthermore, the evolving significance of biomethane as a renewable fuel under-scores the urgency of the proposed MDCA models. As biomethane gains prominence in decarbonizing energy systems, our holistic approach, encompassing economic, environmental, social, and technical aspects, aligns seamlessly with global visions outlined in reports such as the ADBA's "Biomethane: The Pathway to 2030" [62].

However, it is crucial to acknowledge the potential challenges in applying the proposed MDCA frameworks to specific project scenarios and needs. Data availability and quality, stakeholder engagement, and resource constraints are formidable considerations. Overcoming these challenges requires meticulous assessment, effective communication, and, potentially, adjustments to the models' weighting or the inclusion of additional subcriteria.

In conclusion, while this study significantly contributes to the advancement of sustainable biogas initiatives, practical validation of these decision-making models in real-world projects remains imperative. Future research endeavors, involving collaboration between biogas production experts and public administration decision makers, can further refine and balance the selection of criteria, ensuring the continued evolution and effectiveness of MDCA frameworks in guiding the development of truly sustainable biogas projects.

3.6 Conclusions

In conclusion, the decision-making models proposed in this study present a robust and versatile framework for enhancing the planning, implementation, and evaluation of biogas projects. The comprehensive nature of these models, encompassing technical, economic, social, and environmental considerations, positions them as valuable tools for project managers and policymakers seeking to make informed decisions. The adaptability of the framework allows for customization based on project-specific needs, promoting flexibility in addressing diverse challenges.

Beyond their immediate implications for project management and policymaking, the findings of this study highlight critical avenues for future research in the realm of biogas decision making. Specifically, there is a discernible need for the further exploration of social and environmental criteria within the biogas project context. This opens opportunities for researchers to delve into the intricacies of community engagement, environmental impact assessment, and the integration of sustainable practices within the decision-making process.

Moreover, the observed gap in research signals a need for dedicated efforts in understanding how decision-making models can be seamlessly integrated into the practical development of biogas projects. Bridging this gap will involve exploring implementation strategies, assessing the effectiveness of these models in real-world scenarios, and identifying best practices for their incorporation into the decision-making processes of biogas project development.

As the biogas landscape continues to evolve, and with an increasing emphasis on sustainability and societal impact, this study propels the discourse forward by not only providing valuable decision-making tools but also by outlining a roadmap for future research endeavors. By addressing these research gaps, the broader scientific community can contribute to the advancement of sustainable biogas initiatives, ensuring their positive impact on the environment, society, and overall project success.

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APPENDIX

num	ID	obj_code	cycle	residue	country	journal	year	nature	approach	purpose	data	analisys	criterias
1	LIANG T et al (2021)	OBJ01	POC04	RES01	COU12	JOU10	2021	NAT01	APP01	PUR02	DAT02	ANA01	ECO02;ENV02;TEC08;TEC11;TEC11
2	RUPF G et al 2017	OBJ01	POC06	RES01	COU12	JOU08	2017	NAT01	APP01	PUR02	DAT02	ANA01	ECO01;ECO02;ECO08;ENV01;ENV02;SOC05;TEC01;TEC01;TEC03;TEC07;TEC08;TEC08;TEC11
3	RAO B et al 2014	OBJ05	POC06	RES01	COU10	JOU11	2014	NAT01	APP01	PUR02	DAT02	ANA01	ECO01;ECO02;ECO02;ECO04;ECO07;ECO07;ECO12;ENV01;SOC04;SOC04;TEC05;TEC06;TEC08;TEC11;TEC11
4	FEIZ R et al 2020	OBJ06	POC06	RES04	COU06	JOU11	2020	NAT01	APP01	PUR02	DAT02	ANA04	ECO02;ENV02;ENV02;ENV02;ENV05;TEC04;TEC08;TEC09
5	ROUBIK H et al 2018	OBJ04	POC01	RES02	COU12	JOU11	2018	NAT01	APP01	PUR02	DAT02	ANA07	ECO07;TEC01;TEC02;TEC11;ECO04;ENV01;ENV01;TEC01
6	BOJESEN M BOERBOOM L SKOV-PETERSEN H 2015	OBJ02	POC05	RES02	COU12	JOU11	2018	NAT01	APP01	PUR02	DAT02	ANA01	ECO02;TEC01
7	KALINICHENKO A HAVRYSH V PEREBYYNIS V 2016	OBJ04	POC02	RES01	COU07	JOU11	2016	NAT01	APP01	PUR02	DAT02	ANA03	ECO03;ENV06;SOC01;SOC04;SOC05
8	CHODKOWSKA-MISZCZUK et al 2020	OBJ02	POC01	RES01	COU12	JOU11	2020	NAT01	APP01	PUR01	DAT01	ANA02	ECO03;ENV06;SOC01;SOC04;ENV03;ENV03;ENV03;TEC01;TEC03;TEC03;TEC03;TEC03;TEC03;TEC03;TEC05;TEC08;TEC09;TEC09;TEC09;TEC11
9	IANNOU-TTOFA et al 2020	OBJ04	POC01	RES02	COU12	JOU07	2021	NAT01	APP01	PUR02	DAT02	ANA08	ECO01;ECO01;ECO02;ENV01;ENV02;TEC06;TEC08
10	BERHE M et al 2017	OBJ02	POC02	RES01	COU12	JOU05	2017	NAT01	APP01	PUR01	DAT01	ANA07	TEC03;TEC09;TEC09;TEC09;TEC09
11	BHATT A H TAO L 2020	OBJ04	POC04	RES06	COU05	JOU11	2020	NAT01	APP01	PUR02	DAT02	ANA03	ECO03;ECO05;ECO05;ENV02;ENV02;ENV04;ENV05;SOC02;SOC03;SOC05;TEC04;TEC08;TEC09;TEC11
12	LINDFORS A et al 2019	OBJ05	POC01	RES01	COU12	JOU01	2019	NAT01	APP02	PUR02	DAT02	ANA01	ECO01;ECO01;ECO02;ECO05;ECO12;TEC03;TEC08;TEC09;TEC11
13	BARRAGAN-ESCADON A et al 2020	OBJ02	POC01	RES01	COU12	JOU01	2020	NAT01	APP01	PUR02	DAT02	ANA03	ECO08;ENV01;ENV01;ENV01;ENV01;ENV01;ENV01;ENV01;SOC05;TEC01;TEC01;TEC01;TEC01
14	SILVAS ALCADA-ALMEIRA L DIAS L C 2014	OBJ01	POC05	RES02	COU12	JOU04	2014	NAT01	APP01	PUR02	DAT02	ANA01	ECO01;ECO02;ENV03;TEC08;TEC11
15	KONNEH K V et al 2021	OBJ01	POC02	RES01	COU12	JOU01	2021	NAT01	APP01	PUR02	DAT02	ANA01	TEC04;TEC08
16	WAGNER M et al 2018	OBJ06	POC01	RES06	COU01	JOU11	2018	NAT01	APP01	PUR01	DAT01	ANA04	ECO01;ECO01;ECO02;ECO02;ECO05;ECO06;ECO11;ECO12;TEC07;TEC
17	BARTOLI A et al 2020	OBJ02	POC04	RES05	COU11	JOU06	2020	NAT01	APP01	PUR02	DAT02	ANA03	ECO03;SOC02;SOC03;SOC03;TEC11
18	AMMENBERG J et al 2018	OBJ02	POC03	RES01	COU06	JOU11	2018	NAT01	APP02	PUR02	DAT02	ANA08	ENV01;ENV01;ENV01;TEC01;TEC01;TEC01;TEC01;TEC01
19	SOHA T HARTMANN B 2022	OBJ01	POC05	RES01	COU12	JOU11	2022	NAT01	APP01	PUR02	DAT02	ANA01	TEC03;TEC07;TEC07;TEC08;TEC08;TEC08
20	GANDHI P et al 2018	OBJ05	POC02	RES04	COU10	JOU11	2018	NAT01	APP01	PUR02	DAT02	ANA01	ECO01;ECO01;ECO02;ECO04;SOC02;TEC07;TEC07;TEC07;TEC08;TEC0
21	MENG L et al 2020	OBJ03	POC04	RES01	COU03	JOU02	2020	NAT01	APP01	PUR02	DAT02	ANA01	ECO01;ECO02;ECO02;ECO07;ENV03;TEC04;TEC04;TEC04;TEC04;TEC06
22	KALINICHENKO et al 2017	OBJ01	POC03	RES01	COU07	JOU11	2017	NAT01	APP01	PUR01	DAT02	ANA03	ECO01;ECO06;ECO06;ENV02;TEC09
23	KLUCZEK A 2018	OBJ04	POC02	RES02	COU05	JOU11	2018	NAT01	APP01	PUR01	DAT02	ANA04	ENV01;ENV02;ENV07;TEC03;TEC04;TEC05;TEC06;TEC07
24	CHRISPIN M C et al 2020	OBJ03	POC03	RES03	COU09	JOU10	2020	NAT01	APP01	PUR01	DAT02	ANA08	ENV03;TEC09
25	LI F et al 2016	OBJ02	POC03	RES05	COU03	JOU07	2016	NAT01	APP01	PUR01	DAT02	ANA08	ECO01;ECO01;ECO04;ECO04;ENV01;ENV03;ENV04;SOC04;TEC04;TEC0
26	PEHLKEN A et al 2020	OBJ06	POC03	RES01	COU01	JOU01	2020	NAT01	APP01	PUR02	DAT02	ANA01	TEC02;TEC08;TEC08;TEC11;TEC11
27	OBILEKE K et al 2020	OBJ06	POC03	RES02	COU12	JOU11	2020	NAT01	APP01	PUR02	DAT02	ANA08	ECO02;ENV03;TEC08
28	UGWU S ENWEREMADU C 2021	OBJ05	POC01	RES03	COU08	JOU11	2021	NAT01	APP01	PUR02	DAT02	ANA01	ECO03;ECO05;ECO09;ECO09;ECO09;ECO12
29	MYSAKOVA et al 2016	OBJ02	POC03	RES01	COU12	JOU11	2016	NAT01	APP01	PUR01	DAT01	ANA02	ECO01;ECO01;ECO02;ECO02;ECO05;ECO07;ECO08;ECO08;ECO10;ECO10;TEC08;TEC08;TEC08
30	Cheraghalipour et al 2022	OBJ04	POC01	RES01	COU12	JOU01	2022	NAT01	APP01	PUR01	DAT02	ANA03	ECO01;ECO02;ECO09;ENV04;ENV05;SOC01;SOC01;SOC02;SOC02;SOC
31	ZHANG W 2018	OBJ06	POC01	RES01	COU03	JOU08	2018	NAT01	APP01	PUR02	DAT01	ANA01	ECO01;ECO01;ECO02;ECO06;TEC08
32	YANG H et al 2020	OBJ01	POC02	RES01	COU02	JOU11	2020	NAT01	APP01	PUR01	DAT02	ANA08	ECO01;ECO04;TEC06;TEC08;TEC08
33	ARODUDU O T et al 2017	OBJ03	POC01	RES01	COU01	JOU03	2017	NAT01	APP01	PUR02	DAT02	ANA04	ECO03;ECO07;ECO10;ECO11;ECO14;SOC02;SOC02;SOC03;TEC03;TEC
34	VERHOOG R et al 2016	OBJ01	POC01	RES01	COU12	JOU11	2016	NAT01	APP01	PUR02	DAT02	ANA08	TEC01;TEC04;TEC08
35	CIAPALA B et al 2017	OBJ05	POC05	RES07	COU11	JOU11	2017	NAT01	APP01	PUR01	DAT02	ANA05	ENV04;ENV06
36	SADHUKHAN J 2014	OBJ01	POC04	RES03	COU02	JOU03	2017	NAT01	APP01	PUR02	DAT02	ANA08	ECO01;ECO02;ECO10;ENV01;TEC02;TEC07;TEC09;TEC11;TEC11
37	TAMPIO E et al 2022	OBJ01	POC01	RES01	COU04	JOU09	2022	NAT01	APP01	PUR01	DAT02	ANA03	SOC02;SOC02;TEC01;TEC09;TEC09;TEC09;TEC10
38	LAASASENAHO K et al 2019	OBJ01	POC05	RES01	COU04	JOU11	2019	NAT01	APP01	PUR01	DAT02	ANA05	ECO05;ECO14;ENV01;ENV02;SOC04;TEC11
39	BRENES-PERALTA L 2020	OBJ03	POC04	RES04	COU12	JOU11	2020	NAT01	APP01	PUR02	DAT02	ANA01	ECO01;ECO02;ENV01;ENV03;TEC04;TEC08
40	Tonrangklang et al 2022	OBJ02	POC02	RES07	COU12	JOU05	2022	NAT01	APP01	PUR01	DAT02	ANA02	ECO01;ECO02;ENV02;ENV03;TEC08
41	HORSCHIG T et al 2019	OBJ02	POC01	RES01	COU01	JOU04	2018	NAT01	APP01	PUR01	DAT02	ANA08	ECO01;ECO02;ENV02;ENV02;ENV03;SOC02;SOC04;TEC07;TEC11
42	AGBOULE et al 2021	OBJ05	POC01	RES01	COU12	JOU01	2021	NAT01	APP01	PUR02	DAT01	ANA01	ECO01;ECO02;ECO04;ECO11;ENV02;TEC07;TEC07;TEC08
43	GUNARATNE T et al 2016	OBJ01	POC02	RES07	COU12	JOU11	2016	NAT01	APP01	PUR01	DAT02	ANA02	ECO03;ECO04;ECO05;ECO05;ECO08;ECO08;ENV01;ENV02;ENV02;ENV02;ENV02;ENV02;SOC01;SOC01;SOC01;SOC01;SOC01;SOC01;SOC02;SOC02;SOC02;TEC01;TEC08;TEC11;TEC11;TEC11
44	HAGMAN L FEIZ R 2021	OBJ01	POC02	RES01	COU06	JOU11	2022	NAT01	APP01	PUR02	DAT02	ANA01	TEC03;TEC03;TEC08;TEC09;TEC09;TEC11
45	PEREZ-CAMACHO M N CURRY R 2017	OBJ06	POC02	RES06	COU02	JOU11	2017	NAT01	APP01	PUR01	DAT02	ANA02	TEC07;TEC09;TEC09;TEC09;TEC09
46	GAIDA D et al 2012	OBJ04	POC01	RES05	COU01	JOU11	2012	NAT01	APP01	PUR01	DAT02	ANA06	ECO10;ENV02;ENV02;ENV03;ENV03;TEC07;TEC07;TEC08;TEC08
47	OSHEA et al 2021	OBJ05	POC02	RES01	COU12	JOU11	2021	NAT01	APP01	PUR02	DAT02	ANA01	ECO02;SOC04;TEC03;TEC03;TEC05;TEC09
48	SMITH J U et al 2015	OBJ03	POC01	RES01	COU08	JOU11	2015	NAT01	APP01	PUR01	DAT02	ANA02	ECO03;ENV01;ENV07;ENV07;TEC03
49	DYER A et al 2021	OBJ01	POC03	RES03	COU05	JOU01	2021	NAT01	APP01	PUR01	DAT02	ANA02	ECO01;ECO02;ECO02;ECO03;ECO07;ECO09;ENV02;ENV02;ENV03;SOC01;SOC01;SOC03;SOC03;SOC04;SOC05;TEC08;TEC09;TEC11;TEC11;TE
50	RAHMAN M M et al 2013	OBJ03	POC02	RES01	COU04	JOU11	2013	NAT01	APP01	PUR02	DAT02	ANA01	ENV02;SOC03;TEC02;TEC03;TEC08;TEC09
51	DE MEDINA-SALAS L et al 201	OBJ02	POC03	RES01	COU12	JOU11	2019	NAT01	APP01	PUR01	DAT02	ANA07	ECO01;ECO01;ECO01;ECO01;ECO01;ECO01;ECO13;ECO13;TEC03;TEC03;TEC03;TEC03;TEC03;TEC08;TEC08;TEC08;TEC08;TEC08;TEC08;TEC0
52	DDIBA A K et al 2021	OBJ03	POC01	RES01	COU12	JOU11	2022	NAT01	APP01	PUR01	DAT02	ANA02	ECO06;TEC03;TEC09;TEC11
53	KANEESAMKANDI Z et al 2020	OBJ03	POC03	RES01	COU12	JOU01	2020	NAT01	APP01	PUR02	DAT02	ANA01	ECO01;ECO02;ECO02;ECO06;ECO06;ECO11;ENV06;SOC01;TEC02;TEC02;TEC02;TEC02;TEC03;TEC03;TEC03;TEC03;TEC03;TEC03;TEC03
54	BIERNASKI I SILVA C 2018	OBJ02	POC03	RES01	COU09	JOU11	2018	NAT01	APP01	PUR01	DAT02	ANA02	SOC03;SOC03;SOC03;SOC03;SOC03;SOC03
55	POGGIO D et al 2016	OBJ04	POC01	RES01	COU02	JOU09	2016	NAT01	APP01	PUR01	DAT02	ANA06	TEC03;TEC09
56	KHAWAJA C et al 2021	OBJ03	POC05	RES01	COU12	JOU02	2021	NAT01	APP01	PUR01	DAT02	ANA05	ECO02;ECO06;ECO10;ECO11;ENV01;ENV02;ENV03;SOC04
57	CHAHER N E H et al 2020	OBJ01	POC03	RES01	COU12	JOU01	2020	NAT01	APP01	PUR01	DAT02	ANA02	ECO01;ECO03;ECO03;ECO06;ECO07;ECO09;SOC02;TEC02;TEC02;TEC02;TEC02;TEC02;TEC02;TEC03;TEC03;TEC03;TEC03;TEC03;TEC03;
58	BAR REHRENSPERGER A 2018	OBJ01	POC04	RES02	COU12	JOU11	2018	NAT01	APP01	PUR01	DAT02	ANA02	SOC01;SOC01;TEC04;TEC04;TEC04;TEC08;TEC08;TEC09