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Proposal of Multicriteria Decision-Making Models for Biogas Production

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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

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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 1.

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 preferences 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 1. 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]

Table 1. *Cont.*

Project	Cycle	Final	Location
	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 1, 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 biodigestion system and transformed into biogas. This biogas can subsequently be refined into various outputs, such as biofertilizer, biogasoline, or electricity [12]. Figure 1 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, capacity, 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).

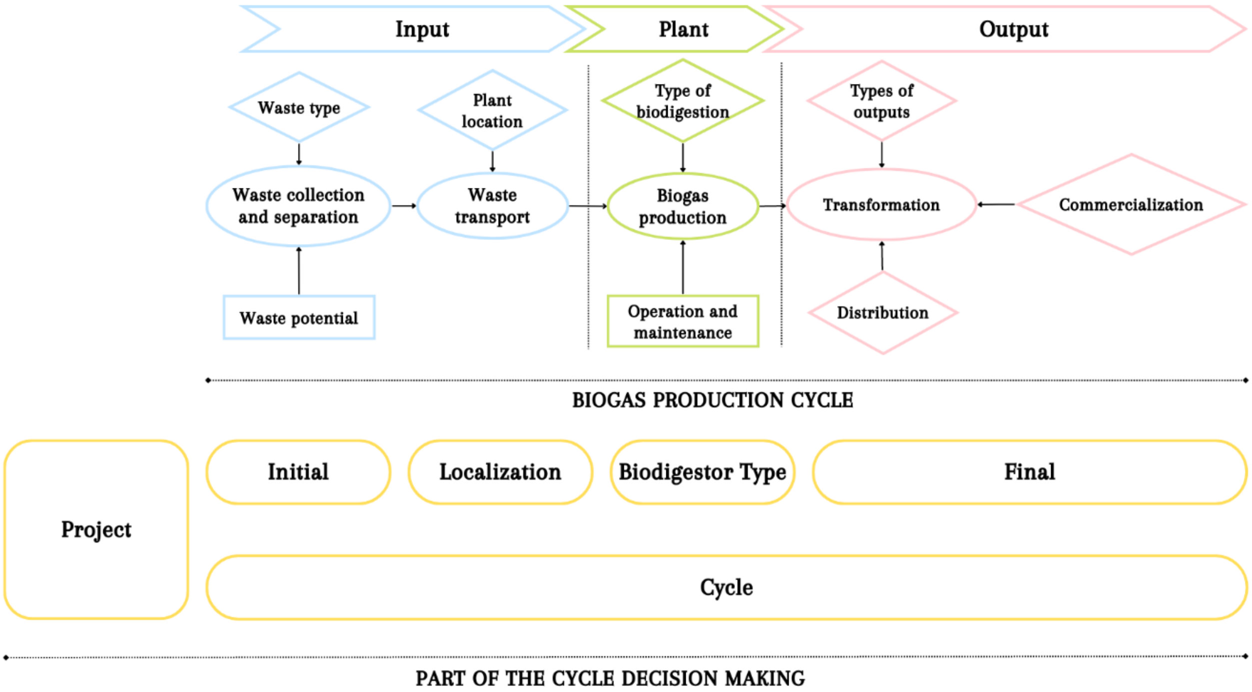

Figure 1. The biogas production cycle and its decision-making moments.

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 projects 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).

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 research'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 economic) 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 2. Environmental and economic subcriteria classification.

	Code	Subcriteria	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, such as demographic density, proximity to areas of environmental preservation, and river springs.
	ENV02	Potential environmental benefit	Environmental benefits provided by the project, such as an increase in the use of biofertilizers, residues reinserted in the economic chain, and 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 emissions avoided by the implementation of the project.
	ENV05	Energy impact	Substitution of the current energy matrix or availability of energy to the community/rural population through the project.
	ENV06	Environmental restriction	Environmental restrictions provided for in the project, such as the regulation of bad odors, noise and/or visual pollution, and impairment of preservation areas.
	ENV07	Current waste treatment	Current disposal methods of organic waste that are 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 in the project.
	ECO03	Market characteristic	Market characteristics that may be more or less conducive to the project, such as competitiveness, market share, interest rate, opportunity cost, and 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	Subsidy	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	Output 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	Gradual loss of value of the biogas plant.

Table 3. Social and technical subcriteria classification.

	Code	Subcriteria	Description
Social	SOC01	Community expectation	Community perception and expectations concerning 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 and public incentive programs.
	SOC04	Generation of jobs	Expected amount of direct and indirect jobs generated by the project.
	SOC05	Social impact	Predicted impacts on the community, such as increased public health, quality of life, decent work, and 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 concerning 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 a greater or lower conversion to outputs.
	TEC09	Output 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).

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. Results

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. Context-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.

3.1. Project

The project phase model, presented in Table 4, 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.

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 pollutant 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.

Table 4. Project model.

Code	Subcriteria	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 characteristic	3.97
ECO02	Initial investment	3.17
ECO09	Subsidy	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 impact	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 benefit	0.79
ENV04	Potential for pollutant emission mitigation	0.79
ENV06	Environmental restriction	0.79

3.2. Biodigester Type

Table 5 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%).

Nevertheless, in the social and environmental domains, only two and three subcriteria 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. Initial

The MDCA model for the initial phase, presented in Table 6, 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 criteria considered in this phase.

Table 5. Biodigester-type model.

Code	Subcriteria	Frequency (%)
TEC08	Composition of biogas produced	11.11
TEC11	Water demand for production	8.33
TEC01	Composition of organic waste	5.56
TEC09	Output 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 impact	2.78
ENV02	Potential environmental benefit	11.11
ENV01	Characteristic of territorial occupation	5.56
ENV05	Energy impact	2.78

Table 6. Initial model.

Code	Subcriteria	Frequency (%)
TEC09	Output 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	Output price	2.04
ECO12	Payback	2.04
ECO14	Depreciation	2.04
SOC01	Community expectation	4.08
SOC02	Community characteristic	2.04

Table 6. *Cont.*

Code	Subcriteria	Frequency (%)
SOC04	Generation of jobs	2.04
ENV02	Potential environmental benefit	4.08
ENV01	Characteristic of territorial occupation	2.04
ENV04	Potential for pollutant emission mitigation	2.04
ENV06	Environmental restriction	2.04

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.

3.4. Cycle

The MDCA for evaluating the entire biogas cycle presented in Table 7 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 7. Cycle model.

Code	Subcriteria	Frequency (%)
TEC09	Exists 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 impact	2.21
SOC01	Community expectation	2.21
SOC03	Public policy	1.47
ENV03	Current pollutant emission	4.41
ENV02	Potential environmental benefit	3.68
ENV05	Energy impact	1.47
ENV04	Potential for pollutant emission mitigation	1.47
ENV01	Characteristic of territorial occupation	0.74

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

3.5. Plant Location

The proposed MDCA model to analyze the location of the biogas production plant is presented in Table 8, 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 8. Plant model.

Code	Subcriteria	Frequency (%)
TEC01	Community expectation	27.27
TEC09	Output 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	Output 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 impact	2.27
ENV01	Characteristic of territorial occupation	29.55
ENV02	Potential environmental benefit	2.27
ENV03	Current pollutant emission	2.27

In this context, the environmental subcriterion "characteristic of territorial occupation" (ENV01) presented the highest percentage frequency within the entire model (29.55%), while the technical subcriterion "community expectation" (TEC01) accounted 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.

3.6. Final

As shown in Table 9, 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 9. Final model.

Code	Subcriteria	Frequency (%)
TEC08	Composition of biogas produced	12.26
TEC11	Water demand for production	7.55
TEC07	Degree of efficiency	5.66
TEC09	Output 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 characteristic	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 impact	0.94
ENV02	Potential environmental benefit	11.32
ENV03	Current pollutant emission	4.72
ENV01	Characteristic of territorial occupation	2.83

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 subcriterion "composition of biogas produced" (SOC04; SOC05; TEC08). The environmental subcriterion "potential environmental benefits" also stands out, representing 11.23% of all the subcriteria found in articles related to the final phase of biogas production.

3.7. 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.

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 proposed models, along with their averages, as shown in Table 10 below. The Table 11 shows the presence of each subcriterion in the six different multicriteria models.

Table 10. Model criteria quantities.

Mode	Cycle	Final	Project	Initial	Location	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

Table 11. 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	

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 subcriterion "operational cost" was incorporated in five out of the six models, being most prevalent in the project model (8.73%).

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The social subcriterion "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" subcriterion was included in five of the six models, being absent only in the one addressing 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.

4. 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 subcriteria 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 maximizes 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 addresses 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 underscores 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.

5. 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 up 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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