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Research paper

Towards Sustainable Energy: Economic and Environmental Factors Influencing Feasibility of Agricultural Waste Derived Biogas for Electricity Systems

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Abstract

More than 70% of the world's electricity generation comes from nonrenewable energy sources, which can cause environmental damage. However, alternative energy sources can bring environmental and economic benefits to companies and society. This study aims (i) to unveil the main economic tools and methods used to determine economic feasibility of using agricultural wastes for biogas and electricity generation systems, as well as the environmental aspects that hold influence over it, (ii) to identify the most relevant recent studies and main researchers in this field globally, and (iii) to propose a future agenda for the field. Employing a systematic literature review, a total of 51 articles were selected, and few characteristics were analyzed in terms of bibliometry, such as authorship, type of study, journals, and country. The economic viability analysis explored attributes such as payback, net present value, sensitivity analysis, internal rate of return, and cost-benefit. From an environmental perspective, life cycle assessment, as a technique, and circular economy, as an approach, have been frequently employed in this field. The analysis revealed that Europe (mainly Sweden and Belgium) emerged as the most important continent to develop studies on this topic. However, China and Brazil have shown a recent increase in the number of publications. Notably, no well-known authors were identified as working on the theme. In terms of types of study, case studies accounted for 80% of the final portfolio. Moreover, 60% of the documents analyzed demonstrated economic viability. This study can contribute to understanding the potential environmental impacts of electricity generation from biogas and assisting in decision-making within the public sector.

Keywords: Energy · Biodigester · Waste Management · Sustainable Development · Bioenergy

1. INTRODUCTION

The world's economy heavily relies on fossil energy sources, including hard coal, oil, natural gas, which are utilized for fuel production, electricity generation, chemicals production and other goods (Zastempowski, 2023). However, the long-term utilization of these depleted fossil energy sources is not considered sustainable (Uihlein and Schebek, 2009; Kalair et al., 2021). Consequently, there is a global trend and an increasing need to enhance the consumption of energy that combines clean energy generation and security, such as wind, solar, biomass, and hydropower (Barros et al., 2020). Growing concerns regarding energy security and environmental impacts can contribute to promoting the development of renewable sources, such as biomass (Carter et al., 2018).

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An increasingly widespread means of sustainable energy generation worldwide is biogas. Traditional substrates used for biogas production include municipal solid waste and organic waste derived from industrial and agricultural activities (Teghammar et al., 2014; Gupta et al., 2023). Manure from livestock industries has long been recognized as a significant source of environmental pollution (Frey et al., 2022). Nonetheless, biogas production utilizing livestock waste has the potential to generate clean electricity while also serving a solution to minimize environmental impacts (de Jesus et al., 2021). Several technologies are currently employed to treat manure discharges in livestock industries, aiming to mitigate environmental impacts. Noteworthy examples include Anaerobic Digestion (Nasir et al., 2012), Waste Treatment Lagoons (Liu and Wang, 2020), Solid-Liquid Separation (Grell et al., 2023), Composting (Zubair et al., 2020), Phosphorus Separation Technologies (Zangarini et al., 2020).

An essential factor identified in the literature is the economic feasibility analysis conducted through indicators that provide quantitative information about the attractiveness index of applying these new technologies. In this context, evaluation tools such as payback, net present value (NPV), internal rate of return (IRR), and cost-benefit analysis, all coupled with sensitivity analyses, are highlighted. Regarding environmental aspects, life cycle assessment (LCA) emerges as the most commonly used method to evaluate the environmental profile of processes and products. LCA is a systematic method based on international standards (ISO 2006a, b), allowing for the assessment of potential environmental impacts in each phase of a system's life cycle. A distinctive feature of Life Cycle Assessment (LCA) is its focus on products from a life-cycle perspective. Its broad scope is valuable for preventing the shifting of environmental impacts—for example, between different life-cycle stages, across regions, or among various types of environmental issues (Finnveden et al., 2009).

More recently, the circular economy has also gained traction in generating clean electricity, for instance, by using biodigesters and solar panels at farms (Nadaleti et al., 2020; Mendoza et al., 2022).The circular economy is an emerging economic model primarily focused on the reuse of waste, transforming it into raw materials and supporting various sustainability strategies—such as reuse, recycling, remanufacturing, reprocessing, and rethinking. This economic model promotes systems that are regenerative by design, aiming to slow down, narrow, and close resource loops (Mukherjee et al., 2023). By doing so, it reduces waste generation and minimizes the extraction of virgin raw materials from nature. Furthermore, accelerating the transition from a linear to a circular economy is increasingly seen as a global priority in response to climate change (Salvador et al., 2023).

Several authors have examined the utilization of biogas for electricity generation, such as Gwavuya et al. (2012), who conducted research in Germany; Akbulut (2012) in Turkey; Nzila et al. (2012) in Kenya; Chen and Chen (2013) and Wang et al. (2014) in China; Torquati et al. (2014) in Italy; Hublin et al. (2014) in Croatia; and Nogueira et al. (2015) in Brazil. Others have explored the combined production of electricity and heat, including Lantz (2012), Akbulut (2012), Ilic et al. (2014), Kang et al. (2014), and Wu et al. (2016). In addition, studies on biofuels were conducted by Starr et al. (2015) in Spain, Chakma et al. (2016) in India, and Ilic et al. (2014) in Sweden. Furthermore, the utilization of biogas for biorefineries was developed in the American continent by He et al. (2012), Moraes et al. (2014) in Brazil, and Cerón et al. (2015) in Colombia.

Nonetheless, a survey of the literature in the field revealed that there seem to be no studies synergistically investigating the economic viability of anaerobic digestion systems for biogas generation, while also considering the environmental perspective, especially using LCA, and a circular economy, thus using waste streams. While the research field of anaerobic digestion is not new, our literature survey highlights a significant gap - there is a scarcity of studies exploring the economic viability of anaerobic digestion systems for biogas generation, particularly when considering the environmental perspective, such as utilizing life cycle assessment, and adopting a circular economy that incorporates waste streams, thus environment and economy are addressed in a decoupled way, the environmental performance of systems is determined only after proven economic feasibility, or the economic feasibility is only assessed after environmental sustainability is proven positive, but they do not seem to be used in unison. Therefore, our research highlights the advantages of both approaches and proposes a comprehensive future agenda for biogas and renewable energy to seek coupling economic-environmental assessment of "agricultural waste-biogas-electricity" systems. Notably, it also proposes. Another unique aspect of our article is the proposition of economically viable and environmentally sustainable options for a biodigester within an agro-industrial system. Moreover, the article introduces novel elements that distinguish it from existing documents in the scientific field. These include presenting key authorship details, categorizing types of studies, identifying relevant journals, and mapping the countries contributing to this field. Additionally, the article delves into a biodigester's input and output dynamics across its life cycle phases.

Therefore, this study aims (i) to unveil the main economic tools and methods used to determine economic feasibility of using agricultural wastes for biogas and electricity generation systems, as well as the environmental aspects that hold influence over it, (ii) to identify the most relevant recent studies and main researchers in this field globally, and (iii) to propose a future agenda for the field. This research undertakes a systematic analysis of the major publications and scientific productions regarding economic viability methods for biogas generation. It examines the publication avenues and main journals where the research has been published, their influence in the academic field as indicated by journal impact factors, and the year of publication of the articles, showing a trend through time. Additionally, the intended objectives, the methodologies employed in these studies, and the conclusions reached are also considered.

This study is in line with the United Nations' Sustainable Development Goals (SDGs), particularly goal number 7, which aims to "Ensure access to affordable, reliable, sustainable, and modern energy for all", and goal number 12 which seeks to "Ensure sustainable consumption and production patterns". These goals, to be fully implemented according to the 2030 Agenda, are justified by alarming statistics such as "3 billion people relying on wood, coal, charcoal, or animal waste for cooking and heating" and "Energy being the dominant contributor to climate change, accounting for around 60 percent of total global greenhouse gas emissions" (UN, 2015).

2. METHODOLOGY

2.1 Design of Systematic Literature Review

A systematic literature review (SLR) was conducted to analyze the economic and environmental feasibility of using agricultural waste for biogas-based electricity generation. The review focused on articles published between 2012 and 2022, a period marked by significant advancements in biogas technologies and the growing emphasis on renewable energy sources following global sustainability initiatives such as the Paris Agreement and the UN's Sustainable Development Goals (SDGs).

The databases Web of Science, Scopus, and ScienceDirect were used to perform the searches during the second half of 2023. The search strategy combined keywords, truncation symbols, and Boolean operators, employing the following query: (("Biodigester" OR "biogas" OR "bioresource" OR "waste treatment") AND ("economic* analysis" OR "economic* viability") AND ("electricity" OR "electric energy")). The query and the results for each database are shown in Table 1.

Table 1. Keywords and the Results of the Databases

Query	WoS	Scopus	SD
(("Biodigester" OR "biogas" OR "bioresource" OR "waste treatment") AND ("economic* analysis" OR "economic* viability") AND ("electricity" OR "electric energy"))	235	533	231
Total		999	
Filter 1 - Exclusion of duplicates		674	
Filter 2 - Screening of titles		340	
Filter 3 - Screening of abstracts and keywords		109	
Final portfolio		51	

The initial search yielded 999 articles. The filtering process was structured as follows: Filter 1 – Removal of duplicates (After eliminating duplicates, 674 articles remained); Filter 2 – Title screening (Articles whose titles did not refer clearly to agricultural waste, biogas production, economic analysis, or electricity generation were excluded - This step resulted in 340 articles); Filter 3 – Abstract and keyword screening (Abstracts and keywords were analyzed to exclude studies not addressing the economic or environmental assessment of agricultural waste-based biogas systems for electricity production - After this phase, 109 articles were retained); and, Fulltext eligibility (Finally, full articles were reviewed to ensure their relevance to the defined research theme, resulting in a final portfolio of 51 studies).

The inclusion criteria were: (i) studies focused on agricultural waste, biogas production, and electricity generation; (ii) application of economic viability analysis (e.g., NPV, IRR, payback) and/or environmental assessment (e.g., LCA, circular economy); (iii) publication in peer-reviewed journals; and (iv) articles written in English. The exclusion criteria included: (i) studies focused solely on biogas for transportation fuel, (ii) papers that analyzed biogas without any economic or environmental assessment, and (iii) non-peer-reviewed literature, such as books, theses, and conference proceedings.

The research theme was operationally defined as the assessment of the economic and environmental viability of biogas systems derived from agricultural wastes for the generation of electricity, explicitly addressing at least one economic feasibility method and/or an environmental evaluation method. The collected articles were organized and managed using EndNote (Version X7.5) and Microsoft Excel, and the bibliometric analyses were visualized with Microsoft Power BI.

2.2 How the Analyzed Documents Were Used

The final portfolio of 51 articles was based on the strict filtering and inclusion/exclusion criteria described in Section 2.1. The content analysis followed the sequence that Elo and Kyngäs (2008) suggested: open coding, categorization, and abstraction. Through these steps, we sought to identify relevant information using a deductive process by coding the studied sample. The outcomes were then divided into four parts (categories): identification of main researchers and reference sources, consolidation of evidence, critical assessment of existing literature, and identification of trends and future agenda. Finally, the relationships between authors were discussed after the presentation of the main data.

Parallelly, the systematic literature review plays a pivotal role in advancing state of the art on this topic for several reasons outlined in the article, following the categories: (i) identification of main researchers and reference sources (see Figure 1, Figure 2, and Appendix); (ii) consolidation of evidence (renewable sources are sustainable, and biogas is a viable option in the agricultural environment); (iii) critical assessment of existing literature (discussion with the authors of the topic showing positive environmental and economic aspects related to the use of agricultural waste for biogas and electricity production systems); (iv) identification of trends and future agenda (section 4 of the manuscript aims to show future exploration on this topic, based on the systematic review of the literature that this article performed).

When analysing the content of each article, a reading form was filled out in order to collect all information relevant to the analyses to be performed. The pieces of information collected from each paper were:

a) Title
b) Authors
c) Country and continent of affiliation of the corresponding author
d) Year of publication
e) Journal
f) Type of study (case study or review)
g) Methods (e.g., payback, net present value, internal rate of return) and variables (e.g., initial investment cost, operation and maintenance costs, energy efficiency) used for economic feasibility analysis.
h) Whether a sensitivity analysis was conducted, and for which purpose
i) Type of biomass used for anaerobic digestion
j) Benefits of producing biogas from the utilized biomass
k) Challenges in producing energy from biomass
l) Method/concept (e.g., life cycle assessment - LCA, circular economy) for the assessment of environmental performance
m) When an LCA is conducted, the impact categories considered
n) Whether the environmental performance was determinant to define the feasibility of “agricultural waste-biogas-electricity” projects

o) Advantages (both environmentally and economically) from switching from non-renewable energy sources to biobased ones
p) Development trends and potential for future research

The analysis of c)-e) can be seen in section 2.3, f) can be seen throughout section 3 as a whole, g)-k) can be seen in section 3.1, l)-n) can be seen in section 3.2, o) served as inspiration to distill the lessons presented in section 3.3, and p) was the starting point for the discussions in section 4.

As part of the scoping of this paper, a biodigester is considered an end-of-life system and, as such, does not inherently encompass the full life cycle of products. However, this study focused on analyzing the key economic tools and methods used to assess the economic viability of utilizing agricultural waste for biogas and electricity generation systems, along with the environmental factors that influence this viability.

2.3 Authorship, Types of Study, Journals, and Countries

This section offers a synopsis of the identified literature, aiming to fulfill this manuscript's first and second objectives. Some characteristics were examined, including main authors, types of study, journals, and countries. The countries contributing to developing economic and environmental studies on biogas for electricity generation can be observed in Figure 1, illustrating the number of publications per continent.

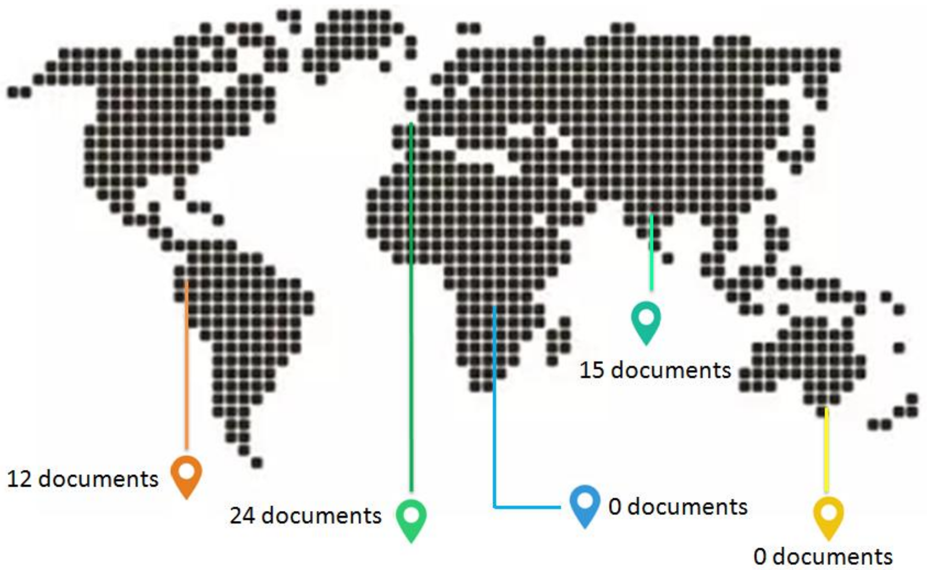

Figure 1. Number of Publications Per Continent

The main continent leading research on this topic is Europe, with 24 articles. Sweden is the main country with seven publications, followed by Germany with three publications. Additionally, Asia is the second continent in research development in biogas for electricity generation, with China contributing nine published articles. China is emerging as a leading force in this field, driven by its substantial population and the imperative to address environmental challenges. Among the countries in the American continent, Brazil takes the lead with eight publications. In Brazil, there is a growing interest in utilizing agricultural waste for biogas and electricity production, particularly in regions where agriculture plays a significant role in the economy. However, there have been no publications from the African continent, neither from Oceania for this portfolio.

It is important to recognize that the progress of these studies can differ based on government policies, available resources, energy requirements, and environmental awareness within each region. Interest in these technologies is expected to increase as countries actively pursue more sustainable energy sources, and seek efficient solutions for agricultural waste management.

Europe seems to be the leading region, not only for research on the feasibility of biogas use but for the actual implementation of technologies and the production of biogas. This can be largely due to its comprehensive and supportive policy frameworks. The Renewable Energy Directive (EU, 2023), setting legally binding targets for renewable energy, including biogas, helps promote biogas through economic incentives, sustainability criteria, and integration into the natural gas grid. These policies have driven significant growth in biogas production and use across Europe. Nonetheless, countries such as China and India have also seen rapid growth in biogas production in the last couple of decades, also driven by policies supporting rural development and waste management (ESCAP, 2007). Larger regions, such as the United States, tend to have less centralized policy frameworks, which might not favour a pollinated development such as seen in Europe. Other countries in the Americas, such as Brazil, have also been emerging as key players in biogas. Policy supporting the use of agricultural waste and promoting biogas as a low-carbon energy source has been one of the sources of incentive (Pereira et al., 2023b). Africa and Oceania, even though they hold potential to use renewable resources for biogas, are still in their infancy, especially in policy development, with efforts focused on overcoming barriers such as high initial costs and lack of awareness (Monti and Polugodina, 2021).

These documents play an important role in enhancing comprehension regarding economic viability and environmental sustainability by leveraging established outcomes. To collect pertinent data, we employ a structured form that captures key metrics such as the payback period, net present value, sensitivity, internal rate of return, benefit-cost (in economic terms). From an environmental standpoint, the analysis encompassed life cycle assessment along with considerations regarding climate change, waste reuse, clean energy, and alignment with SDG.

The studies found were divided into two types (see Table A.1 in Appendix A): case studies, comprising 47 documents, and literature reviews, totaling four documents. The literature reviews aimed to showcase new anaerobic digestion technologies, address the challenges of bioenergy production, and provide a comparison of economic analysis studies (see He et al., 2012; Hughes et al., 2012; Juul et al., 2013; Chakma et al., 2016).

Another analysis considered the journal of each article selected in the systematic literature review. Figure 2 illustrates the distribution of studies per journal, per year, and per type.

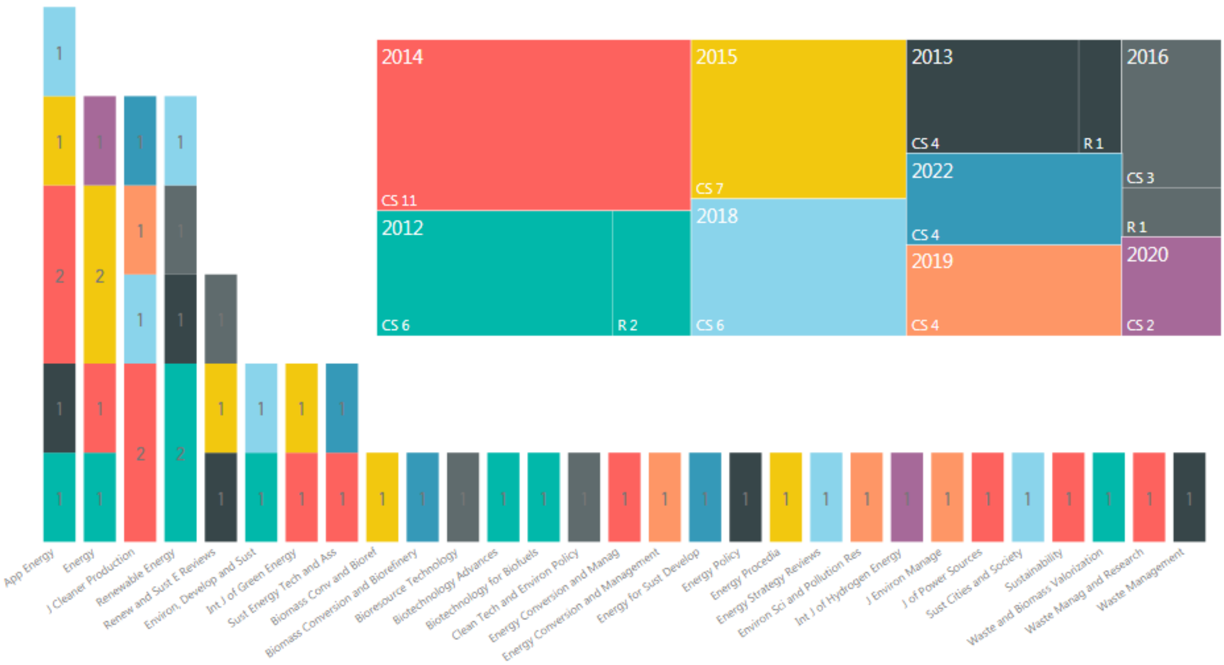

Figure 2. Number of Publications Per Journal, Per Year, and Type (R: Review, CS: Case Study)

Several articles are published in the same journal. Out of the 51 documents found, 27 different journals were identified. The main journal is Applied Energy, with a total of 6 documents (see, Lantz, 2012; Moraes et al., 2014; Nzila et al., 2012; Teghammara et al., 2014; Van Dael et al., 2013; Lauer et al., 2018). Following closely is Renewable Energy, Energy, and Journal of Cleaner Production (5 papers in each journal). In terms of impact factor (IF), Biotechnology Advances (IF: 17.681) exhibited the highest impact factor (see, He et al., 2012); followed by Renewable and Sustainable Energy Reviews (IF: 16.799) (see, Braga et al., 2013; Nogueira et al., 2015; Ali et al., 2016).

In addition, Figure 2 shows that the predominant year of publication in this field, based on the final portfolio of this analysis, was 2014, with 11 documents. However, it is challenging to determine a historical or future perspective regarding the increase or decrease in publications in this field, as the topic remains relevant to this day. Undoubtedly, there will be emerging trends in the coming years, particularly in relation to renewable energies, the adoption of the circular economy, and the mitigation of carbon emissions (carbon credits), among others.

3. RESULTS

3.1 Economic Viability Analysis

The economic feasibility of the final portfolio is typically assessed using economic analysis criteria that measure return on investment, costs, and opportunities. The investigated studies analyzed several characteristics from an economic perspective. Factors such as initial investment cost, operation and maintenance costs, energy efficiency, system life, electricity tariffs and tax incentives, revenue generated, payback, NPV, sensitivity analysis, IRR, and benefit-cost analysis were examined, as shown in Table 2. Investors can use these factors in decision-making processes. From the 51 documents in the portfolio, 33 are related to economic factors associated with biogas production, while 33 are related to environmental factors.

Table 2. Characteristics of Economic Viability Studies

Reference	Economic	Payback period	Net present value	Sensitivity	Internal rate of return	Benefit-cost
de Sousa Bernardes et al. (2022)	x	x		x	x	
He et al. (2020)	x			x		
Miramontes-Martínez et al. (2022)	x		x	x	x	x
Obuobi et al. (2022)	x	x	x	x	x	
Ji et al. (2022)	x			x		
Moura et al. (2020)	x	x			x	
Guo and Yang (2019)	x					x
Ferella et al. (2019)	x	x	x		x	
Lauer et al. (2018)	x	x	x	x		x
dos Santos et al. (2019)	x		x	x		
Fei et al. (2018)	x		x	x	x	
Pääkkönen et al. (2018)	x	x		x		
Huiru et al. (2019)	x	x	x	x	x	x
Pin et al. (2018)	x		x			
Felca et al. (2018)	x		x		x	
Venkatesh et al. (2018)	x			x		
He et al. (2012)	x			x		
Gwavuya et al. (2012)	x		x	x	x	x
Akbulut (2012)	x	x	x		x	
Moraes et al. (2014)	x		x		x	
Sigarchian et al. (2015)	x		x	x		
Nzila et al. (2012)	x	x				
Teghammara et al. (2014)			x	x	x	
Balussou et al. (2012)	x	x	x	x		
Nogueira et al. (2015)	x	x	x	x	x	
Juul et al. (2013)	x					
Wang et al. (2014)	x					x
Gutierrez et al. (2016)	x		x			
Amiri et al. (2013)	x			x		
Ali et al. (2016)	x		x		x	x
Edwin and Sekhar (2014)	x	x	x			
Chen and Chen (2013)	x					x
Starr et al. (2015)			x	x		
Chakma et al. (2016)	x				x	
Akbulut et al. (2014)	x	x				

Reference	Economic	Payback period	Net present value	Sensitivity	Internal rate of return	Benefit-cost
Van Dael et al. (2013)	x	x	x	x		
Torquati et al. (2014)	x					
Braga et al. (2013)	x	x		x		
Ilic et al. (2014)	x			x		
Calise et al. (2015)	x					
Khan et al. (2014)	x	x	x			
Chang et al. (2015)	x	x		x		
Cerón et al. (2015)	x					
Yoshizaki et al. (2012)	x	x	x	x	x	
Siefert and Litster (2014)	x		x	x	x	
Kang et al. (2014)	x	x	x		x	
Wu et al. (2016)	x	x	x		x	
Hublin et al. (2014)	x	x	x		x	

The economic feasibility of the studies analyzed in this review was assessed using classical financial metrics such as initial investment cost, operation and maintenance costs, energy efficiency, system lifetime, electricity tariffs, tax incentives, revenue generation, payback period, net present value (NPV), sensitivity analysis, internal rate of return (IRR), and benefit-cost analysis, as summarized in Table 2. Among the 51 selected articles, 89% employed at least one of these methods to evaluate economic viability, with NPV (27 articles), payback period (21 articles), and IRR (20 articles) being the most widely used indicators.

However, despite the widespread use of these methods, the results regarding the economic viability of biogas projects varied considerably across studies. Several contextual factors appear to explain these differences. First, public policy and regulatory frameworks emerged as key determinants of the situation. For example, studies conducted in Germany and Sweden (Gwavuya et al., 2012; Akbulut, 2012; Van Dael et al., 2013) have shown that strong governmental support, through feed-in tariffs and subsidies, significantly enhances the financial attractiveness of biogas systems. Conversely, in countries like Kenya (Nzila et al., 2012) and Brazil (Nogueira et al., 2015), where such incentives were weaker or less structured, the economic feasibility was often more limited or highly sensitive to external factors.

Logistical aspects, particularly transport distances for biomass feedstock, were another crucial factor. Miramontes-Martínez et al. (2024) emphasized that when transportation distances exceed approximately 50 km, additional operational costs can erode profitability, especially in rural regions with dispersed farms. Projects located close to biomass sources demonstrated higher economic resilience by minimizing logistical expenses, a conclusion also observed in the cases analyzed by Akbulut (2012) and Moraes et al. (2014).

Feedstock characteristics also played a critical role. High-energy-content residues, such as food waste or agro-industrial by-products, enabled higher biogas yields and better economic performance (He et al., 2012; Huiru et al., 2019). In contrast, projects based on livestock manure, despite its abundance, faced challenges due to lower methane potentials, which required larger biodigester volumes and resulted in extended payback periods (Akbulut, 2012; Hublin et al., 2014). Similarly, studies such as that of Hughes et al. (2012) with macroalgae and Chakma et al. (2016) with rice straw have shown that not only the energy content but also seasonal availability and storage requirements influence the economic viability.

Technological maturity and plant scale further differentiated the studies' findings. In regions where large-scale, automated digestion plants are common, such as Germany (Balussou et al., 2012) and Sweden (Lantz, 2012), operations achieved greater energy efficiencies and lower maintenance costs, leading to stronger economic outcomes. Small-scale or manually operated plants, prevalent in emerging economies, often face higher operational uncertainties and lower returns (Gutierrez et al., 2016; dos Santos et al., 2019).

Market factors, notably local electricity tariffs and incentive schemes, had a substantial impact. In high-tariff environments or where net metering and tax exemptions were applied, as highlighted by de Sousa Bernardes et al. (2022) in the Brazilian context, projects achieved better financial indicators. In contrast, projects located in regions without favorable tariffs, as discussed by Fei et al. (2018) and Khan et al. (2014), faced more challenging profitability margins.

An important technical aspect that also influences the feasibility of biogas-to-electricity systems is the integration of the generated electricity into the grid. The electricity produced from biogas must be converted and stabilized before being connected to the grid. This process involves the use of converters and inverters to transform direct current (DC) into alternating current (AC), when necessary, and the implementation of frequency and voltage control systems to ensure compatibility with the grid standards (Pablo-Romero et al., 2017; Salvador et al., 2019).

Moreover, biogas-based electricity generation can operate either as isolated generation (off-grid), where energy is consumed on-site without a grid connection, or as distributed generation (on-grid), where surplus energy is injected into the public grid. In the case of on-grid systems, additional technical and regulatory requirements apply, including authorization from utility companies, the installation of bidirectional metering systems for net metering, and the integration of protection and synchronization equipment, such as circuit breakers and protection relays. These technical and regulatory factors introduce additional investment and operational costs that must be carefully considered during economic feasibility assessments.

Additionally, the integration of biogas projects into circular economy models has further enhanced their feasibility. Projects that valorized digestate as biofertilizer or biogenic CO_2 for industrial applications not only improved environmental outcomes but also opened new revenue streams (Cerón et al., 2015; Fei et al., 2018; Barros et al., 2023). These strategies enhance overall financial performance by diversifying income sources and adding value to process residues, thereby moving biogas projects beyond a single-output energy model.

Therefore, the economic viability of agricultural waste-to-biogas-to-electricity systems is highly context-dependent. Favorable regulatory environments, proximity to biomass sources, the selection of high-energy feedstocks, technological sophistication, local energy market structures, the ability to integrate effectively into the grid, and the adoption of circular economy principles all emerge as critical success factors. Understanding and optimizing these interconnected elements is essential for maximizing the economic performance of biogas projects globally and ensuring their long-term sustainability.

3.2 Environmental Factors

Environmental factors were also accounted for in documents found in the body of literature, as shown in Table A.1 (Appendix A). A total of 27 documents reports the applications of environmental issues, such as climate change, environmental impacts, use of LCA, and actions involving the practice of circular economy, showing that hardly ever "agricultural waste-biogas-electricity" projects are only based on their environmental feasibility.

The main technique used in the investigations was LCA, which helped investigate the production of electricity from biogas (see, e.g., Nzila et al., 2012; Chen and Chen, 2013; Wang et al., 2014; Fei et al., 2018; Venkatesh et al., 2018). LCA is a systematic approach that scrutinizes the environmental impacts of a product, process, or activity across its entire life cycle, from the extraction of raw materials to final disposal. Therefore, the approach is used to measure environmental aspects and performed through the compilation of flows in order to help the management in identifying opportunities for improvements in the production system (Barros et al., 2020). LCA makes several contributions, including the identification of processes with the greatest potential environmental impact on the system; quantification of greenhouse gas emissions; comparison of different equipment technologies; and impact assessment of equipment construction, installation, maintenance, useful life, and end of life.

Pin et al. (2018) showed the electricity generation potential from biogas for a case study of anaerobic digestion in a sewage treatment plant produced by a population of approximately 420,000 people. This study considered important insights using waste treatment to generate electricity. In addition, the results of the study by Fei et al. (2018) showed that the municipal solid waste landfill is the worst management option, where, for instance, incineration can be a more energy-efficient use (20.5% energy recovery), nevertheless, the high amounts of chemical consumption may increase the environmental impacts in the life cycle. On the other hand, mechanical-biological treatment showed the highest energy efficiency when connected with biogas purification (38.5% energy recovery) (Fei et al., 2018).

Agro-industrial cooperatives have been looking for alternatives for managing manure in an economically feasible and environmentally friendly manner Akbulut et al. (2014). In the case of the agricultural sector, the main raw materials used for the production of biogas are agricultural residues from crops; animal waste, such as swine and cattle; wastes from the food industry, and others (see for example Akbulut, 2012; Calise et al., 2015; Chang et al., 2015; Hublin et al., 2014; Torquati et al., 2014; Zieliński et al., 2019). In this sense, using biodigester technology to generate biogas smooths the reuse of waste generated in the agriculture sector. It may generate products/services that add value to the system. These technologies will depend on the volume of input raw material and the type of output the farm intends to have, such as heat, biofertilizer, biomethane, electricity, and others. In the case of the agricultural sector, the main raw materials used for the production of biogas are agricultural residues from crops; animal waste, such as swine and cattle; wastes from the food industry and others (see, e.g., Calise et al., 2015; Chang et al., 2015; Hublin et al., 2014; Torquati et al., 2014).

The most monitored type of environmental impact when assessing the environmental sustainability of energy production from agrowastes is climate change (CC) impacts, measured in CO2-equivalent (CO2-e) (Wu et al., 2016). Producing biogas through AD and subsequently electricity, can result in GHG emissions (such as CH4), due to leakage from the digester and the spread of digestate in the fields (when that is the case), causing CC impacts (Torquati et al., 2014). These impacts are dependent on which systems are in place, such as the type and scale of AD infrastructure, the feedstock used, among other variables. Nevertheless, some common main causes of environmental impacts for such systems include the following. Direct GHG emissions are caused during the operation of the system, and the operation is also responsible for the main energy requirements (in MJ) (Chen and Chen, 2013). Logistics is also sensitive, meaning that even the environmental (also economic) feasibility of the system is dependent on transportation distances, and over a certain threshold (specific for each system) is might no longer be beneficial to produce electricity from agrowastes (Miramontes-Martínez et al., 2024). However, the impacts of electricity generated from AD of agrowastes have often proven to be smaller when compared to those of energy generated by fossil fuels (Torquati et al., 2014), thus a significant reduction in environmental impacts can be observed when using agrowastes for energy production instead of fossil fuels (Torquati et al., 2014). A few reasons for that involve the benefits and avoided impacts caused both by the replacement of energy from fossil fuels with energy from renewable sources, but also extends it to downstream processes, such as the use of the digestate as a replacement of synthetic N-fertilizers (Miramontes-Martínez et al., 2024).

Overall, it can be observed that measures need to be taken to increase environmental gains and reduce costs in systems that produce electricity from biogas. Directing applications to the agricultural sector, the circular economy finds valuable resources in waste. Beyond the opportunities for electricity generation, production of biomethane, used as fuel for light and heavy-duty vehicles, and thermal energy production can be pointed out as economically viable actions, allowing a greater competitive advantage, more energy security, thus enhancing the economic and environmental aspects of sustainability. In fact, measures are often taken to increase environmental gains and reduce costs, where one can notice the interlinked nature of the economic and environmental dimensions of such projects. As mentioned in the introduction section, this work is aligned with the SDGs, mainly goal number 7, to provide clean and accessible energy, and as reported, biogas represents this generation of energy.

3.3 Environmental and Economic Advantages

Switching from non-renewable energy sources to alternative sources yields various environmental and economic advantages. Some of these benefits include: (i) Environmental sustainability: Alternative energy sources, such as solar, wind, and mainly biomass, typically exhibit a lower environmental impact compared to non-renewable sources like fossil fuels. The reduction of greenhouse gas emissions and atmospheric pollution contributes to environmental sustainability. (ii) Diversification of the energy matrix: The shift to alternative sources enables the diversification of the energy matrix, decreasing reliance on non-renewable resources. This fosters a more stable and secure foundation for energy supply. (iii) Job creation and economic stimulation: The alternative energy industry often fosters job creation and contributes to economic growth. The development and maintenance of infrastructure related to renewable energy generate employment opportunities across various sectors. (iv) Reduced vulnerability to fluctuations in fossil fuel prices: Utilizing alternative sources can diminish vulnerability to fluctuations in fossil fuel prices, offering greater stability in long-term energy costs. (v) Viable waste management solutions: Within the agricultural environment, numerous wastes are generated and often discarded. However, implementing technologies for the processing and sustainable disposal of waste, such as composting, biodigesters, and electricity production, can prove advantageous for the system. (vi) Stimulating innovation: The transition to alternative energy sources promotes technological innovation, driving the development of more efficient and sustainable solutions.

Economically viable projects characterized by a short payback period, NPV, and IRR often align with environmental objectives, such as reducing greenhouse gas emissions and promoting the sustainable management of agricultural waste. Conversely, projects initially designed to enhance environmental performance, for instance, through the application of LCA to minimize life -cycle impacts frequently reveal hidden economic benefits, including cost reductions from waste minimization and energy recovery.

LCA serves as a valuable bridge between economic and environmental approaches. It enables the identification of environmentally sound system configurations that also enhance operational efficiency and lower costs. By incorporating LCA into project planning, economic decisions are grounded in long-term environmental considerations, helping to avoid “false economies” that result from externalizing environmental costs.

3.4 A Brief Description of a Biodigester Case Study in Brazil

The case study presented in this research was developed on a rural agricultural property selected for its availability and specific characteristics. The property is part of an agro-industrial cooperative and is in the municipality of Castro, in the state of Paraná, Brazil. The local economy is primarily based on pig and dairy production. Castro is the second-largest producer of pigs in Paraná and the fifth largest in Brazil. It is also the leading milk producer in the country (IBGE, 2017).

The rural property engages in the cultivation of corn, soybeans, wheat, beans, ryegrass, and straw. It also operates a composting unit for mushroom production and maintains pig farming activities. Additionally, the farm utilizes a biodigester that primarily produces biofertilizer and biogas. Sustainability awareness and practices are integrated into the farm's daily operations. The property slaughters approximately 25,000 pigs annually and spans about 800 hectares dedicated to agriculture. Figure 3 shows part of the case study farm.

Figure 3. Case Study

The biodigester is used to generate biofertilizer for crops and biogas, which in turn produces electricity (for farm operations), heat (for residential floor heating, pig farm heating, and grain drying), biomethane (to fuel farm vehicles such as cars and tractors), and cooking gas for homes. This case study is thoroughly detailed in a published paper (see Barros et al., 2023), which evaluates the measurement of circularity using a new circular economy tool proposed by the authors.

The farm envisions expanding the use of its biodigester, especially by incorporating neighboring farms and the agro-industrial cooperative. This expansion could enhance biogas production, thereby increasing electricity generation and biomethane availability for vehicles. A long-term goal of the farm is to achieve self-sufficiency in energy production and consumption, ultimately replacing diesel with renewable alternatives.

4. DISCUSSION

This section presents the main findings of the review, interpreting their significance in light of the systemic model, identifying practical implications for policymakers, acknowledging study limitations, and proposing directions for future research.

4.1 Input and Output Options of a Biodigester Throughout its Life Cycle Phases

The analysis of the selected studies reveals that understanding the economic and environmental feasibility of biogas systems requires a holistic consideration of the biodigester's entire life cycle. At each stage, specific inputs and outputs determine not only technical performance but also financial sustainability and alignment with broader sustainability goals. Figure 4 illustrates this dynamic, mapping raw material inputs, transformation processes, and potential outputs across the different phases of biodigester operation.

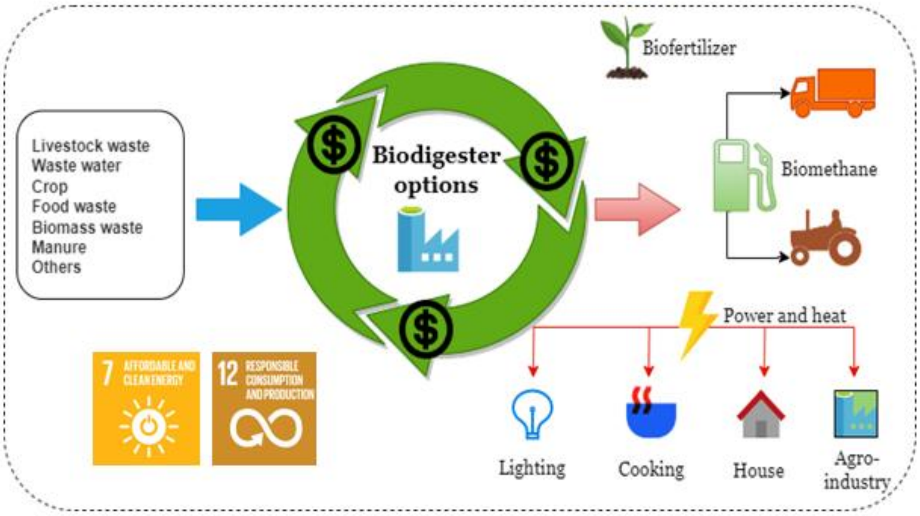

Figure 4. Biodigester Life Cycle Stages

Figure 4 presents a generic environmental and economic analysis of a biodigester and its associated opportunities. Throughout all stages, costs (such as construction, raw material purchases, and maintenance) and revenues (including sales, avoided costs, and cheaper raw material procurement) are considered. The methods utilized, such as payback, NPV, IRR, and sensitivity analysis, are considered.

From an environmental perspective, the primary inputs to the system are renewable raw materials or organic wastes that lack viable destinations, such as agricultural residues, animal manure, and agro-industrial by-products. By redirecting these inputs to the biodigester, farms and cooperatives can generate multiple simultaneous outputs, yielding both environmental and economic benefits. These outputs include biofertilizer for internal agricultural use, biomethane for fueling farm vehicles, cooking gas for domestic activities, heat for pig and poultry production, bottled CO_2 for sale to soft drink industries, and electricity for self-consumption or commercialization. The multifaceted nature of output enhances the role of biogas systems within the circular economy framework (Cortez et al., 2022; Zabaniotou et al., 2018), enabling each farm to explore the most advantageous value streams tailored to local needs and market conditions.

However, the deployment of biogas-to-electricity technologies faces several critical challenges that directly impact the life cycle performance. One major obstacle is the inadequacy of infrastructure for biogas production, collection, and distribution (de Jesus et al., 2021). Coupled with high upfront capital investments and technological costs for biogas purification, energy conversion, and grid integration (Kabeyi and Olanrewaju, 2022), these barriers often deter smaller producers and cooperatives from adopting biodigesters without external support.

Seasonal variability also poses a significant risk to the input supply. Agricultural waste availability and biogas yields fluctuate according to climatic conditions and crop cycles (Lovrak et al., 2020), introducing operational uncertainties. This underscores the importance of robust logistical planning and, where possible, the establishment of cooperative networks that aggregate waste from multiple farms to stabilize feedstock input volumes.

Regulatory and political factors further condition the deployment environment. Clear policies, incentive programs, and ambitious targets are essential for facilitating the transition to sustainable energy systems and mitigating investment risks (Lazaro et al., 2023; Pereira et al., 2023a). Conversely, regulatory uncertainty, bureaucratic hurdles, or insufficient subsidies introduce volatility that undermines investor confidence and project viability.

Throughout the operational phase, the life cycle dynamics continue to evolve. Operation and maintenance (O&M) activities require consistent inputs in terms of skilled labor, spare parts, monitoring technologies, and compliance reporting. The output streams, however, offer diversified opportunities for revenue generation and environmental gains. Projects that valorize digestate as a biofertilizer, capture CO_2 for industrial use, and efficiently inject surplus electricity into local grids are more likely to achieve long-term financial resilience.

At the maintenance and upgrading phase, additional inputs include technological upgrades (e.g., installing more efficient digesters or inverters) and adaptations to evolving grid standards and environmental regulations. Outputs at this stage center on system efficiency improvements, cost reductions, and extended operational lifespan, further reinforcing project feasibility.

Finally, the decommissioning phase, though often neglected in planning, introduces its own set of input and output considerations. Inputs involve financial costs related to dismantling, material recovery, recycling, and site restoration, whereas outputs relate to environmental compliance and potential opportunities for material reuse. These end-of-life activities must be factored into initial feasibility studies to ensure accurate life cycle costing (Ioannou-Ttofa et al., 2021).

In a broader context, biogas production systems directly contribute to achieving the Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production). By promoting renewable energy solutions based on the reuse of agricultural waste, biodigesters align with global efforts to mitigate climate change, reduce greenhouse gas emissions, and foster rural economic development.

Unlike other renewable energy systems, such as hydropower, wind, and solar, which are inherently weather-dependent, biogas production offers a more stable and predictable energy generation pathway. This stability enhances energy security, especially for rural and agro-industrial communities, while simultaneously valorizing waste streams that would otherwise represent environmental liabilities.

Moreover, growing societal awareness of climate change, advances in biogas technologies, and the progressive implementation of supportive policies create a favorable landscape for biogas expansion. Trends indicate that investments in biogas electricity generation will not only contribute to achieving carbon neutrality targets but will also strengthen regional economies through job creation, rural electrification, and the fulfillment of Environmental, Social, and Governance (ESG) commitments by agricultural and industrial stakeholders.

Overall, the content analysis suggests that maximizing the economic and environmental potential of biodigesters requires strategic management of input and output options throughout all phases of the life cycle. Policymakers, project developers, and cooperative managers must adopt a systems thinking approach, ensuring that biogas projects are not only technically feasible but also operationally resilient, economically viable, and environmentally beneficial throughout their entire life cycle.

Furthermore, this study contributes to the achievement of sustainable development goals outlined in the UN's 2030 Agenda, particularly SDG 7, which aims to ensure access to affordable, reliable, sustainable, and modern energy for all; and SDG 12, which seeks to ensure sustainable consumption and production patterns.

In this global context, the circular economy strives to promote and advance energy solutions utilizing renewable resources, such as bioenergy. It offers viable solutions, including properly managing agricultural waste (Zabaniotou et al., 2018). The various options discussed, considering the production of biogas from a biodigester, exemplify actions aligned with the principles of the circular economy (Cortez et al., 2022). Each farm and location can explore the benefits that yield the most favorable outcomes, such as electricity generation or biofertilizer production, among others.

On the one hand, electricity generation systems relying on hydropower, wind, and solar energy are weather-dependent, while on the other hand, the production of biogas is not. By employing biodigester technology for biogas generation, it becomes possible to facilitate the reuse of agricultural waste and create value-added products and services within the system.

Perceptions regarding the utilization of agricultural waste for electricity generation from biogas can be established based on some factors. Heightened awareness of climate change and a quest for more sustainable energy sources have become focal points on organizational agendas. Additionally, there has been notable progress in the development of more efficient technologies for biogas production and electricity generation in recent years. In certain countries, the implementation of policies supporting renewable energy, coupled with the introduction of financial incentives by governments, has stimulated investments in electricity generation projects from biogas.

The trends in this field are optimistic. Renewable energy and the repurposinge of agricultural waste represent an irreversible trajectory. The increasing involvement of agricultural and agro-industrial entities in this market is expected to contribute to regional and national economic development. This aligns with the goals of emissions reduction, achieving zero carbon initiatives, and fulfilling Environmental, Social, and Governance (ESG) agreements that organizations are actively pursuing.

4.2 Practical Implications for Policy Makers

The results of this study provide concrete lessons for policymakers seeking to promote the sustainable development of biogas-based electricity systems. The systemic dependencies identified highlight the need for comprehensive, context-sensitive policy approaches that address multiple dimensions simultaneously — technical, economic, environmental, and regulatory.

Firstly, policymakers must focus on establishing stable and predictable incentive structures. Long-term financial mechanisms, such as feed-in tariffs, subsidies for capital investments, tax credits, and operational support schemes, are crucial in reducing investor risk and promoting the adoption of biogas technologies. Significantly, incentives should not be limited to plant installation alone but should also cover grid integration, stabilization equipment, and ongoing operational maintenance phases to ensure financial resilience throughout the project life cycle.

Secondly, the study highlights the importance of logistical optimization. Energy policies should prioritize supporting decentralized biogas production models, particularly in rural and agricultural regions. This may involve grants for the creation of local biomass collection centers, the development of cooperative biomass supply chains, and the promotion of small-scale digester technologies. Reducing transportation distances for biomass not only lowers operational costs but also enhances the environmental sustainability of biogas projects.

Thirdly, valorization of multiple outputs must become a policy priority. Beyond electricity, biogas systems can generate biofertilizers, biomethane, bottled CO_2, and thermal energy, all of which contribute to the financial attractiveness of projects. Policymakers should design certification programs or additional incentive mechanisms that reward projects that adopt circular economy principles and maximize resource utilization. Recognition of multi-output systems enhances the systemic value proposition of biogas initiatives and aligns with the Sustainable Development Goals.

Fourthly, regulatory simplification is essential to enable distributed generation initiatives. Policymakers should work toward streamlining permitting procedures, standardizing interconnection requirements for grid injectiong it into the grid, and facilitating access to affordable, reliable metering systems. Regulatory barriers must be minimized to accelerate project deployment and integration into existing energy infrastructures.

Fifthly, and critically, regional context must guide policy design. Policies must be tailored to local conditions — including biomass availability, farm size distributions, existing energy infrastructures, and socio-economic profiles — rather than applying a one-size-fits-all approach. Customized support schemes are more effective in addressing the specific challenges and opportunities of different agricultural regions, enhancing adoption rates and maximizing socio-economic and environmental returns.

Additionally, the environmental insights gained from the life cycle analysis (see Section 3.3) underscore the importance of integrating environmental sustainability goals into policy frameworks. Policymakers should encourage practices aligned with Environmental, Social, and Governance (ESG) principles, promote access to carbon credit markets, and design regulations that facilitate the circular economy, thus contributing directly to achieving Sustainable Development Goals (SDG 7 and SDG 12).

From an economic perspective (see Section 3.2), understanding the evolving cost structures and economic feasibility of biogas systems empowers policymakers to design targeted financial instruments. Well-structured financial programs can bridge the investment gap, making biogas projects attractive not only to large agro-industrial players but also to small and medium-sized farms, thus democratizing access to renewable energy solutions.

Ultimately, by incorporating these lessons into new directives, regulations, and incentive programs, policymakers can create a favorable environment for biogas and electricity generation systems based on agricultural waste. In doing so, they will simultaneously advance climate change mitigation, enhance rural economic development, promote energy security, and reinforce national commitments to sustainable development agendas.

4.3 Limitations

Although this review employed a rigorous methodological approach, several limitations must be acknowledged. First, the reliance on peer-reviewed publications may introduce a selection bias, potentially excluding valuable insights from gray literature, technical reports, and project evaluations not published in academic outlets. Second, the heterogeneity among the selected studies — including differences in methodological rigor, regional contexts, system scales, and timeframes — complicates direct comparison of findings and limits the generalizability of conclusions. Future meta-analytical studies applying standardized evaluation criteria could address this limitation.

Third, the conceptual model proposed, while based on extensive literature synthesis, remains theoretical and would benefit from empirical validation through case studies or comparative analyses across different geographic and regulatory environments. Lastly, due to the dynamic nature of energy policies, market conditions, and technology costs, some conclusions may evolve. Continuous updating of systematic reviews and incorporation of longitudinal studies are recommended to maintain the relevance of findings.

4.4 Future Agenda in the Field of Biogas and Renewable Energy

Global efforts to mitigate climate change and achieve the United Nations' Sustainable Development Goals (SDGs) are expected to stimulate research in renewable energy technologies, particularly biogas. Addressing the third objective of this study, this section proposes a concrete and structured future research agenda grounded in the findings and limitations identified throughout this review.

A critical area for advancement involves conducting region-specific techno-economic analyses, particularly in tropical and subtropical agricultural settings. Climatic conditions, biomass characteristics, and rural infrastructure constraints in these regions differ markedly from those in temperate areas, necessitating tailored assessments to support investment and policy decision-making (Ioannou-Ttofa et al., 2021; de Jesus et al., 2021).

Another critical dimension is the need for longitudinal studies that track the long-term financial and operational performance of biogas projects. Such research should incorporate the effects of changing energy tariffs, feedstock variability, evolving regulatory environments, and technological advancements over time, providing more realistic evaluations of investment risks and project sustainability (Kabeyi and Olanrewaju, 2022).

The exploration of hybrid business models integrating energy generation with ancillary services, such as biofertilizer production, carbon credit generation, and biogenic CO_2 commercialization, represents a promising avenue. These models can diversify revenue streams, increase financial resilience, and enhance the overall scalability of biogas systems, especially in rural and peri-urban areas (Cortez et al., 2022; Barros et al., 2023).

Research on integrating biogas into decentralized renewable energy microgrids is also vital. Decentralized systems have the potential to significantly improve energy access for off-grid or weak-grid rural communities while simultaneously fostering local economic development (Lovrak et al., 2020). Technical feasibility assessments, combined with socio-economic impact evaluations, would provide valuable insights for both policymakers and investors.

Further work is needed to expand socio-economic impact assessments of biogas deployment. Understanding how these systems affect rural livelihoods, agricultural productivity, food security, employment, and gender dynamics would enrich the evaluation of biogas beyond mere technical or financial indicators (Zabaniotou et al., 2018; de Jesus et al., 2021).

Simultaneously, there is a growing need for integrated economic and environmental analyses. Combining life cycle assessments (LCA) with financial modeling would facilitate more comprehensive decision-making, allowing stakeholders to balance profitability with environmental sustainability goals (Lovrak et al., 2020).

Finally, continuous monitoring of emerging trends in biogas technologies, regional deployment patterns, and innovative applications is essential. Tracking developments such as biomethane production, CO_2 capture technologies, and their respective market integrations will enable a forward-looking understanding of the evolving opportunities and challenges for biogas systems (Lazaro et al., 2023; Pereira et al., 2023a). To structure these research opportunities more concretely, Table 3 presents a proposed future research agenda, highlighting key themes, supporting authors, and suggested methodological approaches.

Table 3. Suggested Future Research Agenda for Biogas Electricity Generation Studies

Future Research Topic	**Supporting Authors/References**	**Suggested Methodological Approach**
Techno-economic assessments in tropical and subtropical regions	Ioannou-Ttofa et al. (2021); de Jesus et al. (2021)	Case studies and techno-economic modeling (NPV, IRR, LCOE)
Longitudinal analyses of biogas projects' financial performance	Kabeyi and Olanrewaju (2022)	Panel data econometrics; dynamic financial modeling
Development of hybrid business models (energy + carbon credits, biofertilizers, CO_2 capture)	Cortez et al. (2022); Barros et al. (2023)	Multi-case comparative analysis; business model innovation frameworks
Integration of biogas into decentralized renewable microgrids	Lovrak et al. (2020)	Simulation-based feasibility studies; socio-technical systems modeling
Socio-economic impact assessments of biogas deployment	Zabaniotou et al. (2018); de Jesus et al. (2021)	Mixed-methods research (surveys, interviews, impact evaluation)
Simultaneous economic and environmental life cycle assessments (E-LCA)	Lovrak et al. (2020); Zabaniotou et al. (2018)	Life Cycle Assessment (ISO 14040/44) + financial feasibility studies
Monitoring trends in technologies, regions, and applications	Lazaro et al. (2023); Pereira et al. (2023a)	Bibliometric analysis; technology foresight and innovation mapping

By advancing research along these lines, the academic and professional communities can more effectively unlock the full potential of biogas technologies. These research efforts are essential to advancing sustainable, inclusive, and resilient energy systems and to support global initiatives for climate mitigation, rural development, and energy access.

6. CONCLUSION

The main conclusions of the manuscript are described below:

- Focus on economic feasibility methods and environmental factors in agricultural waste-dervied biogas for electricity generation.
- Systematic literature review covering 51 articles (2012–2022) from WoS, Scopus, and ScienceDirect.
- 89% of studies used economic analysis tools, such as, net present value (NPV) (27 studies), payback period (21 studies), internal rate of return (IRR) (20 studies), sensitivity analysis (25 studies), cost-benefit analysis (8 studies).
- Key economic barriers: high initial investment, lack of commercialization, and policy incentives.

- 27 studies considered environmental factors, and life cycle assessment (LCA) was the primary tool for environmental evaluation.
- Circular economy principles were increasingly adopted.
- Biogas from agricultural waste helps reduce greenhouse gases and promotes sustainable waste reuse.
- Europe led in the number of publications (especially Sweden, Germany, Belgium).
- China and Brazil showed significant recent growth in related research.
- The top journals included Applied Energy, Renewable Energy, and Journal of Cleaner Production.
- A case study on a farm in Brazil's main milk producing region describes how a biodigester uses a biogas plant to generate electricity, heat, biomethane and biofertilizer.
- Results can guide public policy for supporting biogas development (e.g., tax incentives, subsidies).
- Integration with Sustainable Development Goals (SDGs), particularly SDG 7 and 12.

It has been shown that anaerobic digestion for biogas generation is a form of action against global climate change, providing accessible, clean, and renewable energy. In addition, the circular economy is increasingly being treated as a means to achieve the goals of sustainable development in the agricultural and agro-industrial environment.

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AUTHOR CONTRIBUTIONS

Murillo Vetroni Barros: Data collection, data analysis and interpretation, manuscript writing.
Renan Alves Dourado: Study design and outline, data collection, data analysis and interpretation.
Mayara Cristina Ostwal: Study design and outline, data collection, data analysis and interpretation.
Rodrigo Salvador: Manuscript writing, manuscript review.
Cassiano Moro Piekarski: Supervision and guidance.

DECLARATIONS

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APPENDIX

APPENDIX A: CHARACTERISTICS OF THE STUDIES IN THE FINAL PORTFOLIO

Reference	Type of Study	Country	Journal	Impact Factor	Environmental	Economic	Payback period	Net present value	Sensitivity	Internal rate of return	Benefit-cost
He et al. (2012)	Review	Canada	Biotechnology Advances	17.681		x			x		
Lantz (2012)	Case Study	Sweden	Applied Energy	11.446	x						
Hughes et al. (2012)	Review	Scotland	Biotechnology for Biofuels	7.670	x						
Gwavuya et al. (2012)	Case Study	Germany	Renewable Energy	8.634		x		x	x	x	x
Akbulut (2012)	Case Study	Turkey	Energy	8.857		x	x	x		x	
Moraes et al. (2014)	Case Study	Brazil	Applied Energy	11.446	x	x		x		x	
Sigarchian et al. (2015)	Case Study	Sweden	Energy	8.857		x		x	x		
Nzila et al. (2012)	Case Study	Belgium	Applied Energy	11.446	x	x	x				
Teghammara et al. (2014)	Case Study	Sweden	Applied Energy	11.446	x			x	x	x	
Balussou et al. (2012)	Case Study	Germany	Waste and Biomass Valorization	3.449		x	x	x	x		

Reference	Type of Study	Country	Journal	Impact Factor	Environmental	Economic	Payback period	Net present value	Sensitivity	Internal rate of return	Benefit-cost
Nogueira et al. (2015)	Case Study	Brazil	Renewable and Sustainable Energy Reviews	16.799	x	x	x	x	x	x	
Juul et al. (2013)	Review	Denmark	Waste Management	8.816	x	x					
Wang et al. (2014)	Case Study	China	Journal of Cleaner Production	11.072	x	x					x
Gutierrez et al. (2016)	Case Study	Ireland	Renewable Energy	8.634		x		x			
Amiri et al. (2013)	Case study	Sweden	Renewable Energy	8.634	x	x			x		
Ali et al. (2016)	Case Study	Pakistan	Renewable and Sustainable Energy Reviews	16.799	x	x		x		x	x
Edwin and Sekhar (2014)	Case Study	India	Energy Conversion and Management	11.533		x	x	x			
Chen and Chen (2013)	Case Study	China	Energy Policy	7.576	x	x					x
Starr et al. (2015)	Case Study	Spain	Energy	8.857	x			x	x		
Chakma et al. (2016)	Review	India	Clean Technologies and Environmental Policy	4.700	x	x				x	
Akbulut et al. (2014)	Case Study	Turkey	International Journal of Green Energy	3.206	x	x	x				

Reference	**Type of Study**	**Country**	**Journal**	**Impact Factor**	**Environment al**	**Economi c**	**Paybac k period**	**Net present value**	**Sensitivit y**	**Interna l rate of return**	**Benefi t-cost**
Van Dael et al. (2013)	Case Study	Belgium	Applied Energy	11.446	x	x	x	x	x		
Torquati et al. (2014)	Case Study	Italy	Sustainability	3.889	x	x					
Braga et al. (2013)	Case Study	Brazil	Renewable and Sustainable Energy Reviews	16.799	x	x	x		x		
Djatkov et al. (2012)	Case Study	Serbia	Renewable Energy	8.634	x						
Ilic et al. (2014)	Case Study	Sweden	Journal of Cleaner Production	11.072		x			x		
Calise et al. (2015)	Case Study	Italy	Energy Procedia	0		x					
Khan et al. (2014)	Case Study	Sweden	Sustainable Energy Technologies and Assessments	7.632		x	x	x			
Chang et al. (2015)	Case Study	Taiwan	International Journal of Green Energy	3.206	x	x	x		x		
Cerón et al. (2015)	Case Study	Colombia	Biomass Conversion and Biorefinery	4.050	x	x					
Yoshizaki et al. (2012)	Case Study	Japan	Environment, Development and Sustainability	4.080		x	x	x	x	x	
Siefert and Litster (2014)	Case Study	USA	Journal of Power Sources	9.794		x		x	x	x	
Kang et al. (2014)	Case Study	Korea	Energy	8.857		x	x	x		x	

Reference	**Type of Study**	**Country**	**Journal**	**Impact Factor**	**Environmental**	**Economic**	**Payback period**	**Net present value**	**Sensitivity**	**Internal rate of return**	**Benefit-cost**
Wu et al. (2016)	Case Study	China	Bioresource Technology	11.889	x	x	x	x		x	
Hublin et al. (2014)	Case Study	Croatia	Waste Management and Research	4.432	x	x	x	x		x	
Fei et al. (2018)	Case Study	China	Journal of Cleaner Production	11.072	x	x		x	x	x	
Pääkkönen et al. (2018)	Case Study	Finland	Renewable Energy	8.634		x	x		x		
Huiru et al. (2019)	Case Study	China	Energy Conversion and Management	11.533		x	x	x	x	x	x
Pin et al. (2018)	Case Study	Brazil	Energy Strategy Reviews	10.010		x		x			
Felca et al. (2018)	Case Study	Brazil	Sustainable Cities and Society	10.696	x	x		x		x	
Venkatesh et al. (2018)	Case Study	Sweden	Environment, Development and Sustainability	4.080	x	x			x		
de Sousa Bernardes et al. (2022)	Case Study	Brazil	Journal of Cleaner Production	11.072	x	x	x		x	x	
He et al. (2020)	Case Study	China	Energy	8.857	x	x			x		
Miramontes-Martínez et al. (2022)	Case Study	Mexico	Biomass Conversion and Biorefinery	4.050	x	x		x	x	x	x

Reference	**Type of Study**	**Country**	**Journal**	**Impact Factor**	**Environmental**	**Economic**	**Payback period**	**Net present value**	**Sensitivity**	**Internal rate of return**	**Benefit-cost**
Obuobi et al. (2022)	Case Study	China	Energy for Sustainable Development	5.655	x	x	x	x	x	x	
Ji et al. (2022)	Case Study	China	Sustainable Energy Technologies and Assessments	7.632	x	x			x		
Moura et al. (2020)	Case Study	Brazil	International Journal of Hydrogen Energy	7.139	x	x	x			x	
Guo and Yang (2019)	Case Study	China	Environmental Science and Pollution Research	5.190	x	x					x
Ferella et al. (2019)	Case Study	Italy	Journal of Cleaner Production	11.072		x	x	x		x	
Lauer et al. (2018)	Case Study	Germany	Applied Energy	11.446	x	x	x	x	x		x
dos Santos et al. (2019)	Case Study	Brazil	Journal of Environmental Management	8.910		x		x	x		