REVISTA DE
ADMINISTRAÇÃO IMED

The biogas chain: a sustainable energy transition alternative for Brazil

A cadeia do biogás: uma alternativa de transição energética sustentável para o Brasil

Marcos Fava Neves(1); Leticia Franco Martinez(2); Gabriel de Oliveira Teixeira(3); Beatriz Papa Casagrande(4); Flávio Ruhnke Valério(5)

1 Professor, School of Business FEARP/University of São Paulo and EAESP/Fundação Getúlio Vargas, Avenida dos Bandeirantes 3900, 14040-905, Ribeirão Preto, SP, Brazil.
E-mail: favaneves@gmail.com | ORCID: https://orcid.org/0000-0002-5693-7543
2 PhD student, School of Business FEARP/University of São Paulo, Avenida dos Bandeirantes 3900, 14040-905, Ribeirão Preto, SP, Brazil.
E-mail leticiafrancomartinez@gmail.com | ORCID: https://orcid.org/0000-0001-6811-7393
3 PhD student, School of Business FEARP/University of São Paulo, Avenida dos Bandeirantes 3900, 14040-905, Ribeirão Preto, SP, Brazil.
E-mail: gabriel.oliveira.teixeira@usp.br | ORCID: https://orcid.org/0009-0001-7587-1535
4 Master's Degree Student, School of Business FEARP/University of São Paulo, Avenida dos Bandeirantes 3900, 14040-905, Ribeirão Preto, SP, Brazil.
E-mail: beatrizcasagra@hotmail.com | ORCID: https://orcid.org/0000-0002-9040-9349
5 PhD student, School of Business FEARP/University of São Paulo, Avenida dos Bandeirantes 3900, 14040-905, Ribeirão Preto, SP, Brazil.
E-mail flavio.valerio@usp.br | ORCID: https://orcid.org/0000-0002-7050-9860

Revista de Administração IMED, Passo Fundo, vol. 13, n. 2, p. 20-40, julho-dezembro, 2023 - ISSN 2237-7956
[Recebido: setembro 13, 2023; Aprovado: novembro 21, 2023; Publicado: dezembro 21, 2023]
DOI: https://doi.org/10.18256/2237-7956.2023.v13i2.4932

Endereço correspondente / Correspondence address
Leticia Franco Martinez
School of Business FEARP/University of São Paulo,
Avenida dos Bandeirantes 3900, 14040-905, Ribeirão Preto, SP, Brazil.

Sistema de Avaliação: *Double Blind Review*
Editora-chefe: Giana de Vargas Mores
Editor Técnico: Wanduir R. Sausen

Como citar este artigo / How to cite item: clique aqui!/click here!

Abstract

The development of society is directly related to the exponential growth in demand for energy. This is due to rapid population growth, urbanization, and the economy's evolution. Proportionally, the amount of waste generated without a proper destination also grows. Adopting environmentally responsible and economically viable behaviors through new technologies has become essential. Biogas is part of this context as a source of clean and renewable energy generated from substrates from agriculture, industry, urban solid waste, and sewage treatment plants. In addition to creating significant business opportunities, the biogas chain has enormous potential in Brazil to decarbonize the world energy matrix. This alternative source represents an acceptable form of waste management, as it transforms environmental liabilities into energy assets, consolidating the circular economy practice. This study describes each link in the biogas production chain and suggests points of attention for its development. It was carried out in three stages: a collection of secondary data, analysis of secondary data, and validation by subject matter experts. The main improvement points found as a result are the qualification of people, the image of biogas, and energy transition.

Keywords: Biogas; Biomethane; Renewable energy; Decarbonization; Circular economy; Brazil.

Resumo

O desenvolvimento da sociedade está diretamente relacionado ao crescimento exponencial da demanda por energia. Isso se deve ao rápido crescimento populacional, à urbanização e à evolução da economia. Proporcionalmente, também cresce a quantidade de resíduos gerados sem destinação adequada. Adotar comportamentos ambientalmente responsáveis e economicamente viáveis por meio de novas tecnologias tornou-se essencial. O biogás insere-se nesse contexto como fonte de energia limpa e renovável gerada a partir de substratos provenientes da agricultura, indústria, resíduos sólidos urbanos e estações de tratamento de esgoto. Além de criar oportunidades de negócios significativas, a cadeia do biogás tem enorme potencial no Brasil e para descarbonizar a matriz energética mundial. Esta fonte alternativa representa uma forma aceitável de gestão de resíduos, pois transforma passivos ambientais em ativos energéticos, consolidando a prática da economia circular. Este estudo descreve cada elo da cadeia produtiva do biogás e sugere pontos de atenção para o seu desenvolvimento. Foi realizado em três etapas: coleta e análise de dados secundários e validação por especialistas no assunto. Os principais pontos de melhoria encontrados são a qualificação das pessoas, a imagem do biogás e a transição energética.

Palavras-chave: Biogás; Biometano; Energia renovável; Descarbonização; Economia circular; Brasil.

1 Introduction

The development of society is directly connected to the exponential growth of energy demand. In this sense, fossil fuels are the main contributors to this segment, although they are not sustainable and present serious environmental problems. Moreover, climate change has become a significant concern for the world, and this scenario has been intensifying the search for renewable resources (Olabi & Abdelkaremm, 2022) and the increase in anthropogenic emissions of greenhouse gases (GHG) has led society to seek a path towards a low-carbon economy (Marques & Marcovitch, 2014). Simultaneously, rapid population growth, high urbanization rate, and economic evolution are directly related to the progressive quantity of waste material with no correct destination (Silva *et al.*, 2020).

The planet's natural resources are limited. Therefore, the transition from linear business models - which are currently the majority - to circular models is necessary (Salvador *et al.*, 2020). The circular model involves sustainable thinking mainly focused on reducing, reusing, and recycling with a systemic view of the business, aiming at economic prosperity, followed by environmental and social quality, unlike the linear model (Kirchherr *et al.*, 2017). Bioenergy is a good example, being the name of energy from biomass, that is, organic matter of vegetal and animal origin (Salvador *et al.*, 2021).

Without bioenergy, the reduction target for global greenhouse gas emissions of 2°C will not be achieved. The United Nations (UN) Sustainable Development Goals, which include climate action to secure livelihoods for centuries to come, suggest that we have a moral duty to develop and provide bioenergy on a large scale to develop the social pillar and promote significant fossil carbon sequestration (Souza *et al.*, 2017).

Bioenergy combined with carbon capture and storage has a vital role, as biomass production causes carbon to return to the soil and vegetation, eventually, this carbon will be consumed by animals and microorganisms and subsequently returned to the atmosphere (Janiszewska *et al.*, 2022). Questions and criticisms about CO_2 emissions from burning biomass make no sense, as this practice is part of the biogenic carbon cycle ($BioCO_2$). Bioenergy systems operate within this system, and as plants grow, carbon is naturally absorbed. On the other hand, the use of fossil fuels increases the total amount of carbon in the "biosphere-atmosphere" system (Souza *et al.*, 2017; Iea, 2023).

Studies show that biomass can supply the world's energy demand (Salvador *et al.*, 2021). By 2050 is estimated that low-carbon initiatives based on the circular economy can reduce such gases by up to 63% (Velenturf & Purnell, 2021). It is worth mentioning in this context, the concept of "Waste-to-Energy" (WtE), that is any waste treatment technology that generates energy, no matter which - heat, electricity, or fuels - from raw material. That has several advantages, as it addresses the challenge of waste disposal and offers an excellent opportunity for energy security, enabling production processes and energy consumption to be in the same geographical location, which does not occur with fossil fuels. "WtE" can be considered a semi-renewable energy source and an alternative or complement to fossil fuels that account for more than 80% of global energy consumption (Rafiee *et al.*, 2021).

Biogas is inserted into this context as a clean and renewable energy source, generated from substrates derived from agriculture, industry, landfills, and sewage treatment plants (Cibiogás, 2022a). It is an example of a product result coming from "WtE" technology. It is one of the products of anaerobic digestion, that is, the degradation of organic matter by microorganisms without oxygen (O_2). An anaerobic biodigester reactor offers the ideal conditions for microorganisms to turn organic matter into biogas and digested material, mainly composed of methane, which can generate electric, thermal, and vehicular energy. It is important to mention that purification is an essential step that must be applied depending on the use of biogas, which will result in biomethane (Mutz *et al.*, 2017).

Biogas can slash global greenhouse gas emissions by 10% to 13%, showcasing significant untapped potential on a global scale. Untill 2019, there were approximately 50 million micro-biogas plants and 132,000 biogas plants functioning at various scales, with an additional 700 plants undergoing modernization. However, these facilities utilize merely 1.6% to 2.2% of the potential linked to anaerobic digestion and biogas production, employing about 344,000 individuals (WBA, 2019). Leveraging biogas for electricity generation could potentially cater to 16% to 22% of global electricity consumption, while its use for biomethane production has the potential to substitute for 26% to 37% of the current natural gas consumption worldwide (WBA, 2021).

Brazil is one of the countries with the most significant potential for biogas production and the fifth largest in terms of its ability to reduce greenhouse gas emissions worldwide (Cibiogás, 2022a). The biogas segment in Brazil has shown exponential growth in recent years. From 2020 to 2021 alone, biogas use increased by 10%, and the number of plants in operation increased by 16%. Between 2011 and 2021, the number of plants in the country escalated from only 56 to 653, significantly increasing the amount of biogas produced, which evolved from 283 million to 2,349 million Nm^3 in the same period (Cibiogás, 2022a).

Currently, the main application of Brazilian biogas is electricity generation, which occurs in 87% of the plants. In 2021, 71% of the produced volume of biogas was used for this purpose, and 23% of biogas was used for biomethane production, although only 1% of plants had this purpose (Cibiogás, 2022a).

The biogas industry in Brazil has immense potential for creating new business paths and reducing carbon emissions in the energy sector. Despite the country's capacity to produce around 82 billion cubic meters of biogas annually – enough to meet 35% of its current energy needs and 70% of its fuel needs – only 2% of this capacity is currently used. This underutilization highlights vast opportunities for expansion in this production chain. Furthermore, biogas offers an effective solution for wastewater

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treatment and production waste management, converting environmental liabilities into energy assets and promoting the circular economy (Galvão, 2017; Rafiee *et al*., 2021).

Agriculture is the primary substrate source for biogas production in Brazil. It represents 80% of the active plant's input, but its share in the total volume is only 11%. Plants that process municipal solid waste have only 9% of the plants in operation, but they produce 74% of the country's biogas (Cibiogás, 2022a).

Even carbon capture and carbon usage technologies can be used in biogas plants. One of the applications of these technologies is "Power-to-X" production (where X stands for gas or liquid), which has the potential to be combined with renewable energy systems (e.g., wind or solar) and serves as an electricity storage option. This storage option solves the problem caused by the fluctuating nature of renewable energy, which leads to an alternating energy supply (Baena-Moreno *et al*., 2020).

This work's main objective was to contribute to the literature related to the topic of decarbonization via renewable energy, with a focus on biogas. The Brazilian scenario stood out, as it is an agricultural country with important access to substrates to produce this type of energy. This work describes this production chain in detail and, to make this possible, the authors carried out three scientific steps: secondary data collection, secondary data analysis, and validation by experts. With this, it was possible to answer the research question "What are the main points of contact in the biogas production chain, from inputs to commercialization, and what proposals improve the future of this energy source, especially in Brazil?".

2 Literature review

From the literature review of this work, it is expected to understand the main concepts related to the analyses that will be carried out later in this research.

2.1 Production chain and green supply chain

The development of the term "production chain" emerged around 1950 based on systems theory and in conjunction with the term "holistic". Thus, it is essential to know that a complex system cannot be fully understood if the individual parts are studied separately (New, 1997).

Materials and information come and go along the production chain and management seeks to integrate these activities through good relationships to achieve competitive advantage in a sustainable way (Seuring & Müller, 2008). The flow of goods through the chain keeps the modern world alive. Demand defines how organizations meet their expectations and justifies adapting their operations to make this happen (New, 1997).

In agribusiness, several theories can work together in analyzing production chains: however, “agribusiness systems, clusters, networks, supply chains, inter-organizational relationships, transaction cost economics, and others” (Neves *et al.*, 2019) provide more significant opportunities in planning application because they are more specific and provide the opportunity for in-depth study (Castro, 2001).

Consumers are crucial in the production chain, as it is only justified if they accept the products and services. However, control of the community, national, or multinational governments is also essential (New, 1997). Studies on agro-industrial chains contribute mainly because they directly or indirectly influence the elaboration of public policies and the development of organizational strategies (Zylbersztajn, 1995).

The vision of the production chain is attractive for strategists to understand the whole and assess the impact that competition could have on the operational environment, which adds value to developing a strategic plan that makes the company more competitive (Neves, 2008).

The concept of a “Green Supply Chain” refers to a meticulous approach to supply management that prioritizes environmental considerations and emphasizes the potential outcomes of production. This involves practices like recycling, minimizing waste, integrating environmental data into processes, and innovating to develop new products (Bowen *et al.*, 2001). Sustainable Supply Chain Management (GSCM) can be viewed as an integrated subsystem of a sustainability-oriented supply chain. This subsystem establishes direct connections between environmental concerns and organizational practices, such as reverse logistics, acquisition of environmentally friendly products, and environmentally responsible manufacturing and distribution strategies (Jabbour *et al.*, 2016).

2.2 Circular economy

Problems associated with the linear economy are environmental damage and the need for energy security since it is an economy based on fossil fuels. The transition to a sustainable circular economy occurs where biomass residues are recycled for energy production and waste and greenhouse gas emissions are minimized. The WtE supply chain offers the opportunity to simultaneously solve the problems of energy demand, waste management, and greenhouse gas emissions to achieve a circular economy system (CES). In other words, CES is based on a “win-win” philosophy in which economic prosperity and a healthy environment can reconcile (Pan *et al.*, 2015). This means that, environment, energy, and CO_2 emissions must be linked to establish the CES business model in an industrial system. CES must be based on the principles of the 5Rs (reduce, reuse, recycle, recovery, and reclamation) (Pan *et al.*, 2015).

The most important advantage of the circular economy is that the value of the product and material is retained longer. The transition from a linear to a circular

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economy is also expected to bring attractive economic development and create jobs due to the organizational, social, and technical revolution. It is crucial to support the circular economy not only at the regional and national levels but also at the local level. Policy and regulatory re-design are needed to support environmentally friendly product design and motivate manufacturers to produce responsibly (Velenturf & Purnell, 2021). The transition to a circular economy requires mechanisms that enable balance. Bioenergy and biogas are, therefore, opportunities that require detailed analysis (Kapoor *et al*., 2020).

The principles of the circular economy present an opportunity for the agricultural sector to assist individual consumers. Through the reduction of carbon emissions in production, the gradual elimination of single-use plastics, and the provision of clear information regarding food origin, agricultural entities can establish stronger connections with their customer base (Magnus, 2023).

2.3 Biogas and biomethane

Biogas is a renewable energy source derived from the decomposition of organic material from agriculture (especially the sugar sector), livestock, industry, and wastewater disposal (CETESB, 2022). The term biogas had several names, such as “swamp gas” or “landfill gas”, precisely because there are several favorable environments for this process in nature, characterized by low oxygen concentrations such as swamps, oceans, estuaries, and others. Humans recognized the possibility of producing fuel gas from organic wastes by observing the natural combustion of this gas on the surface of marshes. Later, this fermentation process was used to treat domestic wastewater and convert the organic matter. The gas produced was used for lighting. In the early 20th century, digesters began to be developed in India and China to produce methane gas from animal manure, mainly from cattle (CETESB, 2022).

A few decades ago, biogas was considered a “poor man’s fuel”. However, today, it is one of the leading options in international energy planning because access to biogas resources leads to decentralization of the energy grid, whether it is gas or electricity, promoting renewable technologies such as photovoltaic (PV) and wind power and offsetting the variability of these energies (Rafiee *et al*., 2021).

Biogas produced from animal waste can consistently bring benefits to rural businesses, such as recovering the value of agricultural waste, reducing electricity consumption from the residual power matrix, reducing environmental impact, lowering costs, and helping to close material and energy loops by developing practices based on a circular economy. In addition, biogas can be a starting point for several products of great value in rural farms, such as electricity, biofertilizers, biomethane, and carbon dioxide recovery. Furthermore, it can also be used in cooking (Jesus *et al*., 2021).

Among animal excrements, cow dung is mainly used as a substrate because it is abundant and available everywhere. Cow dung is used not only as a substrate but also for thermal insulation and as a fertilizer for soil improvement. Previous studies have shown its effectiveness in biogas production as a substrate (Obileke *et al.*, 2022).

Biomethane is considered a green fuel from biogas. Thus, it comes from processing products, organic and landfill wastes, and wastewater; it has similar properties to natural gas and can be used for vehicles (Coelho *et al.*, 2018). A striking difference between biogas and biomethane is the higher heat capacity of the latter. Therefore, its transportation and storage in the air are more attractive due to its higher energy density. It can be said that biomethane is a substitute for fossil natural gas (NG) but of renewable origin, called RNG (Renewable Natural Gas Production) (Coelho *et al.*, 2018).

A new decree from the Federal government reshapes the regulations governing gas, sparking growth in the natural gas sector. This leads to heightened competition, price drops, wider adoption, increased investments, and the expansion of transmission network pipelines. Additionally, the decree puts biomethane on par with natural gas and enables connections between the transmission system and compressed natural gas (CNG) facilities. Essentially, it permits the integration of biomethane into gas networks, fostering competitive expansion in bioenergy across new regions via pipeline infrastructure (MME, 2021).

This versatile product finds application in curbing greenhouse gas emissions in sectors heavily reliant on fossil hydrogen, such as oil refineries, methanol, and ammonia production (Irena, 2020). Leveraging biomethane for green ammonia production aids in manufacturing nitrogen fertilizers. Notably, an agreement between Raízen, a biogas plant owner, and Yara, a leading global fertilizer producer based in Norway, includes incorporating this raw material into Yara's production process. This strategic move is expected to slash the company's emissions by roughly 80%, aligning with ambitious carbon neutrality objectives (Yara Brasil S.A., 2022).

It is very unusual to see a single rural property that generates waste and produces biogas and biomethane. Many farms and agro-industrial cooperatives close to each other jointly supply agricultural residues or biomass to a central point to produce biogas, which helps strengthen the economic cycle (Jesus *et al.*, 2021).

3 Materials and methods

This study consists of qualitative and exploratory research based on secondary data. The qualitative methodology allows one to understand and acquire a wide range of information on a smaller sample, leading to a better understanding of the facts and social reality in the context in which it is inserted. The qualitative research aims to conduct an in-depth analysis to relate the elements studied to the events of interest. There are no measurements or statistical inferences in this context. Nevertheless, qualitative research requires the researcher's creativity since it depends largely on his skills and insights related to the subject (Vieira & Zouain, 2007).

The paper followed three stages in its development to meet our main objective, to describe this production chain in detail and provide indications for its development at a global level: Stage 1 - Collection of secondary data (via bibliographic and documentary research): to characterize the biogas chain (bibliographical research) biogas chain (bibliographical research), the most recognized databases in the world were used, such as Science Direct, Scientific Electronic Library Online (SciELO) and Scopus, focusing on periodicals such as "Journal of Cleaner Production", "Biomass and Bioenergy ", "Sustainable Production and Consumption", "Challenges" and "Energy". A total of 25 articles were analyzed in this phase and selected mainly based on their scientific impact (Impact Factor).

In addition, 20 renowned organizational reports on the biogas market were consulted, provided by important bodies in the sector such as the National Industrial Learning Service (SENAI-PR), Ministry of Mines and Energy (MME), IRENA System, IEA Bioenergy, Geo Biogas & Tech, Brazilian Agricultural Research Company (EMBRAPA), Environmental Company of the State of São Paulo (CETESB), Brazilian Association of Investors in Self-Production of Energy (ABIAPE), International Center for Renewable Energy (CIBiogás), Brazilian Association of Biogas and Biomethane (ABIOGÁS), National Electric Energy Agency (ANEEL) and the World Biogas Association (Documentary research); Stage 2 - Secondary data analysis: based on data mining in Stage 1, essential aspects were developed for a better knowledge of the subject, to conceptualize and describe the biogas chain in the context of the circular economy, understanding its uses and demonstrating the benefits the introduction and promotion of this alternative energy source. Stage 3 – Validation by experts (5 in-depth interviews): we validated the proposals with five experts from the Brazilian leader Geo Biogas & Tech through online meetings. The president, the people and organizational behavior analyst, the R&D and processes manager, the quality director, and the new business analyst.

Based on the secondary data collection and analysis, and the collaboration of experts, it was possible to make a brief analysis of this chain and understand its environmental, economic, and social contribution. Subsequently, the first version of the biogas production chain design was developed and later approved by the same experts. This adapted version has a realistic view of the market and is the main product of this study.

4 Results

4.1 Biogas processing and its possible applications

The demand for higher productivity and population growth, as well as the resulting increase in waste generation, poses more challenges to agricultural production and other sectors, so it is necessary to make this practice more efficient and, at the same time, protect the environment. Environmental concerns are becoming one of the most critical demands of today's society, especially for companies (Ferdes *et al.*, 2022; Galvão, 2017). For the overall sustainable development of the ag industry, the proper determination of ag-industrial residues and wastes must be addressed. Therefore, disruptive innovations and systemic solutions considering energy, food, waste, and the environment are crucial (Galvão, 2017). Using waste as a feedstock offers an intelligent alternative that brings significant socioeconomic benefits (Ferdes *et al.*, 2022).

Different biogas applications significantly impact the development of a circular economy, as the benefits of this production model can be linked to the benefits of alternative sources. This link can be made through the ability of biogas to reduce the carbon footprint, improve waste management, increase renewable energy production, create new jobs, improve agricultural productivity, and reduce the impact of climate change. It can help to achieve 12 of the 17 Sustainable Development Goals (SDGs) established by the United Nations (UN) (Obaideen *et al.*, 2022).

In addition, this alternative energy source is intergenerational as organic material is produced in several industries daily and in significant quantities, which is a competitive advantage over wind or solar energy, that are considered unsteady because they depend on the sun and wind to function. In addition, it is possible to store this gas at a low cost; its production is decentralized and independent of pipelines; the energy is available so that its production does not disrupt distribution networks; and finally, electrical energy can be offered during hours of high consumption (ABIOGÁS, 2022c).

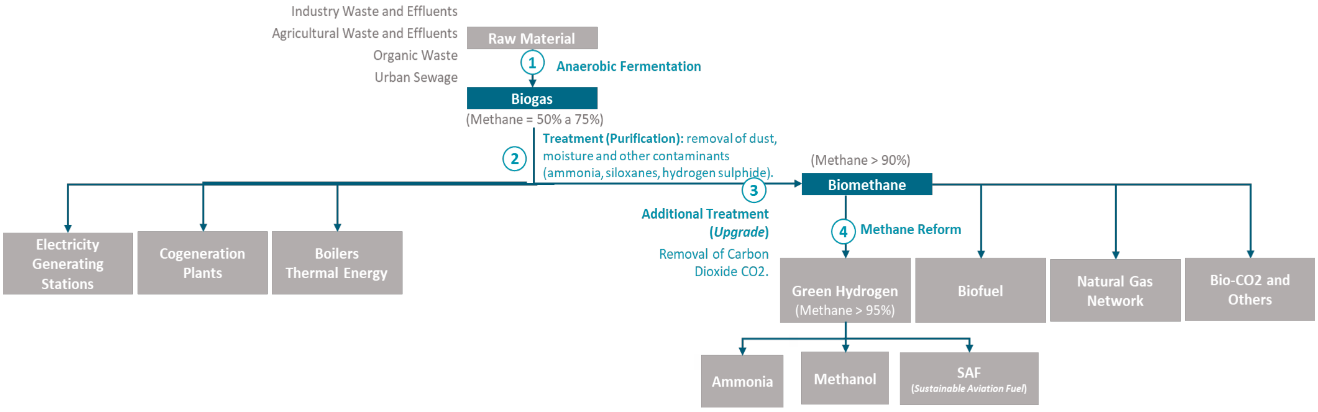
Organic residues spontaneously produce gases that can significantly pollute the environment once released into the atmosphere. The methane released has more than 20 times the impact on global warming than carbon dioxide (CO_2) in 100 years. On the other hand, once produced in a controlled environment with proper processing, biogas becomes a potential alternative energy source, especially for rural communities (ABIOGÁS, 2022c; Rafiee *et al.*, 2021).

This process produces a gas mixture of 50 to 70% methane (CH_4), 25 to 50% carbon dioxide (CO_2), and traces of other gases in the amount produced (CETESB, 2022). However, for biogas to be used for various purposes, it must be broken down into its components, which must undergo conversion processes. Biogas can be used in boilers by direct combustion for cogeneration, a process that allows the simultaneous production of heat and electrical energy from one fuel source. Biogas is a viable and accessible alternative technology for animal waste treatment in small and medium rural areas. This dynamic can produce steam in grain dryers, forced air furnaces for rural heating facilities, and even agro-industrial processes (Geo Biogas & Tech, 2022).

Another advantage of the biogas production process is the digestate produced by the anaerobic fermentation of organic matter, which has soil-improving properties. Through separation techniques, improvement, and enrichment with minerals, it can be converted into an organic-mineral fertilizer that is best applied to crops (Geo Biogas & Tech, 2022). These powerful biofertilizers can return to rural areas to fertilize the soil, recycle nutrients, and make them bioavailable to plants, follow carbon-free dynamics, and enrich organic matter in the ecosystem (EMBRAPA, 2022).

When biogas is purified, it can be turned into biomethane, a fuel that is a "biogas upgrade" version, with a high methane content in its composition (at least 90%), which binds properties that make it interchangeable with natural gas. Therefore, it can be used in cars or trucks suitable for conversion to Natural Gas Vehicle (NGV) and can replace diesel. It could be said that biomethane is a substitute for natural fossil gas that comes from renewable sources (RNG) (Coelho *et al.*, 2018). Figure 1 shows the entire biogas process until purification and conversion to biomethane.

Figure 1. Biogas and biomethane production process.



Source: elaborated by the authors (2022).

Biomethane can also decarbonize hydrogen production, which mainly uses fossil natural gas as input. This pathway can integrate the process without increasing costs and use the same infrastructure with green hydrogen production. This product has many applications and can reduce greenhouse gas emissions in areas where fossil hydrogen is widely used, such as oil refineries, methanol production (used as a solvent in industrial processes), sustainable aviation fuel (SAF) production, and ammonia production (used in nitrogen fertilizer production) (Irena, 2020).

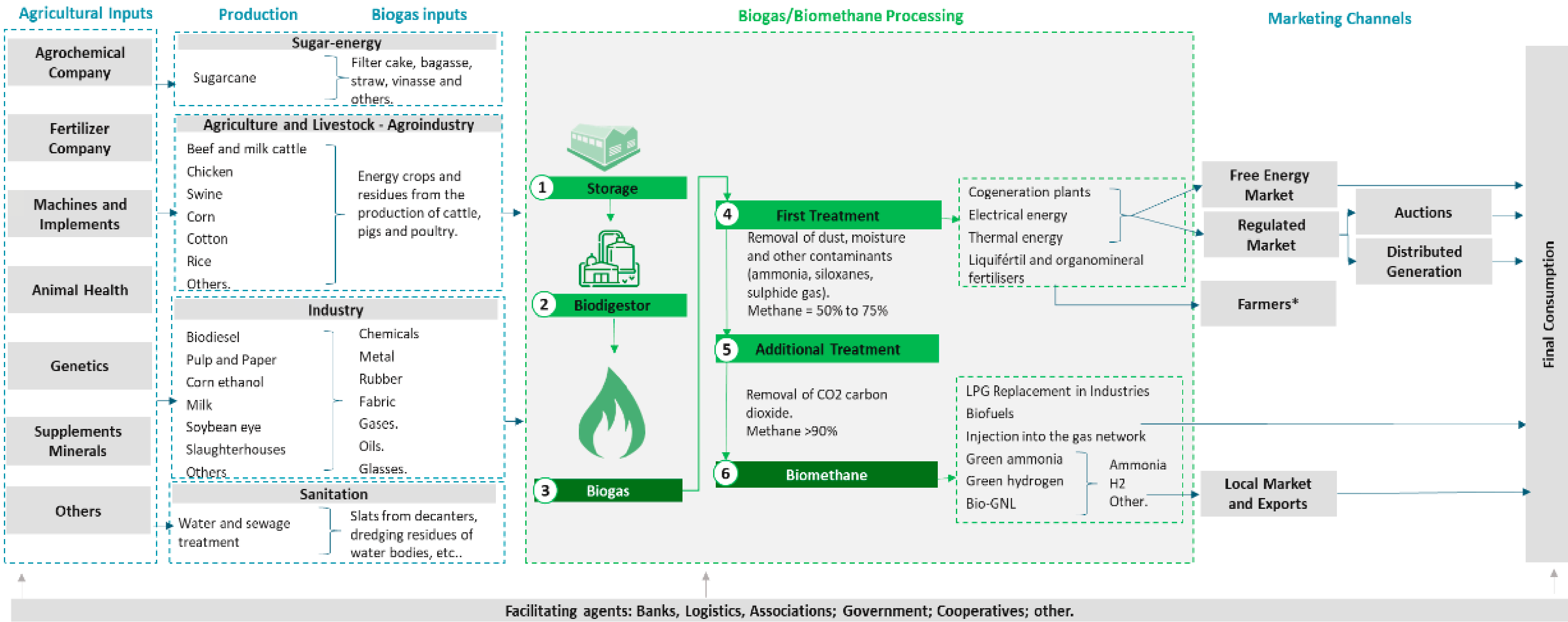
In addition, green hydrogen is configured as an abundant, efficient bioenergy that has the potential to become one of the primary fuels to replace oil because its energy capacity is up to three times greater than gasoline; therefore, it is considered one of the fuels of the future and has proven to be a comprehensive alternative in several countries. During COP-21 (21st Climate Conference), a campaign called "Race to Zero" was signed by several countries to reach the goal of zero greenhouse gas emissions. This scenario encourages high investments in technologies to produce clean and renewable hydrogen (Cibiogás, 2022b).

4.2 Biogas and biomethane production chain

In particular, the biogas production chain includes the supply of feedstock, the processing, production, purification, and upgrading of biogas, and the markets associated with the end use of the biogas itself and the products derived from it (Rafiee *et al.*, 2021).

Figure 2 is a representation of the biogas production chain that echoes some of the points discussed so far, such as the inputs from which biogas is produced, the storage and use of biogas plants, the stages of biogas upgrading and their respective compositions, the main outlets, the forms of commercialization and access to the end user. This chain design illustrates the production flows on the substrates of different areas, the step-by-step processing of biogas, the main products coming from this source, and commercialization channels.

Figure 2. Biogas production chain.



Source: elaborated by the authors (2022).

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4.2.2 Production and industrialization agents

Starch factories, breweries, and slaughterhouses are examples of enterprises where biogas is mainly used as a heat source to avoid fuel wood, liquefied petroleum gas (LPG), or natural gas due to the high heat demand that the industries usually have (Senai, 2016). Studies have shown the potential for using residues from the sugarcane industry, and one of the best examples is vinasse. Biodiesel is also an important industry in Brazil, which still belongs to the biofuel sector. The pulp and paper industries are also characterized by the possibility of treating the effluents from production plants and paper bleaching (Grando, 2021).

4.2.3 Commercialization

The electrical energy obtained from biogas can be commercialized in different ways Brazil. The market is divided into the free contract environment and the regulated contract environment. In the first case, purchase and sale negotiations are conducted based on freely negotiated bilateral contracts the name suggests with specific conditions and rules established between the parties, whether in terms of price, quantity, or duration, to name a few aspects (Aneel, 2023a).

The free energy market accounts for about 35% of the total electricity consumption in the National Interconnected System, which coordinates and controls the generation and transmission of electricity in Brazil (Aneel, 2023b). However, the trend is for commercialization to increase simultaneously in this environment as the market becomes more flexible and opens to smaller consumers, including residential consumers (Aneel, 2023b). This transition expects to increase competition in the energy supply, which will help reduce costs and, thus, the final price consumers pay (Brazil, 2021).

On the other hand, the regulated environment is formed by the so-called captive consumers, which are characterized by the fact that they buy electricity from the concessionaire responsible for distribution in their region. They can only purchase electricity directly through the distribution company, which is nowadays the most common model for households and small businesses. Negotiations are conducted through contracts signed between generators and distributors participating in auctions for the purchase and sale of energy. Specific rules apply that cannot be changed by the actors (Aneel, 2023c).

Electricity auctions are currently the main form of energy contracting in Brazil and regulate the commercialization of electric energy through public bids. The Chamber conducts them for the Commercialization of Electric Energy with a delegation from the National Agency for Electric Energy (ANEEL), which regulates the tariff flag system for energy prices (Aneel, 2021c). Another marketing modality that still falls within the regulated area is distributed generation (DG). This means that it is characterized by micro and mini-generation of energy from renewable sources

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or cogeneration. It is an innovation that can reconcile financial savings, social and environmental awareness, and self-sufficiency (Aneel, 2023d). Electricity generation occurs at or near the consumer and has advantages over a centralized generation, saving investment in transmission and reducing losses in these systems, improving services' stability. Nevertheless, the growth of DG has excellent potential in the coming years, as it enables significantly higher energy efficiency (Inee, 2023).

Self-generation is also an alternative, where the energy generated is used to meet the facility's energy needs, depending on the feasibility of the operation (Abiape, 2020). There are also several ways to market biomethane, such as injection into the distribution grid as compressed (Bio-CNG) or liquefied (Bio-LNG) gas. The biggest room for the biomethane market is in its internalization, i.e., supplying regions not covered by the country's small natural gas distribution network, enabled by its distributed generation capacity, since biomethane currently does not have a competitive cost compared to natural gas in regions supplied by pipelines (Lima, 2020).

5 Discussions

Biogas is changing the productive sectors, affecting both national and international industries. All production processes generate waste from sectors such as metallurgy, textiles, footwear, paper, and chemicals. The residues are diverse, but the difficulty is the same: the treatment of these substrates. Investing in a technology that allows the production of biogas in these segments helps to increase the profit margin by reducing the costs associated with energy. In addition, it replaces fossil fuels with biofuels, which reduces the emission of greenhouse gases and cooperates with human health.

From an economic point of view, biogas and biomethane can not only be an alternative for electric, thermal, and biofuel energy but also reduce production costs and provide more income opportunities, increasing the competitiveness of companies that understand how to adapt to the demands of the market. Moreover, it is expected to become even more important in the face of the water crisis and high energy costs that the world is facing. It is crucial to remember that this is a more complex task requiring appropriate technology, people skills, and a culture focused on innovation and engagement.

From an environmental point of view, energy from biogas can be an essential alternative for countries to meet the commitments they made at COP-26 in Scotland, especially regarding the reduction of methane emissions by 2030, a gas considered by researchers to be more harmful to the climate than CO_2 and blamed for 30% of the increase in the Earth's temperature. From a social point of view, market revenues can increase the quality of life since waste is taken to appropriate places, and access to energy becomes less costly to all, even in the most challenging areas.

For corporate governance, biogas needs organizations that address risk management, act ethically, transparently, and responsibly, and think about alternative energy sources to improve the quality of their supplies. Even if indirectly, corporate management ensures that the actors involved in the production processes also care about the environment and society. It is unlikely that a company will be well evaluated on these criteria if others are at a harmful level. In addition, investments in the biogas market develop the supply chain through the demand for equipment for the digestion process and investments for project implementation, maintenance, and support offered by specialists in this field. All this involves the provision of services and the generation of income.

From a technological point of view, biogas production is expanding. Organizations are promoting innovation and growing to meet more significant energy needs. In an environment that favors the production of clean and renewable energy sources and fuels, biogas is expected to gain importance in these sectors. This alternative allows the expansion of energy stability. It contributes to the environmental commitments crucial for food safety and the efficiency of agricultural production systems, leading to competitiveness and economic growth. Thus, this dynamic is based on a cycle of sustainability and development in the economic, environmental, and social spheres.

Nevertheless, some barriers to biogas commercialization must be overcome by different factors depending on the level of the country's development. These include economic factors (high investment is required), institutional factors (low political support), socio-cultural factors (low consumer interest and resistance to change), environmental factors (lack of access to necessary water resources), and the market (competition with other fuels) (Obaideen *et al.*, 2022).

Understanding biogas evolution and global markets is essential to identify possible production process improvements and exploit the apparent potential in the analysis presented. According to the research conducted and with the help of experts interviewed by the market leaders, three main points were highlighted to be considered:

1. Qualification of employees: since it is a very technical and difficult-to-understand subject, it is still challenging to find experienced professionals in the market. Companies can invest in training and internal development so that the team becomes more qualified for biogas activities, as Geo Biogas & Tech has done internally.
2. The image of biogas: this energy source has been neglected and lost credibility due to technical, political, economic, and commercial misunderstandings - the lack of proper information dissemination about biogas has contributed to this. Disseminating knowledge about the importance and existing benefits and disclosing the immense energy production potential of biogas can help increase stakeholder engagement.
3. Energy transition: It is undeniable that the number of opportunities for biogas can contribute to the energy transition that comes with changes in the structure of the Brazilian energy matrix. There are institutional and regulatory barriers to the development of strategies that allow the Brazilian

potential to be exploited. Greater coherence in decarbonization, reduction of information asymmetries, and overall policy direction are needed to enable projects in this area.

These were some of the leading indicators found in the study of the production chain of biogas. Others should be included because, as shown, there is great potential for biogas, especially in Brazil. Thus, there is still room for further studies that deepen and focus more on the organizational strategic plan of this sector.

It can be noted that in Brazil, there are many favorable regulations for biogas to boost the sector of the economy. The clearer the production chain and the greater the legal and fiscal incentives, the greater the opportunities for the community, considering environmental, social, and economic aspects, which are also related to the points addressed in this study.

5 Conclusions

This study has analyzed the biogas chain, its inclusion in the circular economy context, and the benefits that may result for society from its development. Biogas is a viable alternative to fossil fuels and has a direct impact on reducing the CO_2 footprint and air and water pollution. It is considered an exciting solution for waste management. It also offers excellent potential for use in electrical power supply to enable decentralized Regulation and position itself strategically for energy security. However, this still needs to be explored.

To properly exploit all the opportunities that biogas can offer to the environment, it is crucial to change the mindset and move from the traditional idea that society is only dealing with "leftovers" or "waste" to the idea that we are dealing with something of value, with partial products that can meet the needs of the end user, which strengthens the circular economy and waste reduction model.

Although the concept 'WtE' is mentioned at the beginning of the paper, a new nomenclature is proposed: "Waste and Byproducts to Energy (WBtE)," based on the understanding that it is not only about reducing waste but also about creating value. To achieve this value, the points and suggestions for improvement presented should be considered essential drivers for better promotion of the biogas chain with qualified people, a good image of the product potential, and initiatives that stimulate and expand its use in the country.

The main limitations of this research can be summarized in the fact that it is a very technical and new topic, especially in Brazil. Therefore, it is not easy to access the literature and find people to discuss the topic in-depth and collaborate on the results. For future research, more participants should be recruited for interviews, including people from other countries where biogas already.

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