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POTENTIALS AND CHALLENGES OF BIOGAS PRODUCTION FROM SWINE FARMING IN SOUTHERN BRAZIL

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ABSTRACT

Pig farming, largely concentrated in small and medium-sized rural properties, generates significant amounts of organic waste, which, when inadequately managed, contributes to environmental pollution and greenhouse gas emissions. Then, this study aims to analyze the potential and challenges of biogas production from pig farming waste in southern Brazil, emphasizing its relevance as a sustainable alternative to address energy, environmental and economic demands. Anaerobic digestion of waste enables the production of biogas (mainly methane), which can be used as a source of thermal or electrical energy. Additionally, it produces biofertilizers that reduce dependence on chemical inputs. Biogas use offers benefits such as climate change mitigation, diversification of the rural energy matrix, and promotion of the circular economy. However, several barriers persist, including high initial investment costs, the need for technical training, and regulatory obstacles. The text proposes strategies to overcome these issues, such as financial incentives, specific public policies, and the strengthening of cooperative arrangements. Thus, biogas emerges as a strategic tool for sustainable rural development and is aligned with the United Nations Sustainable Development Goals (SDGs).

Keywords: Anaerobic digestion, renewable energy, circular economy, greenhouse gas mitigation, environmental management, sustainable agriculture.

1. INTRODUCTION

Swine farming stands out as one of the main agricultural activities in Southern Brazil, especially in the states of Rio Grande do Sul, Santa Catarina, and Paraná. This region concentrates the majority of the country's pig production, resulting in the generation of large volumes of animal

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waste (IBGE, 2024). When improperly managed, these residues pose one of the major environmental challenges of the activity, with significant risks of soil and water contamination, in addition to the emission of greenhouse gases (GHGs).

In this context, biogas production emerges as a strategic and promising alternative, capable of transforming environmental liabilities into energy assets. By promoting the reuse of swine waste, this technology directly contributes to the sustainability of the production chain, while also assisting in climate change mitigation and diversification of the rural energy matrix.

The growing concern over the environmental impacts of agriculture and the pursuit of alternative and sustainable energy sources have driven the adoption of bioenergy technologies in rural areas. Anaerobic digestion of animal waste, the main process involved in biogas production, enables not only the capture and use of methane as an energy source but also the generation of biofertilizers and a significant reduction in GHG emissions, aligning with the principles of circular economy and agroecology.

Southern Brazil, due to its high concentration of small and medium-sized swine production units, offers favorable conditions for the dissemination of biodigestion systems, establishing itself as a reference region in the energy recovery of swine waste. However, despite the numerous environmental, economic, and social benefits associated with biogas production, significant challenges still remain, such as high implementation costs, the need for specialized technical training, regulatory hurdles, and a lack of structured public policies to support its large-scale expansion.

This chapter aims to present the technical foundations of biogas production from swine waste, highlight its multiple benefits for the swine production chain and the environment, analyze the main barriers to its expansion, and discuss this technology's contributions to achieving the Sustainable Development Goals (SDGs) of the 2030 Agenda. By addressing the potentials and challenges of biogas production in the context of Brazilian swine farming — with an emphasis on the Southern region — we seek to offer a critical and forward-looking analysis of the possibilities for integrating intensive animal production, bioenergy generation, and rural sustainability.

2. FUNDAMENTALS OF BIOGAS PRODUCTION

Biogas production is based on the anaerobic digestion of organic matter, a biological process in which microorganisms, mainly methanogenic bacteria, break down organic residues in an oxygen-free environment. The main product of this process is a gas mixture composed mainly of methane (CH_4) and carbon dioxide (CO_2), along with traces of other gases such as hydrogen sulfide (H_2S), ammonia (NH_3), and water vapor (KUNZ et al., 2019; APPELT et al., 2020).

In agriculture, the primary substrates used for biogas production include pig, cattle, poultry, and sheep manure, in addition to organic waste from agro-industries (Figure 1). In swine farming, pig slurry is widely used due to its high organic load and ease of collection in confined systems. The same applies to intensive dairy farming, where the waste has high methanogenic potential (GERARDI, 2003).

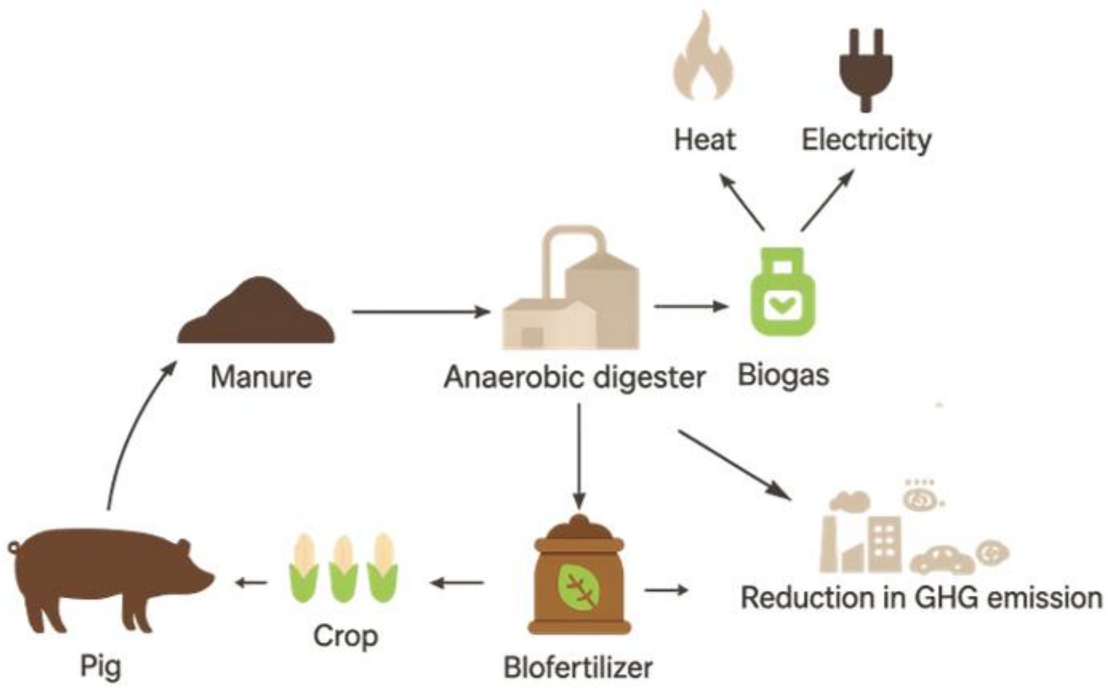

Figure 1: Circular bioenergy flow from pig manure through anaerobic digestion and resource recovery.

This substrate is fed into closed and airtight biodigesters, operating under mesophilic (30–40°C) or thermophilic (50–60°C) conditions, with a hydraulic retention time (HRT) ranging from 20 to 40 days. Maintaining temperature, pH, carbon-to-nitrogen (C/N) ratio, and agitation are critical factors for digestion efficiency and process stability (OLIVEIRA et al., 2021; ABDON et al., 2022).

Studies show that one ton of swine manure can generate between 400 and 500 m³ of biogas, equivalent to approximately 3,000 kWh/year in electrical energy. In the case of cattle, the potential is around 30 to 40 m³ of biogas per animal per month in well-managed systems (EMBRAPA, 2020; CIBiogás, 2021). Variations depend on the type and quality of the substrate, the technology used, and the production scale.

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The biogas generated can be used in various ways: for electricity and heat generation (in internal combustion engines or cogeneration systems), as vehicle fuel (biomethane) after purification, or even injected into natural gas networks, depending on technical and regulatory feasibility (LOPES et al., 2017; ANP, 2023).

In addition to its energy value, the biodigestion process offers significant environmental and agronomic benefits. It helps reduce greenhouse gas emissions — especially methane and nitrous oxide —, reduces odors, inactivates pathogens, and promotes safer waste management (COSTA; BUENO, 2018; IEA, 2021). It also produces digestate, a liquid and solid by-product rich in macro and micronutrients such as nitrogen (N), phosphorus (P), and potassium (K), which can be used as a biofertilizer, reducing dependence on synthetic fertilizers and fostering circular economy practices in agriculture (SIEGEL; SANTOS, 2022; PROCHNOW et al., 2023).

In regions with high animal production, such as Southern Brazil, integrating biodigesters into farms represents a technically and environmentally strategic solution, contributing to production sustainability, energy diversification, and climate change mitigation (MENEZES et al., 2020; CIBiogás, 2021).

3. BENEFITS OF BIOGAS PRODUCTION IN SWINE FARMING

The adoption of biogas production systems in swine farming is a highly strategic technological alternative from both environmental and economic perspectives. The use of biogas to meet internal energy demands on farms can lead to significant reductions in electricity costs, ranging between 20% and 25%, according to estimates by Embrapa (COSTA et al., 2020). This cost-saving is particularly relevant in a context of rising electricity tariffs in Brazil and provides greater cost predictability for producers.

Beyond financial savings, the use of methane (CH_4) — a gas with a global warming potential 25 times greater than carbon dioxide (CO_2) — reduces greenhouse gas (GHG) emissions. According to the Intergovernmental Panel on Climate Change (IPCC, 2014), capturing and using the methane present in swine waste can mitigate up to 75% of the emissions associated with poor waste management. This action contributes directly to Brazil's climate targets under the Paris Agreement, and also meets the growing demands of consumer markets for traceability and environmental sustainability in agricultural production (SOUZA et al., 2021).

Another relevant aspect concerns the improvement of organic waste management. The use of biodigesters enables the controlled treatment of swine manure, significantly reducing the risks of soil, groundwater, and surface water contamination, which are often compromised by the improper disposal of pig farming waste (MATOS et al., 2020). Furthermore, the anaerobic digestion process generates a by-product known as digestate, which is rich in nutrients such as nitrogen (N), phosphorus (P), and potassium (K), and can be used as a biofertilizer in agriculture.

Studies indicate that digestate can replace between 30% and 60% of the mineral fertilizers used in crop production, which reduces agricultural production costs, improves soil health, and contributes to more sustainable farming practices (OLIVEIRA; LIMA, 2022). This substitution also lessens external dependence on industrial inputs, with positive impacts on Brazil's trade balance and the economic resilience of producers.

Another important benefit is the possibility of marketing the surplus energy generated by biodigestion systems. When production exceeds the property's energy demand, biogas can be converted into electricity or purified to obtain biomethane—a vehicle fuel compatible with natural gas. This surplus energy can be injected into the distribution grid through the net metering system regulated by ANEEL, or sold to third parties, generating additional income for producers (FERNANDES et al., 2019).

Additionally, the monetization of carbon credits represents another environmental revenue opportunity. Producers who adopt low-carbon technologies, such as biodigesters, can access the carbon credit market, especially within voluntary initiatives or environmental certification programs such as RenovaBio, in the case of biofuels (MMA, 2023). This adds value to the activity and encourages the adoption of environmentally friendly practices.

Therefore, the multiple benefits of biogas—spanning cost savings, environmental sustainability, income diversification, and improved waste management—make it a key tool for strengthening the swine production chain in Southern Brazil. Its adoption aligns with the transition to low-carbon agriculture, greater climate resilience, and the integration of animal, energy, and crop production systems (OLIVEIRA; LIMA, 2022).

Despite the numerous environmental, energy, and agronomic advantages, the expansion of biogas production from animal waste faces several technical, economic, social, and institutional challenges, particularly among small and medium-sized rural producers.

One of the main barriers is the high initial cost of installing biodigestion systems. Depending on the scale and technology employed, the investment in 2020 was approximately USD 100,000 per unit for mid-sized farms, potentially exceeding this amount in more complex systems with electricity generation and biogas purification for biomethane. This cost is relatively high, especially given the lack of specific credit lines with terms suited to the financial reality of family farmers, who often struggle to provide guarantees or prove stable income (COSTA; BUENO, 2018; CIBiogás, 2021).

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In addition to financial factors, operating and maintaining the systems requires specialized technical knowledge of anaerobic microbiology, digester management, control of operational parameters (such as temperature, pH, organic load, and retention time), and equipment maintenance (OLIVEIRA et al., 2021). The lack of technical training and effective rural extension services undermines system efficiency and longevity, discouraging farmers after the first few years of operation, especially when technical failures or interruptions in biogas generation occur.

Regulatory bureaucracy also represents a significant hurdle. The processes for environmental licensing, water use permits, grid connection (in the case of distributed generation), and approval by regulatory bodies such as ANEEL are time-consuming, costly, and vary between states and municipalities. The absence of standardized regulations and overlapping responsibilities among environmental, sanitary, and energy agencies create legal uncertainty and discourage investment in the sector (MIRANDA et al., 2020).

Another challenge involves the logistics of collecting, storing, and transporting animal waste, especially on small farms with low production density. Although swine manure is the main substrate used in Brazil, biogas production can also be expanded using cattle manure, poultry litter, and even feedlot waste—provided proper handling systems and integration between production units are in place, which requires collective organization and infrastructure (GUIMARÃES et al., 2022).

The lack of structured and continuous public policies to support bioenergy in rural areas also hinders the large-scale development of biodigestion. Despite isolated programs and some state-level incentive initiatives, a robust national policy is still lacking—one that includes tax incentives, cross-subsidies, and remuneration mechanisms for the environmental services provided by anaerobic digestion (such as GHG mitigation and reduction of pollutant loads in waste).

To overcome these barriers, coordinated involvement of various institutional actors is essential, including government agencies, universities, agricultural cooperatives, technical assistance providers, and financial institutions. The creation of cooperative or consortium models for biodigester implementation, as well as the promotion of technical training programs, are promising pathways. Moreover, recognizing biogas in the carbon market and including it in mechanisms for a just energy transition could significantly increase the economic viability of such projects in Brazil.

4. BIOGAS, SWINE FARMING, AND THE SUSTAINABLE DEVELOPMENT GOALS (SDGS)

The transformation of swine waste into biogas represents an innovative and strategic solution to several challenges faced by the agricultural sector, especially in Southern Brazil. In a region where

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swine production is highly concentrated and the environmental impacts of improper waste management are substantial, adopting anaerobic digestion not only mitigates environmental liabilities but also promotes a range of social, economic, and ecological benefits that directly align with the United Nations' 2030 Agenda Sustainable Development Goals (SDGs) (Figure 2).

Figure 2: Biogas from swine farming as a driver of multiple sustainable development goals (SDGs).

Biogas production from animal waste contributes to the energy transition in rural areas by enabling decentralized generation of clean and renewable energy, promoting access to modern and sustainable energy sources (SDG 7). This progress is essential in a global context of searching for alternatives to fossil fuels, strengthening the energy security of farms and promoting more efficient use of natural resources (SDG 12). Additionally, by capturing methane—one of the most potent greenhouse gases—from manure and using it as an energy source, the system contributes significantly to reducing emissions from the agricultural sector, in alignment with climate action goals (SDG 13).

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The benefits of biodigestion extend beyond energy and climate. Proper waste treatment through this technology improves water quality and reduces soil contamination, contributing to ecosystem conservation, biodiversity, and public health (SDG 6 and SDG 15). Water, often threatened by pollution from agricultural activities, directly benefits when effluents are processed to reduce organic and microbial loads before any discharge or agricultural reuse (SDG 6).

Economically, using biogas and biofertilizer as by-products of anaerobic digestion enhances the resilience of rural production chains. Small and medium producers can benefit from reduced costs for electricity and agricultural inputs, as well as new income opportunities—contributing to the eradication of rural poverty and the promotion of inclusive and sustainable economic growth (SDG 1 and SDG 8). These dynamic drives regional development based on fairer, more efficient production models that value rural territories and communities (SDG 11).

The incorporation of clean technologies on farms also promotes innovation and modernization in agriculture, driving the development of smarter, more sustainable, and environmentally friendly production systems (SDG 9). Valuing waste as an energy and agricultural input promotes closed-loop systems and circular economy practices, reducing waste and encouraging more responsible production and consumption patterns (SDG 12).

In this context, biogas production stands as a concrete example of how agriculture can be reorganized through the lens of sustainable development, balancing productivity with environmental responsibility and social inclusion. By aligning with the principles of the 2030 Agenda, sustainable swine farming based on energy recovery of waste contributes simultaneously to climate, water, and soil protection, while promoting technological innovation, food security, and rural community well-being (SDG 2, SDG 3, SDG 11, and SDG 13).

For this potential to be fully realized, it is essential to strengthen public policies that encourage the use of biodigesters, expand access to green rural credit, support producer training, and foster cooperation networks among farmers, universities, governments, and the private sector (SDG 17). Biogas production, therefore, should not be seen merely as a technical solution but as an integrated rural development strategy aligned with the multiple sustainability goals defined by the United Nations.

5. PROPOSALS FOR THE SUSTAINABLE EXPANSION OF BIOGAS PRODUCTION FROM ANIMAL WASTE

The broad and sustainable adoption of biogas production from animal waste—especially in intensive swine farming in Southern Brazil—requires the implementation of coordinated public policies, financial incentives, and continuous technical support (Figure 3). The energy recovery of

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livestock waste represents an efficient strategy for environmental management on farms, the reduction of greenhouse gas emissions, and the generation of clean and decentralized energy.

One of the main proposals to enable this expansion is to broaden and simplify specific credit lines for renewable energy in rural areas. Current financing programs, such as the National Program for Strengthening Family Farming (PRONAF) and the ABC+ Program (Low-Carbon Agriculture), still present operational bottlenecks, such as documentation requirements and guarantees that do not reflect the reality of small producers (MORAES et al., 2021). Creating targeted bioenergy credit lines with subsidized interest rates, long repayment periods, and technical grace periods could significantly increase farmers' access to biogas systems.

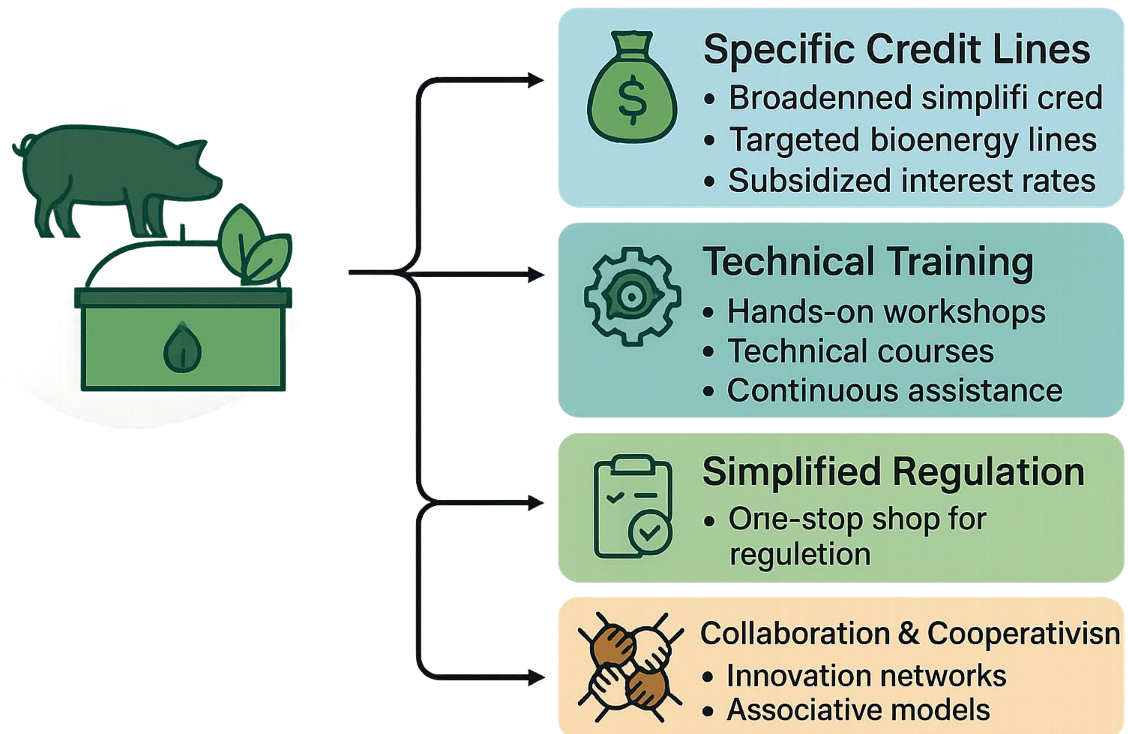

Figure 3: Strategic pillars for the sustainable expansion of biogas production from animal waste.

Another key pillar is strengthening the technical training of farmers, workers, and extension agents. The efficient operation and maintenance of biodigestion systems require specific knowledge in microbiology, thermodynamics, agricultural engineering, and organic waste management. Ongoing training programs, hands-on workshops, technical courses, and the development of local multipliers linked to cooperatives and universities are essential to ensure the

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success and longevity of production units (CUNHA et al., 2022). Continuous technical assistance is also critical to prevent operational failures and optimize system performance.

From a regulatory standpoint, it is crucial to simplify environmental licensing and grid connection processes, which are currently excessively bureaucratic and vary across states and municipalities. Establishing a "one-stop shop" for biogas system regulation—integrating environmental, energy, and sanitary authorities—could reduce costs and implementation timelines. Exempting state taxes, such as ICMS on equipment purchases and surplus electricity sales, should also be considered as an additional incentive for rural producers.

Environmental certification of producers who adopt biogas systems, combined with price differentiation policies and access to preferential markets, could also function as an economic incentive. Swine products with environmental sustainability certification tend to be more valued in both domestic and international markets, especially among consumers concerned with climate change and the environmental impact of intensive livestock farming (FERRARI; RODRIGUES, 2021).

A successful example of biogas implementation in Southern Brazil is observed in the municipality of Concórdia, in Santa Catarina, where Embrapa Suínos e Aves has recorded the experience of a family property that incorporated a biodigester system into its pig farming operations. The property, which shelters nearly 500 finishing pigs, deployed a covered lagoon-type biodigester with the capacity to treat about 10 m³ of liquid manure daily. The system produces biogas employed for thermal applications such as water and piglet housing heating, thereby cutting back on the consumption of firewood and liquefied petroleum gas (OLIVEIRA et al., 2021). Besides power production, the digestate has been applied in fertigation for corn and pasture fields, thus completing the nutrient cycle and diminishing the reliance on chemical fertilizers. As reported in the study, this setup has resulted in a cutback of greenhouse gas emissions by close to 30% and a notable advancement in the farm's compliance with environmental regulations (OLIVEIRA et al., 2021).

Another significant example is the cooperative effort in the municipality of Entre Rios do Oeste, Paraná, where regional pig producers, supported by Itaipu Binacional and the local government, established a shared biogas facility under collective administration. Waste from around 22 integrated pig-rearing units is delivered daily to the plant, where it is digested and converted into biogas, powering a 75 kW generator linked to the national grid through a distributed generation framework. The financial feasibility of this structure is strengthened through the marketing of energy credits and the redistribution of savings among the farmers involved (ZILIO et al., 2020). This collaborative initiative highlights how regional cooperation and common-use infrastructure can bypass limitations of scale and extend biogas technologies to small and mid-sized farms,

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underscoring the relevance of local governance and cooperative frameworks in fostering resilient development in rural areas (ZILIO et al., 2020).

Moreover, it is essential to strengthen collaboration between universities, research institutions, rural extension companies, cooperatives, and the public sector, forming innovation networks aimed at adapting biogas technologies to regional conditions. Applied research should prioritize low-cost, modular, scalable, and family-farm-adapted solutions, integrating manure management systems, fertigation, and thermal or electric energy generation.

Finally, successful experiences show that rural cooperativism and the collective management of biodigesters can be viable paths to overcoming the technical and financial challenges of small-scale biogas production. Associative models or inter-municipal consortia allow for better resource use, cost reduction, and the creation of shared structures for environmental management, training, and marketing of the generated energy (PIRES et al., 2020).

6. COMPARATIVE PERSPECTIVE ON BIOGAS DEVELOPMENT: BRAZIL AND OTHER COUNTRIES

The trajectory of biogas in Brazil is marked by its strong association with livestock farming, especially in the southern regions, where intensive swine and poultry production generates large quantities of organic waste. Unlike Germany—whose expansion was based mainly on energy crops such as corn, driven by incentive tariffs—the Brazilian model prioritizes the conversion of agricultural waste and industrial effluents into energy (GUIMARÃES et al., 2020). This strategy contributes both to the mitigation of environmental liabilities and the generation of renewable energy in rural areas, supported by credit lines such as PRONAF and the ABC+ Program, although bureaucratic obstacles still limit its expansion.

Germany leads globally with more than 9,500 operational plants, stable policies, and well-structured grid access regulations. However, it has faced criticism for encouraging monocultures and land-use conflicts (NAEGELER et al., 2019). China and India invested heavily in household-scale biodigesters, but many systems were deactivated due to a lack of ongoing technical support (RAJENDRAN et al., 2021).

Despite the differences, these countries share structural challenges such as complex environmental licensing processes, limited technical assistance, high implementation costs, and unstable public policies (IEA, 2024; VEIGA; MARTINS, 2024). In Brazil, although these obstacles also exist, there are advantages such as abundant availability of residual biomass, a tropical climate favorable to digester performance, and local innovation networks led by universities, cooperatives, and municipalities that promote solutions adapted to family farming (LEMOS et al., 2024). By

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strengthening these strategies, the country may become a benchmark for sustainable and inclusive biogas expansion in the Global South (IEA, 2024).

7. FINAL CONSIDERATIONS

Biogas production from swine waste stands out as a promising strategy to promote environmental, energy, and economic sustainability in the agricultural sector—especially in Southern Brazil, where pig farming is highly concentrated. This technology enables the efficient use of organic waste, mitigating greenhouse gas emissions, such as methane (CH_4), and significantly reducing the environmental footprint of animal production.

In addition to environmental benefits, biogas offers significant economic advantages, such as the generation of electricity and heat for self-consumption or commercialization, the valorization of digestate as a biofertilizer, and the reduction of costs associated with agricultural inputs and conventional energy. This multifunctionality positions biogas as a major driver of rural energy transition, aligning with global decarbonization goals and the achievement of the Sustainable Development Goals (SDGs), especially SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

However, for biogas to move beyond being a sporadic alternative and become a consolidated, widely replicated solution on Brazilian farms, it is essential to overcome the technical, economic, and regulatory bottlenecks that still hinder its expansion. The adoption of effective public policies—ensuring easier access to rural credit, tax incentives, and streamlined licensing processes—is crucial. At the same time, technical training and continuous support programs must be expanded, especially in regions dominated by small and medium producers, promoting operational autonomy on farms.

Strengthening applied research—in collaboration with universities, cooperatives, and public institutions—is also strategic to develop more accessible technological solutions tailored to different production scales. Successful experiences with local production arrangements and cooperative systems demonstrate that it is possible to integrate biogas use into more sustainable and resilient production chains.

Therefore, with coordinated planning, investment, and institutional commitment, biogas has the potential to turn environmental challenges into economic opportunities, positioning Brazil as a global leader in renewable energy derived from agriculture. It is a concrete solution that unites innovation, sustainability, and territorial development.

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