Biogas Generation Potential from Swine Manure in the Microregion of Feira de Santana, Brazil

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This study assesses the potential for biogas generation from swine manure in the microregion of Feira de Santana, Bahia, Brazil, an area with significant pig farming activity. The improper disposal of swine manure poses significant environmental risks, including water and soil pollution and the emission of greenhouse gases. This research aims to quantify the energy potential of these residues by applying anaerobic digestion technology. The methodology involved collecting data on the swine population from official sources such as IBGE and ADAB for the year 2018. Theoretical models and stoichiometric equations were used to estimate the daily and annual production of manure, the potential for biogas generation, and its corresponding energy value. The results indicate a significant potential for biogas production, estimated at approximately 16,083 m3/day, with a methane (CH4) content of about 9,650 m3/day. This volume could be converted into approximately 36.67 MWh of electricity daily, assuming a 35% conversion efficiency. The conclusion highlights the technical feasibility and environmental benefits of implementing biodigesters in the region, transforming an environmental liability into a valuable renewable energy asset, contributing to the local energy matrix and promoting sustainable development. The most viable application identified is the use of biogas as a substitute for cooking gas (LPG), offering a rapid financial return for farmers.
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Climate change and the search for sustainable energy sources are central themes in the global scientific and political agenda. The high dependence on fossil fuels, which accounted for about 81% of the global energy matrix in 2019 [1], makes the current energy model unsustainable. In this context, renewable sources like biomass gain prominence. Brazil has significant potential for biomass-derived energy due to favorable climatic conditions and a strong agribusiness sector.

Among the various sources of biomass, livestock residues, especially from pig farming, stand out. Pig farming is a rapidly growing economic activity in Brazil, but it generates a large volume of waste with high polluting potential. These wastes can contaminate soil, water resources, and the atmosphere through the emission of gases such as methane (CH_4) and nitrous oxide (N_2O) [2]. Anaerobic digestion technology, using biodigesters, presents itself as a promising solution to treat this waste, transforming an environmental liability into two valuable products: biogas, a renewable fuel, and biofertilizer, a nutrientrich organic fertilizer.

This study aims to quantify the potential for biogas generation from swine manure in the microregion of Feira de Santana, Bahia, a region with a representative share of the state's pig production. The goal is to provide a quantitative basis to encourage the adoption of this technology, reducing environmental impacts and creating a new source of income for local farmers.

Materials and Methods

This study was conducted through an exploratory research approach, based on data collection and bibliographic review to estimate the biogas potential from confined swine herds in the microregion of Feira de Santana. The methodological framework was designed to provide a robust estimation of biogas generation, considering the specific characteristics of swine manure and the regional context.

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Data Collection and Characterization of the Study Area

The microregion of Feira de Santana, located in the state of Bahia, Brazil, was selected due to its significant pig farming activity. Data regarding the swine population in confinement for the year 2018 were meticulously collected from official and reputable sources, primarily the Brazilian Institute of Geography and Statistics (IBGE) and the State Agency for Agricultural Defense of Bahia (ADAB). These institutions are recognized for their comprehensive and reliable agricultural statistics, ensuring the accuracy of the baseline data. According to the collected data, the microregion of Feira de Santana housed a total of 74,147 confined pigs in 2018. This figure represents a substantial portion, specifically 6.65%, of the total swine herd in the state of Bahia, highlighting the region's importance in the state's pig farming sector and the potential environmental impact of its waste if not properly managed.

Estimation of Manure Production

The initial step in quantifying the biogas generation potential involved estimating the daily production of swine manure. This estimation is crucial as the volume and characteristics of the raw material directly influence the amount of biogas that can be produced. The daily production of swine manure (PDDS) was calculated using Equation 1, which considers the total number of animals and their specific manure production rate. This approach allows for a precise estimation tailored to the size of the swine herd in the study area.

Where:

$$\mathrm{PDDS} = \sum(\mathrm{N^o} \cdot \mathrm{PE}) \qquad (1)$$

PDDS is the daily production of swine manure, expressed in cubic meters of manure per day (m^3_manure/day).

N^o denotes the number of heads within a specific animal category (e.g., confined pigs).

PE signifies the specific manure production per head, measured in cubic meters of manure per head per day (m^3_manure/head/day). This value is typically derived from empirical studies and varies depending on factors such as animal age, diet, and housing conditions. For this study, average values from established literature were utilized to ensure consistency and comparability with similar research.

Methane Emission Factor and Biogas Production Estimation

To understand the environmental implications and the energy potential, the methane emission factor was considered. The methane emission factor (CH_4_emissions) was calculated based on the Intergovernmental Panel on Climate Change (IPCC) methodology from 2006 [3], which provides standardized guidelines for estimating greenhouse gas emissions from various sources, including livestock. Equation 2 illustrates this calculation:

$$\mathrm{CH_4\_emissions} = (\mathrm{M_i} \cdot 365 \cdot \mathrm{EF_i}) \cdot 10^{-3} \qquad (1)$$

Where:

M_i is the average daily mass of organic matter produced per pig, measured in kilograms (kg).

EF_i is the anaerobic emission factor, with a value of 1.5 kg CH_4/kg, as specified by IPCC (2006). This factor accounts for the amount of methane produced per unit of organic matter under anaerobic conditions.

Following the estimation of manure production and considering the methane emission factors, the daily biogas production (P_B) was estimated. This calculation is fundamental to determining the energy recovery potential from the swine manure. Equation 3, derived from established principles of anaerobic digestion, was employed for this purpose:

$$P\_B = B_0 \cdot \mathrm{SV} \cdot \mathrm{Q} \qquad (1)$$

Where:

P_B represents the daily biogas production, expressed in cubic meters per day (m^3/day).

B_0 is the maximum theoretical biogas production capacity, which, according to IPCC (2006), is 0.45 m^3/kg_SV. This value represents the maximum volume of biogas that can be generated per kilogram of volatile solids under ideal conditions.

SV denotes the volatile solids content, a critical parameter that indicates the biodegradable organic matter present in the manure. For this study, a value of 53.1 g_SV/L was adopted, also in accordance with IPCC (2006) guidelines. Volatile solids are the primary substrate for anaerobic digestion, and their concentration directly impacts biogas yield.

Q is the total volume of manure produced per day, expressed in cubic meters per day (m^3/day), as calculated in the previous step (Section II.B).

Energy Potential Calculation and Conversion Efficiency

Once the daily biogas production was estimated, the next crucial step was to determine its energy potential. This involved converting the volume of biogas into electrical energy, providing a tangible measure of its value as a renewable energy source. The conversion process considers the methane content within the biogas and the efficiency of the energy conversion system. It is widely accepted that the methane content in biogas typically ranges from 50% to 80%, with an average of approximately 60% for swine manure [4]. Methane is the primary combustible component of biogas, responsible for its energy content.

The energy conversion efficiency of a generator set, which transforms the chemical energy of biogas into electrical energy, was assumed to be 35%. This value is a realistic representation for typical small to medium-scale biogas-to-electricity systems. According to Oliveira (2009) [5], a commonly cited equivalence in the field, 1 m3 of biogas is equivalent to approximately 6.5 kWh. This conversion factor was used to translate the estimated biogas volume into its equivalent electrical energy output. The calculation for the daily electrical energy generation was performed using the following relationship:
Electrical Energy (kWh/day) = P_B (m^3/day) ×Energy Equivalence (kWh/m^3)×Conversion Efficiency (%).

This comprehensive methodological approach ensures that the estimations of biogas potential and energy generation are robust, relying on established scientific principles and data from credible sources. The detailed breakdown of each step allows for transparency and reproducibility of the results, contributing to the reliability of the study's findings.

Detailed Parameters and Justifications for Calculations

To ensure the robustness and accuracy of the biogas potential estimation, specific parameters and assumptions were adopted based on established scientific literature and guidelines from reputable organizations. These parameters are critical for the reliability of the calculations presented in this study.

Specific Manure Production (PE)

The value of 0.0091 m^3/head/day for specific manure production per pig was derived from a synthesis of various studies on swine waste management. This average accounts for different growth stages and feeding regimes commonly found in confined pig farming operations. It is important to note that actual manure production can vary based on factors such as animal weight, feed intake, water consumption, and housing system. However, for a regional-scale assessment, an average value provides a practical and sufficiently accurate basis for estimation. This value typically includes both solid and liquid fractions of the manure, which are relevant for anaerobic digestion processes.

Maximum Theoretical Biogas Production Capacity (B_0)

The IPCC (2006) [3] provides a default value of 0.45 m^3/kg_SV for the maximum theoretical biogas production capacity. This parameter represents the stoichiometric potential of volatile solids to be converted into biogas under ideal anaerobic conditions. It is a theoretical maximum, as real-world biodigesters may not achieve 100% conversion efficiency due to various operational factors such as temperature, pH, retention time, and the presence of inhibitory substances. Nevertheless, using this theoretical value allows for a consistent and comparable estimation across different studies and regions.

Volatile Solids Content (SV)

The volatile solids content of swine manure is a crucial indicator of its organic matter concentration and, consequently, its biogas potential. A value of 53.1 g_SV/L (or 53.1 kg_SV/m^3) was adopted, also in accordance with IPCC (2006) guidelines [3]. Volatile solids are the fraction of total solids that are combustible and represent the organic material available for microbial degradation during anaerobic digestion. Variations in diet, animal age, and manure handling practices can influence the SV content. However, the chosen value is representative of typical swine manure characteristics and provides a reliable basis for calculation.

Methane Content in Biogas

While biogas composition can vary, a methane (CH_4) content of approximately 60% was assumed for the energy potential calculations. This is a commonly observed concentration for biogas derived from swine manure, with ranges typically falling between 50% and 80% [4]. The higher the methane content, the greater the calorific value of the biogas. This assumption directly impacts the estimated electrical energy output, as methane is the primary energy-carrying component of biogas.

Energy Equivalence of Biogas

The conversion factor of 6.5 kWh per cubic meter of biogas is a widely accepted empirical value in the field of bioenergy [5]. This factor simplifies the translation of biogas volume into its equivalent electrical energy potential, facilitating comparisons with other energy sources. It is important to note that this equivalence assumes a certain calorific value for methane and a standard efficiency for its conversion into electricity.

Energy Conversion Efficiency of Generator Set

An efficiency of 35% for the generator set was used to calculate the final electrical energy output. This percentage reflects the typical efficiency of internal combustion engines used in small to medium-scale biogas power generation systems. Factors such as engine type, maintenance, and load can influence actual efficiency. However, 35% provides a reasonable and conservative estimate for planning purposes.

These detailed parameters and their justifications underpin the quantitative analysis presented in this study, ensuring that the estimations are grounded in scientific principles and reflect realistic conditions for biogas production from swine manure. The transparency in parameter selection allows for a clear understanding of the assumptions made and the potential for future refinements based on more specific local data or advanced research findings.

Results and Discussion

The comprehensive analysis of swine population data and the application of established methodological frameworks yielded significant insights into the biogas generation potential from swine manure in the microregion of Feira de Santana. This section presents the quantified results, discusses their implications, and provides comparative analyses to contextualize the findings within broader energy and environmental landscapes.

<u>Quantification of Swine Population and Manure Production</u>

Based on the most recent available data from ADAB (Agência Estadual de Defesa Agropecuária da Bahia) for the year 2018, the microregion of Feira de Santana is home to a substantial swine population, totaling 74,147 confined pigs. This figure underscores the regions´ prominence in the states´ pig farming industry and, consequently, the considerable volume of organic waste generated. To accurately estimate the daily manure production, an average manure production rate of 0.0091 m^3/head/day was adopted from existing literature and empirical studies, as referenced in Table 7 of the original TCC [7]. This value represents a conservative yet realistic estimate for confined swine operations.

Applying this specific production rate to the total swine population, the total daily manure production (Q) for the microregion of Feira de Santana was calculated as follows: $Q = 74{,}147$ heads $\times 0.0091 m^3/$head/day $\approx 674.7 m^3/$day.

This daily volume of approximately 674.7 cubic meters of swine manure represents a significant environmental challenge if not properly managed. However, it also signifies a substantial untapped resource for renewable energy generation. The consistent and large-scale availability of this feedstock is a critical factor in the economic viability and sustainability of biogas production facilities.

Biogas and Methane Generation Potential

With the daily manure production quantified, the next step involved estimating the potential for biogas generation. Utilizing Equation 3 from the methodology section, which incorporates the maximum theoretical biogas production capacity (B0 = 0.45 m^3/kg_SV) and the volatile solids content (SV = 53.1 kg_SV/m^3), the daily biogas production (P_B) was calculated: P_B = 0.45 m^3/kg_SV × 53.1kg_SV/m^3 × 674.7m3/day ≈ 16, 083.49m^3/day.

This calculation reveals a remarkable potential for biogas production, exceeding 16,000 cubic meters per day. Biogas is a mixture of gases, primarily methane (CH_4) and carbon dioxide (CO_2), along with trace amounts of other gases. The methane content is the most critical component for energy utilization due to its high calorific value. For swine manure biogas, the methane concentration typically ranges from 50% to 80%, with a conservative average of 60% methane content assumed, which is consistent with typical values observed in anaerobic digestion of swine waste [4].

Based on this assumption, the daily methane production (P_M) was estimated: P_M = 16,083.49 m^3/day ×0.60 ≈ 9, 650.09m^3/day.

The production of nearly 9,650 cubic meters of methane per day is particularly significant. Methane is a potent greenhouse gas, approximately 25 times more effective at trapping heat in the atmosphere than carbon dioxide over a 100-year period [3]. Capturing and utilizing this methane through anaerobic digestion not only provides a renewable energy source but also substantially mitigates greenhouse gas emissions that would otherwise be released into the atmosphere from the decomposition of raw manure. This dual benefit underscores the environmental imperative and economic opportunity presented by biogas technology.

There is typical composition of biogas, highlighting the variability in methane content. The values used in this study (60% CH_4) fall well within the expected range, reinforcing the reliability of the energy potential estimations.

Energy Potential and Economic Comparison

The conversion of the generated biogas into usable energy, particularly electrical energy, represents the ultimate goal of this assessment. Considering the established equivalence of 6.5 kWh per cubic meter of biogas [5] and assuming a realistic energy conversion efficiency of 35% for a typical generator set, the daily electrical energy generation potential was calculated: Energy = 16,083.49 m^3/day ×6.5kWh/m^3 × 0.35 ≈ 36, 667MWh/day.

This figure, approximately 36.67 MWh per day, signifies a substantial contribution to the local energy matrix. To put this into perspective, the TCC highlights that this daily generation corresponds to approximately 2.5% of the installed capacity of the Sobradinho Hydroelectric Plant in Bahia [6]. While this percentage might seem small in the context of a large hydroelectric plant, it is crucial to recognize that biogas offers a decentralized, distributed energy source, which can enhance energy security and reduce transmission losses.

Furthermore, it represents a consistent, baseload power source, unlike intermittent renewable sources such as solar or wind, making it a valuable addition to the energy mix.

Beyond electricity generation, the energy content of the biogas can be compared to conventional fossil fuels to better appreciate its value. The TCC provides a compelling comparison: the daily biogas production is equivalent to approximately 3,537 liters of gasoline. This volume of gasoline is sufficient to fuel about 70 Hyundai HB20 cars daily, assuming average fuel consumption. This analogy vividly illustrates the high energy value contained within the swine manure, transforming what is often considered a waste product into a valuable energy commodity. Such comparisons are vital for policymakers and farmers to grasp the economic incentives associated with adopting biogas technology.

Environmental and Socio-Economic Implications

The findings of this study extend beyond mere energy quantification, touching upon significant environmental and socio-economic implications. From an environmental perspective, the anaerobic digestion of swine manure offers a robust solution to several pressing issues. It significantly reduces the emission of methane and nitrous oxide, both potent greenhouse gases, thereby contributing to climate change mitigation efforts. Furthermore, the process effectively treats the manure, reducing its biochemical oxygen demand (BOD) and chemical oxygen demand (COD), which are key indicators of water pollution potential. The resulting digestate, or biofertilizer, is a nutrient-rich effluent that can replace synthetic fertilizers, reducing chemical runoff and improving soil health. This closed-loop system embodies the principles of a circular economy, transforming waste into valuable resources.

Socio-economically, the adoption of biodigester technology can bring substantial benefits to the rural communities in the Feira de Santana microregion. For individual farmers, it offers energy independence, reducing reliance on expensive and volatile fossil fuels like LPG for cooking and potentially electricity from the grid. This can lead to significant cost savings and improved household budgets. Moreover, the production of biofertilizer can enhance agricultural productivity and reduce input costs, further boosting farmersíncomes. At a broader regional level, the development of a biogas industry can create new employment opportunities in the construction, operation, and maintenance of biodigesters, as well as in the distribution of biogas and biofertilizer. This contributes to local economic development and diversification.

However, it is important to acknowledge the challenges associated with the widespread adoption of this technology. The initial capital investment for biodigester construction can be substantial, particularly for small-scale farmers. This highlights the need for supportive government policies, financial incentives, and accessible credit lines to facilitate adoption. Additionally, technical knowledge and training are required for the proper operation and maintenance of biodigester systems. Despite these challenges, the overwhelming environmental and economic benefits strongly advocate for the promotion and implementation of biogas technology in regions with high concentrations of livestock farming.

In summary, the results demonstrate that swine manure in the Feira de Santana microregion is not merely a waste product but a valuable resource capable of generating significant amounts of renewable energy. The detailed quantification of biogas and methane potential, coupled with the energy conversion analysis, provides a compelling case for investing in anaerobic digestion technology. The environmental benefits of greenhouse gas reduction and pollution control, combined with the socio-economic advantages of energy independence and income generation, position biogas as a key component of a sustainable future for the region.

Conclusion

The comprehensive study on the potential for biogas generation from swine manure in the microregion of Feira de Santana, Bahia, unequivocally demonstrates the significant technical and environmental viability of this renewable energy source. The meticulous quantification of manure production and subsequent estimation of biogas yield reveal a substantial untapped resource. Specifically, the estimated daily production of 16,083 m3 of biogas, with a high methane content, underscores its capacity to contribute meaningfully to the local energy matrix.

The conversion of this biogas into electrical energy, with a potential generation of approximately 36.67 MWh daily, highlights its transformative power. This not only addresses the pressing issue of waste management in pig farming but also offers a sustainable alternative to conventional energy sources. The environmental benefits are manifold, including the reduction of greenhouse gas emissions, mitigation of water and soil pollution, and the production of nutrient-rich biofertilizer, which promotes sustainable agricultural practices

While the prospect of converting biogas to electricity is highly attractive from an energy security and environmental standpoint, it often entails considerable initial capital investment, which can be a barrier for small and medium-sized producers. Therefore, the study identifies the direct use of biogas as a substitute for liquefied petroleum gas (LPG) for cooking as the most immediate and economically viable solution for these farmers. This application offers a quicker financial return, enhances energy autonomy for rural families, and significantly reduces their operational costs.

To fully realize this potential, it is imperative that robust public policies and accessible credit lines are established and promoted. These measures would incentivize the adoption and implementation of biodigester technology across the region. Such initiatives would not only mitigate the adverse environmental impacts associated with intensive pig farming but also foster a circular economy model. This model transforms agricultural waste into valuable resources, generates new income streams for farmers, and contributes to the diversification and long-term sustainability of the regional energy matrix. The findings of this research provide a strong foundation for advocating for the widespread adoption of biogas technology, paving the way for a more sustainable and energy-independent future for the microregion of Feira de Santana.

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