BIOSCIENCE JOURNAL

SWINE MEAT PRODUCTION INTEGRATED WITH ENERGY COGENERATION: CHALLENGES AND OPPORTUNITIES IN USING ANAEROBIC BIODIGESTION

Sibele Augusta F. LEITE[1], Nicole Silva GOMES[1], Lucas Alves B. DOS SANTOS[1], Ana Teresa P. DELL'ISOLA[2], Brenno Santos LEITE[1]

[1] Institute of Science and Technology, Universidade Federal de Viçosa, Viçosa, Minas Gerais, Brazil.
[2] Institute of Agricultural Sciences, Universidade Federal de Viçosa, Viçosa, Minas Gerais, Brazil.

Corresponding author:
Brenno Santos Leite
brennoleite@ufv.br

How to cite: LEITE, S.A.F., et al. Swine meat production integrated with energy cogeneration: challenges and opportunities in using anaerobic biodigestion. *Bioscience Journal*. 2023, **39**, e39087. https://doi.org/10.14393/BJ-v39n0a2023-66926

Abstract
As environmental concerns and regulatory requirements increase over time, new alternatives for swine manure disposal emerge. Among them, anaerobic biodigestion is a relevant technology because it reduces the organic load of wastewater before its final disposal and provides economic benefits to farmers with biogas and biofertilizer production. Efficiently managing the anaerobic biodigestion process remains a challenge in developing countries, mainly due to the lack of information from swine meat producers to deal with the complexity of this system. A risk analysis can represent a promising tool for farm assistance because it provides a process overview. Hence, this study reports the results of a process mapping in a swine meat production farm in Minas Gerais, Brazil. This mapping was performed while monitoring biodigestion operational parameters and allowed the identification of the primary causes of process failures and potential environmental impacts. The results showed that anaerobic digestion promotes a relevant environmental gain. However, the need for improved process monitoring, investments in environmental assessment equipment, and technical training for producers also stood out as an improvement opportunity.

Keywords: Process mapping**.** Process monitoring. Risk analysis.

1. Introduction

Swine is one of the most produced and consumed meats worldwide. In 2018, 113 million tons were produced, breaking the world record for production (Martins and Talamini 2020). China is the largest swine meat producer, accounting for 43% of the global production in 2021, followed by the European Union, the United States, and Brazil, in that order (Miele and Martins 2021).

According to the Brazilian Association of Swine Breeders, this farming activity is one of the most significant for the country's economy, generating employment, income, and foreign exchange for the commercial balance of agribusiness (Associação Brasileira de Suinocultura – ABCS 2016). Given production percentages, swine meat production generates 32 Mt of waste annually (Forster-Carneiro et al. 2013; Empresa de Pesquisa Energética – EPE 2014). Most of this farm waste is swine manure that requires treatment to prevent pollution. Composting, stabilization ponds, and anaerobic biodigestion are some possibilities (Souza et al. 2009). However, anaerobic biodigestion is particularly interesting because it reduces the polluting load of wastewater and generates bioenergy and a higher biogas contribution to the energy matrix (Sousa et al. 2020).

Despite the benefits of treating swine manure, it is worth noting that anaerobic biodigestion requires managing activities performed before waste production, such as nutritional and sanitary input control and rational water use on the farm (Brasil 2016). Likewise, the activities conducted after waste generation also demand correct management. Among the criteria for managing the anaerobic biodigestion process is knowing the operating parameters, such as process temperature and hydraulic retention time, and monitoring the organic load, the pH of the reaction medium, and biogas production (Lins et al. 2020).

Applying this management type remains a challenge in anaerobic biodigestion plants in countries such as Brazil due to the lack of human resources training, the inability to provide technical assistance to producers, or the absence of adequate information for this audience (Freitas et al. 2019; Sousa et al. 2020). In many developing countries, these challenges appear when choosing domestic biodigesters instead of medium and large plants because they are easier to operate and maintain (Jafar and Awad, 2021).

Conversely, European Union countries present a well-developed biogas industry to favor a closed organic waste cycle and prevent nutrient leaching. Their biodigesters monitor mixing and temperature constantly, and management quality steps control the process (Horváth et al. 2016). Environmental, economic, and social benefits, such as the reduction of gas emissions, odor, pathogens, and the availability of sustainable fuel, drive the consolidation of biogas production in the European Union. This scenario exists mainly in countries such as Germany, Denmark, France, and Italy, which show a higher presence of agricultural activities and, consequently, the need for managing their impacts (Horváth et al. 2016). Developing countries must trace this path, which remains a challenge.

One way to improve anaerobic biodigestion plants is by using management tools, such as process risk analysis, associated with the causes and environmental impacts. The management and decision-making of companies are often guided by the environmental framework and strategies to minimize risks or because of envisioned opportunities (Elijido-Ten 2017). Hence, this study presents a process mapping performed on a swine meat farm in Minas Gerais, Brazil. The objective was to investigate the main risks associated with the process and the respective causes, environmental impacts, and operational solutions required for the performance improvement of the treatment plant. Therefore, this research was divided into three main steps. First, the case study described the swine farm, its processes, and operation units. Then, the data collection methodology from anaerobic biodigestion was presented to explore the risk analysis.

2. Material and Methods

Case study

The study was performed in the Pedrosa Swine Farm in Itaúna, Minas Gerais, Brazil (20°06’05”S; 44°40’02”W). The property occupies an area of 126.7 hectares (Figure 1) divided according to the following purposes: corn planting, swine feed storage, mechanical and manual machinery storage, animal confinement sheds, administrative offices, restrooms, employee accommodation housing, and wastewater treatment plant.

The swine production system of the farm includes all animal rearing stages, covering around 700 production sows, 570 gestating pigs, 150 in the maternity, 400 in the nursery, and 5,000 in the finishing process.

The Pedrosa Swine Farm has one wastewater treatment unit that provides electrical energy self-sufficiency. The wastewater treatment plant consists of two covered lagoon digesters with 35 x 13 x 4 meters (height x width x depth) and two ponds (settling and stabilization).

The biodigesters are batch-fed daily. Wastewater goes through a pre-filter (grid filter wastewater) to remove the coarser solids (these residues are used for biofertilizer production). Then, wastewater homogenization occurs in a feed tank that directs it at equal flow rates to both biodigesters. After the anaerobic treatment, the effluent feeds two ponds (sedimentation and stabilization) to finish the process.

The biodigester sludge is collected seasonally to convert into a biofertilizer for the corn crop. The cultivated corn becomes swine feed according to the nutritional requirements of each growth stage. Electricity is produced by a cogeneration system with two MWM engines and 280 horsepower (HP). This system supplies the entire electrical energy to operate the farm. Occasionally, the surplus biogas is burnt in a flare. Figure 2 shows the schematic flowchart of the wastewater treatment plant and biogas and biofertilizer production.

Figure 1. Identification of the main areas of the Pedrosa Swine Farm.

The Pedrosa Swine Farm differs from other regional swine meet producers, as it cannot receive electricity from the local concessionaire (electrical power generation company of Minas Gerais - CEMIG) due to geographic reasons. Hence, all energy consumed in the process comes from wastewater treatment (anaerobic biodigestion). Thus, the treatment is the "focus of attention" on the farm and requires special care for normal operating conditions. In this context, the following actions have been implemented on the farm to preserve and prevent harmful changes in the biodigester microbiota:

i) Sanitizing enclosed swine production facilities with the least possible concentration of chemical products;

ii) Controlling and optimizing the pigs' antibiotic dosage, as high concentrations could inhibit the anaerobic process;

iii) Applying rigorous sanitization and access control to confinement shed areas in enclosed swine production facilities to prevent animal contamination;

iv) Implementing an appropriate solid waste management program, including composting organic waste and separating inorganic material.

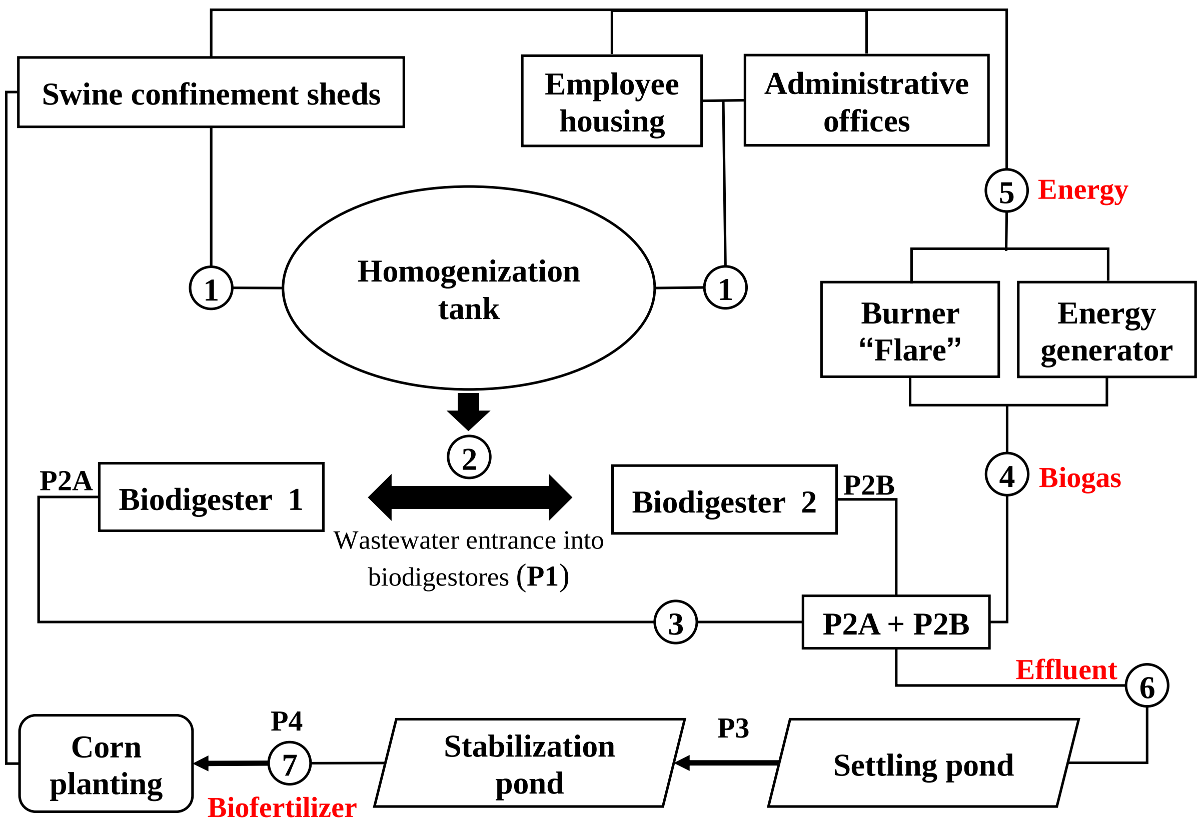

Figure 2. Flowchart of the Pedrosa Swine Farm focused on the main production areas.

Good practices in the swine production chain, added to automation and technology investments, raised the Pedrosa Swine Farm to a prominent position in the Brazilian state of Minas Gerais. The farm has excellent production numbers, including low animal loss and raw material waste, consequently improving environmental performance.

Obtaining process data

Treated wastewater flow and hydraulic retention time (HRT)

The Pedrosa Swine Farm does not have a flow measuring system for untreated wastewater. Therefore, the wastewater flow rate was initially estimated, given the consumed water of around 100,000 liters/day. Measurements were taken for seven days to verify this parameter, considering the filling time of the homogenization tank (Hibbeler 2016).

HRT was calculated from the usable volume of the biodigester (around 80% of the total) and the daily wastewater flow. This value represents the average time wastewater remains inside the biodigester. HRT, in days, was calculated with the ratio between the biodigester volume (m^3) and wastewater flow ($m^3.d^{-1}$) (Kunz et al. 2019).

Sampling plan (wastewater)

The data was collected between September 20, 2019, and February 26, 2020. Sampling occurred in four stages (Figure 1): P1 (wastewater inflow into biodigesters A and B), P2 (effluent outflow in biodigesters A and B), P2-A (effluent outflow in biodigester A), and P2-B (effluent outflow in biodigester B). Then, the laboratory samples were preserved following Standard Methods for Examination of Water and Wastewater (American Public Health Association – APHA et al. 2017) until the physicochemical analysis. The parameters were analyzed as described hereafter.

Effluent nutritional status assessment

The growth and activity of these anaerobic microorganisms should include balanced essential nutrients to facilitate biodigester performance and biogas generation (Gueri et al. 2018). Carbon (C) was quantified to evaluate nutritional status, represented by chemical oxygen demand (COD), nitrogen (N), and total phosphorus content (P).

The COD quantification method was based on the sample's organic matter oxidation through digestion with a potassium dichromate solution and subsequent absorbance reading in a UV-visible spectrophotometer at 600 nm. Nitrogen was quantified with the Total Kjeldahl Nitrogen method, which consists of sample digestion with a catalyst and concentrated sulphuric acid at 370°C. Digestion precedes sample distillation to collect ammonium hydroxide absorbed in a boric acid solution. Nitrogen content is then determined by titration with a standardized acid solution. Total phosphorous was defined with colorimetry, following the molybdenum blue method. Samples were first digested using perchloric acid, and the molybdophosphoric acid was reduced with ascorbic acid. The resulting blue color complex was analyzed with absorbance reading in a UV-visible spectrophotometer at 725 nm. Analyses were performed in triplicate and following the methodological procedures of Standard Methods for Examination of Water and Sewage (APHA et al. 2017)

Monitoring anaerobic biodigestion performance

Anaerobic digestion requires monitoring and controlling physicochemical parameters related to the process. Among them are the intermediate alkalinity/partial alkalinity (IA/PA), COD, volatile solids (VS), pH, and temperature (°C). The IA/PA ratio correlates volatile organic acids and alkalinity accumulation in the biodigesters. This proportion was determined by the volumetric method, in which the previously decanted samples were titrated with a sulfuric acid solution (H_2SO_4) until reaching two fixed pre-pH values (5.0 and 4.4) (Kunz et al. 2019). The methodological procedure for determining COD was mentioned in the previous subtopic. Volatile Solids (VS) concentration was obtained by quantifying the evaporated matter after sample heating in an oven at 550°C until constant mass. The pH and temperature were quantified using a portable pH meter and a measuring probe, respectively, and these parameters helped to interpret other data (APHA et al. 2017).

Biogas production: hydraulic flow and methane concentration

Biogas production was estimated in two models. The first model considered biogas production per animal in the finishing phase (0.24 m^3 of biogas per day for each animal weighing about 90 kg) (Leite et al. 2018), which included around 5,000 animals. The second model used an empirical correlation between the amount of degraded organic matter (determined by COD) and biogas production (Leite et al. 2019). For the empirical model, biogas production was calculated considering process parameters, such as temperature, wastewater flow, treatment efficiency, and methane concentration in the biogas (Chernicharo 2007). Methane concentration was determined using the portable kit presented by Kunz and Sulzbach (2007) and developed by Alfakit (Kunz and Sulzbach 2007).

Risk analysis

The risks and opportunities of anaerobic biodigestion in the Pedrosa Swine Farm were identified according to ISO 14001:2015 guidelines and information collected during the case study. The process mapping methodology was selected to identify the information required for improving the environmental management of anaerobic biodigestion (Tejaswi and Christopher 2017). Disturbances and failures in the process represented risks, and potential environmental impacts and improvement opportunities were identified (Nolan 2015).

3. Results

Wastewater flow and hydraulic retention time (HRT)

The amount of generated wastewater varied considerably on weekdays because of the sanitization routine of sheds, which occurred daily, except on weekends. Wastewater production measured during the study ranged between 23 m^3/day (weekends) to 87 m^3/day (Mondays), and wastewater flow was around 58 m^3/day on the other days. The amount of wastewater expected for this type of pig rearing is about 47 L/animal per day (Brasil 2016). The average daily wastewater production in the Pedrosa Swine Farm (58 $m^3 \times d^{-1}$) represents a generation of less than 10 L/animal per day. This value is also consistent with the water consumed on the farm (100 m^3 x d^{-1}), equivalent to less than 15 L/animal per day. Wastewater generation is intrinsically linked to water consumption. The described result indicates that water management prevented ordinary problems, such as leaks in the hydraulic system, inadequate location and misuse of drinking fountains, rainwater entering waste gutters, and water wasted from cleaning the sheds, among others (Barros et al. 2019).

HRT was calculated using the average of measured flow values. According to the dimensions of biodigesters, the total volume was 1,820 m^3 each, and the estimated useful volume was 1,456 m^3. Wastewater flow was divided equally between the two biodigesters, and the calculated HRT was 50 days.

Nutritional assessment results (wastewater COD/N/P ratio)

Table 1 shows COD, N, and P values used to assess the nutrient availability required for the process. The presented values refer to the biodigester's inlet (P1) and outlet (P2) points. On February 26, samples were collected at the exit points of each biodigester (P2A and P2B) for a more accurate assessment.

Table 1. Parameters analyzed for the nutritional assessment. Values presented represent the average of the results of the performed analysis.

Collect point	Date	COD (g/L)	N (g/L)	P (g/L)	VS (g/L)	Ratio COD:N:P
P1	20/09/2019	50.8	2.9	0.66	25.3	77:4:1
	13/02/2020	54.0	2.3	-	28.3	-
	26/02/2020	30.3	2.1	0.64	23.1	47:3:1
P2	20/09/2020	17.3	2.6	0.43	8.7	40:6:1
	13/02/2020	9.6	2.4	-	6.9	-
P2A	26/02/2020	8.8	1.9	0.41	8.4	21:5:1
P2B	26/02/2020	5.4	2.1	0.42	10.2	13:5:1

All samples demonstrated that wastewater from the swine farm is rich in nitrogen and phosphorus, with a high carbon content deficiency. The organic matter ratio should follow the COD/N/P ratio of 1000:5:1 for an adequate anaerobic biodigestion process. This estimate is based on the microorganism cell composition required for anaerobic biodigestion (Chernicharo 2007). Usually, microorganisms develop well with a carbon/nitrogen (C/N) ratio between 20 and 30, ranging from 10 to 45 in hydrolysis and tolerable acidogenesis (Kunz et al. 2019).

Results of process performance monitoring

Physicochemical parameters were monitored for five days to evaluate biodigestion performance. Figure 3 presents the results of the pH, IA/PA, and temperature in the inlet (P1) and outlet (P2, P2A, and P2A) points of wastewater/effluent. Volatile solids and COD content values were also monitored and presented in Table 1.

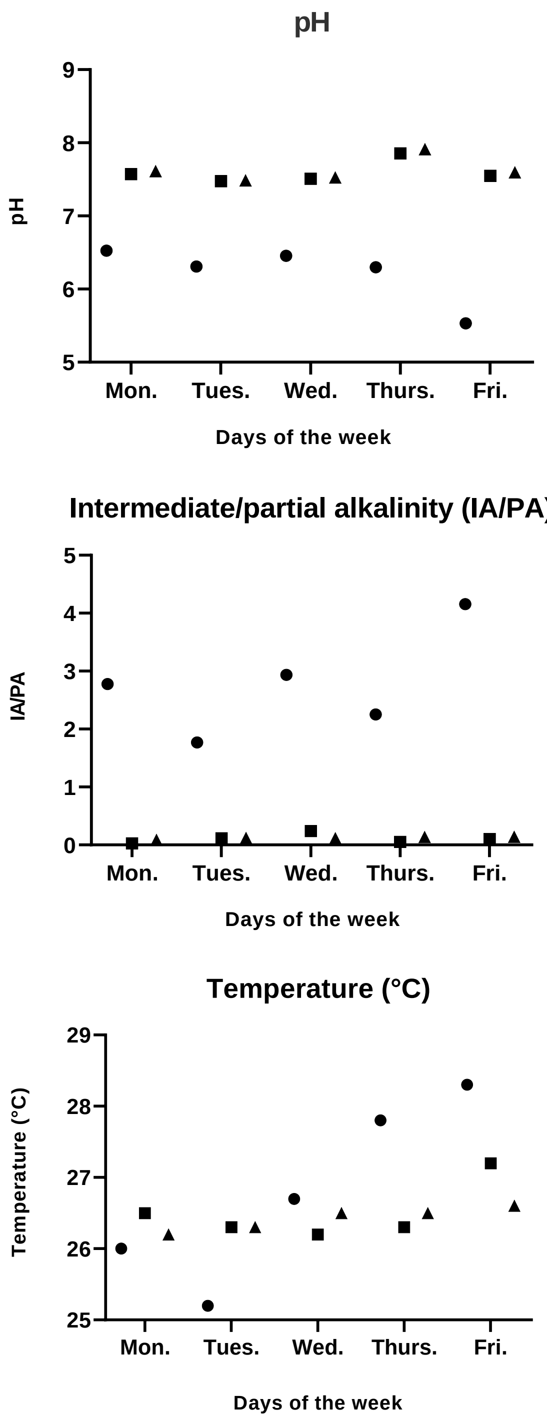

Figure 3. Parameters analyzed for process monitoring (P1 – Wastewater inlet point into biodigesters (•); P2A – Effluent outlet point from biodigester A (■); P2B – Effluent outlet point from biodigester B (▲)).

According to the data, the lowest wastewater pH (in P1) was 5.53, and the highest was 6.52. The pH must be within the recommended values for microorganisms to develop their activities. Chernicharo

(2007) states that the pH should be between 6 and 8, with an optimal range between 7 and 7.2. Kunz et al. (2019) report an optimal variation of 5.2 to 6.3 in the hydrolysis and acidogenesis phases and 6.7 to 7.5 in methanogenesis. The input pH in P1 was lower than the recommended for methanogenesis. However, there was an increase to 7.5 due to by-product decomposition and release during biodigestion, preventing the acidification of the biodigesters.

Similarly to pH, temperature directly affects biological activity in a biodigester, as some microorganisms are sensitive to heat build-up. The optimal temperature range suggested for the action of microorganisms responsible for the hydrolysis and acidogenesis phases is between 25 and 35°C, while those in charge of methanogenesis should present 32 to 42°C (Kunz et al. 2019). Wastewater temperature (in P1) varied from 25.2 to 28.3°C and stabilized along the process (26.2 to 27.2°C). These values are below the ideal range (30 to 35°C) for a mesophilic anaerobic biodigestion process (Chernicharo 2007).

In this study, IA/PA was monitored at the beginning and end of the process to assess the capacity to prevent problems from organic matter overloading, such as acidification and process failure. The biodigester is overloaded when IA/PA >0.4, presents an optimal range between 0.3 to 0.4, and is underloaded at <0.3 (Drosg 2013; Kunz et al. 2019). The IA/PA at the biodigester inlet point (P1) varied from 1.77 to 4.15. At the end of wastewater treatment, the IA/PA from the effluent in P2A and P2B were below 0.3, characterizing them as underloaded and indicating process stability.

After going through the biodigesters, the organic load represented by COD and VS decreased by around 80%, a suitable value for anaerobic biodigestion (López-Pacheco et al. 2021). However, this reduction was even higher after passing through the stabilization ponds. The anaerobic biodigestion system (biodigester + ponds) presented COD = 30,300 mg/L and 2,100 mg/L in input and output, respectively, meaning a 93% reduction. After the biodigesters (P2, P2-A, and P2-B), the organic matter of the effluent significantly decreased, agreeing with the quality parameters required by Brazilian law (Brasil 2011) and making the process independent of the ponds.

Biogas flow estimation and methane concentration analysis

The 5,000 animals representing the finishing unit allowed a biogas production estimation of 1,200 m^3/day. Biogas production was also calculated from COD input and output data from the biodigester and average wastewater flow to increase the reliability of this estimate. This estimation used the following parameters: a COD input of 50 g x L^{-1}, wastewater flow of 58 m^3 x d^{-1}, process temperature of 27°C, atmospheric pressure of 1 atm, gas constant of 0.082, K (COD corresponding to 1 mol of CH_4) of 64 g COD/mol, and a COD output equivalent to 10 g/L (compatible with the verified efficiency). The methane flow was estimated at 890 m^3/day following the process data. Then, biogas was estimated using methane production values and biogas composition analysis. The methane content in the biogas was 60% v/v. The hydrogen sulfide and ammonium gas contents were 0.05 and 0.003% v/v, respectively. Considering methane content, biogas production was estimated at 1,424 m^3/day. Both biogas estimations presented similar values, demonstrating consistency between the models.

The Pedrosa Swine Farm informed that the biogas consumption to produce energy through motor generators is around 1,360 m^3/day. Process measurements and the performed estimates did not show significant excess biogas production. Disturbances in the process can also impact biogas production and, consequently, energy generation.

Risk analysis results

The analysis of the results from HRT performed, of the wastewater nutrient availability, and the process performance monitoring allowed the identifications of risks and their respective causes, potential environmental impacts and, improvement opportunities, presented in Table 2.

4. Discussion

According to Cherubini et al. (2015), the type of manure management system contributes differently to environmental impacts. Using biodigesters for energy proposes seems the best option for a Brazilian swine meat production system. The same study also considers wastewater treatment positive because of the agronomic value of the effluent that presents a higher mineralized nitrogen content (Cherubini et al.2015).

Table2. Risk analysis of the anaerobic biodigestion process at the Pedrosa Swine Farm.

Process risks	Causes	Potential environmental impacts	Improvement opportunities
Failure of the anaerobic biodigestion process because of acidification	Biodigester fed with low-pH wastewater	Direct impact: Water/soil pollution because of the high organic load of the effluent	Process monitoring: pH and IA/PA
Failure of the anaerobic biodigestion process because of the high content of ammonium species	Wastewater with a low C/N ratio	Water eutrophication because of the high content of nitrogen and phosphorous species in the effluent	Process monitoring: pH, IA/PA Wastewater monitoring: carbon content (VS or COD) and nitrogen content
Inadequate wastewater treatment performance and non-compliance with effluent release standards	Inadequate HRT use or volume occupation of biodigesters	Indirect Impacts: Higher energy demand due to lower fertilizer and biogas production	Process monitoring: wastewater flow and organic load (VS/wastewater flow)
Disturbances or failures in the energy generation process	Low biogas production or quality (low methane content)	Direct Impacts: Climate change due to higher CO_2-equivalent emissions Terrestrial acidification because of higher hydrogen sulfide production Higher energy demand due to lower electricity production	Monitoring of biogas flow and quality (methane content)

However, these advantages can be compromised due to the lack of knowledge about the process and the substrate and the monitoring of essential process variables. Among the main identified risks to the process is anaerobic biodigestion failure, which may occur from acidification or the high content of toxic species, high freshwater demand, energy generation disturbances or failures, and hydraulic retention time (HRT) interferences.

Low biogas production or quality may directly cause energy generation failures. However, the root of such a risk is the process disturbance inside biodigesters, as described below.

The low C/N ratio found may inhibit the process, as it favors the formation of ammonia species (a toxic compound to microorganisms) and volatile organic acids that may compromise the ideal pH range of the medium (Neshat et al. 2017).

Nitrogen and phosphorus levels were high in the final effluent due to the low carbon concentration in swine manure, even after wastewater treatment. There is a possibility of eutrophication of water bodies if dumped directly into the water.

Finally, the lack of knowledge of wastewater flow values and the organic load is directly related to inadequate HRT use, which could be under- or over-dimensioned and potentially compromise organic matter methanization and biodegradation. Proper HRT will help improve process efficiency and prevent a volatile acid build-up in the biodigester (Mao et al. 2015). The death of microorganisms due to nutrient shortage is expected in long HRTs. Conversely, short HRTs may cause cell intoxication because of organic overload (Neshat et al. 2017). In this sense, the HRT practiced in the Pedrosa Swine Farm may be investigated to determine organic load, flow, and correct operation of biodigesters.

The main environmental impacts identified and associated with the risks of the process were potential water pollution, eutrophication, or even climate change and atmospheric pollution. Improvement opportunities were related to process monitoring of main parameters and practices to reduce water consumption. However, more daring strategies, such as using co-digestion of swine effluents with lignocellulosic residues or microalgae production or even fertilizers using this effluent, could represent options to minimize the environmental impacts of this activity (Gonçalves et al. 2017; Neshat et al. 2017; López-Pacheco et al. 2021).

The performed risk analysis is relevant to various swine meat producers, especially in South America. The covered lagoon model is extensively used in Brazil, Bolivia, and Argentina, mainly for agroindustry wastewater treatment (Neres et al. 2021; Porto et al. 2021). The scope of this biodigester also presents a low technological level and few configuration variations (Kunz et al. 2019). The swine farm wastewater used in this biodigester is mainly composed of pig excreta and water for cleaning swine confinement sheds. Its composition is based on a typical concentration range of organic carbon, nitrogen, and phosphorus compounds (Souza et al. 2009; Nagarajan et al. 2019). The presented scenario demonstrates that the risk analysis performed at the Pedrosa Swine Farm described in this study may contribute to the environmental management of other farms with a similar layout. It is important to emphasizes that given the Brazilian legislation requirements, the final effluent quality results show that anaerobic biodigestion is efficient and complies with the conditions and standards for effluent discharge (Brasil 2011).

5. Conclusions

Risk analysis is a promising management tool to improve environmental performance in swine farms that use the covered lagoon model for anaerobic biodigestion. Although the Pedrosa Swine Farm has a robust wastewater treatment system that allows biogas and biofertilizer use, the lack of continuous monitoring and flow measurement equipment generates risks to the process, potentially causing environmental and economic impacts. The risk analysis revealed opportunities for process improvement and instructed producers to invest in equipment for environmental assessment and operational procedures. The results are generalized to the farms with this production layout, commonly found in Brazil and South America.

Authors' Contributions: LEITE, S.A.F.: conception and design, analysis, interpretation of data and drafting the article; DOS SANTOS, L.A.B.: acquisition of data and analysis and interpretation of data and drafting the article; GOMES, N.S.: acquisition of data and analysis, interpretation of data and drafting the article; DELL'ISOLA, A.T.P.: analysis and interpretation of data and drafting the article; LEITE, B.S.: conception and design, analysis and interpretation of data, and drafting the article. All authors have read and approved the final version of the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

Ethics Approval: Not applicable.

Acknowledgments: The authors would like to thank the Pedrosa Swine Farm (Granja Pedrosa), the Minas Gerais Research Foundation – FAPEMIG (Process Number: APQ-01037-22) (Minas Gerais, Brazil), and the University of Viçosa (Federal University of Viçosa, Campus Florestal).

References

AMERICAN PUBLIC HEALTH ASSOCIATION – APHA. American Water Works Association - AWWA, Water Environment Federation - WEF. Standard Methods for the Examination of Water and Wastewater. 23rd. ed. [s.l.], 2017.

ASSOCIAÇÃO BRASILEIRA DE SUINOCULTURA - ABCS. Mapeamento da Suinocultura Brasileira. 2016.

BARROS, E.C., et al. Potencial agronômico dos dejetos suínos. 1st ed. Concórdia: Embrapa Suínos e Aves, 2019. Available from https://ainfo.cnptia.embrapa.br/digital/bitstream/item/207427/1/final9052.pdf

BRASIL. Resolução Conama No 430 de 13 de maio de 2011. Brasília, 2011.

BRASIL. Suinocultura de baixa emissão de carbono: Tecnologias de produção mais limpa e aproveitamento econômico dos resíduos da produção de suínos. Brasília: Ministério da Agricultura, Pecuária e Abastecimento, 2016. Available from https://repositorio.iica.int/handle/11324/3106

CHERNICHARO, C.A.L. Anaerobic Reactors. London: IWA Publishing, 2007. Available from: https://doi.org/10.2166/9781780402116

CHERUBINI, E., et al. Life cycle assessment of swine production in Brazil: a comparison of four manure management systems. *Journal of Cleaner Production*. 2015, **87**, 68-77. https://doi.org/10.1016/j.jclepro.2014.10.035

DROSG, B. Process monitoring in biogas plants. 1st ed. [s.l.]: IEA Bioenergy, 2013. Available from: https://www.ieabioenergy.com/wp-content/uploads/2013/12/Technical-Brochure-process_montoring.pdf

ELIJIDO-TEN, E. O. Does recognition of climate change related risks and opportunities determine sustainability performance? *Journal of Cleaner Production*. 2017, **141**, 956-966. Available from: https://doi.org/10.1016/j.jclepro.2016.09.136

EMPRESA DE PESQUISA ENERGÉTICA (EPE). Nota técnica DEA 15/14: Inventário Energético de Resíduos Rurais. Rio de Janeiro: 2014.

FORSTER-CARNEIRO, T., et al. Biorefinery study of availability of agriculture residues and wastes for integrated biorefineries in Brazil. *Resources, Conservation and Recycling*. 2013, **77**, 78-88. https://doi.org/10.1016/j.resconrec.2013.05.007

FREITAS, F. F. et al. The Brazilian market of distributed biogas generation: Overview, technological development and case study. *Renewable and Sustainable Energy Reviews*. 2019, **101**, 146-157. https://doi.org/10.1016/j.rser.2018.11.007

GONÇALVES, A.L., PIRES, J.C.M. and SIMÕES, M. A review on the use of microalgal consortia for wastewater treatment. *Algal Research*. 2017, 24, 403-415. https://doi.org/10.1016/j.algal.2016.11.008

GUERI, M.V.D., SOUZA, S.N.M. and KUCZMAN, O. Parâmetros operacionais do processo de digestão anaeróbia de resíduos alimentares: uma revisão. *BIOFIX Scientific Journal*. 2018, **3**(1), 17-25. https://doi.org/10.5380/biofix.v3i1.55837

HIBBELER, R.C. Mecânica dos Fluidos. 1st ed. São Paulo: Pearson, 2017.

HORVÁTH, I.S., et al. Recent updates on biogas production - a review. *Biofuel Research Journal*. 2016, **3**(2), 394-402. Available from: https://doi.org/10.18331/BRJ2016.3.2.4

JAFAR, R. and AWAD, A. State and development of anaerobic technology for biogas production in Syria. *Cleaner Engineering and Technology*. 2021, **5**, 100253. https://doi.org/10.1016/j.clet.2021.100253

KUNZ, A., STEINMETZ, R.L.R. and AMARAL, A.C. Fundamentos da Digestão Anaeróbia, Purificação do Biogás, Uso e Tratamento do Digestato. 1st ed. Concórdia: Embrapa Suínos e Aves, 2019. Available from: https://ainfo.cnptia.embrapa.br/digital/bitstream/item/197183/1/Livro-Biogas.pdf

KUNZ, A. and SULZBACH, A. Kit Biogás portátil para análise de concentração de gás metano, amônia e gás sulfídrico em biogás. Concórdia: Embrapa Suínos e Aves, 2007. Available from: http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/439433

LEITE, S.A.F., et al. Biogas production on a small swine farm: Study of prediction using different models. *Chemical Engineering Transactions*. 2018, **65**, 85-90. https://doi.org/10.3303/CET1865015

LEITE, S.A.F., et al. Evaluating the Effect of Rumen Microorganisms in the Codigestion Process of Swine Manure and Rice Husk. *International Journal of Environmental Science and Development*. 2019, **10**(9), 280-287. https://doi.org/10.18178/ijesd.2019.10.9.1188

LINS, M.A., et al. Biogas Yield and Productiveness of Swine Manure for Different Reactor Configurations. *Journal of the Brazilian Association of Agricultural Engineering*. 2020, **40**(6), 664-673. http://dx.doi.org/10.1590/1809-4430-eng.agric.v40n6p664-673/2020

LÓPEZ-PACHECO, I.Y., et al. Phyco-remediation of swine wastewater as a sustainable model based on circular economy. Journal of Environmental Management. 2021, **278**, 111534. https://doi.org/10.1016/j.jenvman.2020.111534

MAO, C., et al. Review on research achievements of biogas from anaerobic digestion. *Renewable and Sustainable Energy Reviews*. 2015, **45**, 540-555. https://doi.org/10.1016/j.rser.2015.02.032

NAGARAJAN, D., et al. Current advances in biological swine wastewater treatment using microalgae-based processes. *Bioresource Technology*. 2019, **289**, 121718. https://doi.org/10.1016/j.biortech.2019.121718

NERES, L.M., RAMOS, H.R. and RÉGIS, M.M. Biodigester models used worldwide in the context of intelligent cities. *Revista Nacional de Gerenciamento de Cidades*. 2021, **9**(69), 77-88. https://doi.org/10.17271/2318847296920212802

NESHAT, S.A., et al. Anaerobic co-digestion of animal manures and lignocellulosic residues as a potent approach for sustainable biogas production. *Renewable and Sustainable Energy Reviews*. 2017, **79**, 308-322. https://doi.org/10.1016/J.RSER.2017.05.137

NOLAN, J. Gestão de Riscos na ISO 14001:2015 - O que, por que e como? 14001 Academy, 2015.

PORTO, B.H.C., et al. Socioenvironmental impacts of biogas production in a cooperative agroenergy condominium. *Biomass and Bioenergy*. 2021, **151**, 106158. https://doi.org/10.1016/j.biombioe.2021.106158

SOUSA, I.D.P., et al. Energy potential of biogas from pig farms in the state of Minas Gerais, Brazil. *Journal of the Brazilian Association of Agricultural Engineering*. 2020, **40**(3), 396-404. https://doi.org/10.1590/1809-4430-Eng.Agric.v40n3p396-404/2020

SOUZA, C.F., et al. Caracterização de dejetos de suínos em fase de terminação. *Ceres*. 2009, **56**(2), 128-133.

TEJASWI, D. and CHRISTOPHER, S. Techniques for environmental risk assessment: a review. *Rasayan Journal of Chemistry*. 2017, **10**(2), 499-506. http://dx.doi.org/10.7324/RJC.2017.1021657

Received: 8 September 2022 | **Accepted:** 25 April 2023 | **Published:** 23 June 2023